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Factors influencing the productivity of irrigated crops in Southern Peru, in relation to prediction by simulation models

Aan mijn drie vrouwtjes
Anne-Marijke, Maaike en Klaartje

M. N. Versteeg

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Proefschrift

ter verkrijging van de graad van
doctor in de landbouwwetenschappen
op gezag van de rector magnificus,
dr. C. C. Oosterlee,
in het openbaar te verdedigen
op woensdag 16 januari 1985
des namiddags te vier uur in de aula
van de Landbouwhogeschool te Wageningen

Versteeg, M.N. (1985). Factors influencing the productivity of irrigated crops in Southern Peru, in relation to prediction by simulation models. Doctoral thesis, Wageningen. X + 182 p., 26 tbs, 89 figs, 269 refs, Eng., Span. and Dutch summaries.

The objective of the study was to determine the growth potential of alfalfa, potato, Rhodes grass and maize in the irrigated desert of S. Peru, as at that production level the highest utilization efficiency of irrigation water is usually obtained. Important growth-influencing factors were identified for each crop. In addition, measured results were compared to results from simulation models developed in Wageningen.

Maximum annual alfalfa production was 27 t/ha dry forage. Experimental evidence suggested that assimilate partitioning favouring the root system, was a significant reason why yields were not higher. Other factors analysed were N_2 fixation, NPK fertilization, plant density decline, cultivar differences and weed infestation. Photosynthetis measurements on artificial swards are also presented.

Potato yields of 80 t/ha were recorded. Very high growth rates of 270 kg/ha.d were obtained with the local *andigena* cultivar, but growth duration was shorter and harvest index lower than those obtained in temperate regions. Results of a line source sprinkler irrigation experiment indicated low transpiration coefficients, but also large irrigation losses due to a low uptake capacity of the roots. Further data are given on leaf area development, light interception, cultivar differences, split fertilizer application, NPK uptake and NO_3-N concentration in the petioles.

Both C_4 crops, maize and Rhodes grass, demonstrated high growth rates during summer, but dramatic declines in the other seasons, probably due to cold nights. For high production, ample N supply is of paramount importance. Data concerning NPK concentrations and leaf area index are given for both C_4 crops. Maize growth was also strongly hampered by mechanical resistance of sandy desert soils, but on clay loam very high growth rates of 500 kg/ha.d were reached. Hybrids from other sources and maize grown in a warmer environment at sea level, showed slightly higher initial growth but at the expense of final yield.

The simulation model BACROS predicted the growth of maize and Rhodes grass during summer very well, but during the other seasons the simulations were too high as permanent damage to photosynthetic capacity due to low night temperatures was not taken into account. The very high growth rates of maize on clay loam could not be simulated by the model either. For the latter phenomenon and for the influence of mechanical soil resistance, model adaptations are presented and resulting simulations discussed.

The model PHOTON both under- and over-estimated the photosynthesis measured on artificial swards of alfalfa.

The simulation model ARID CROP was adapted to an alfalfa cutting management model that simulated reasonably accurately above and below-ground growth and reserve levels measured in S. Peru, at different cutting intervals from 21 to 53 days.

Main factors influencing regional irrigated crop production and usefulness of simulation for agriculture in developing countries are discussed.

Keywords: alfalfa, assimilate partitioning, critical concentration, crop growth simulation, cutting frequency, low night temperatures, maize, mechanical soil resistance, nitrogen, nitrogen fixation, nutrient uptake, reserves, Rhodes grass, root dry matter, Peru, phosphorus, photosynthesis, potassium, potato, potential growth, transpiration, water utilization efficiency.

Cover: Irrigating the crop. Picture by Felipe Guamán Poma de Ayala, Peruvian cronicler, XVIth century.

STELLINGEN

1. Simulatiemodellen kunnen als instrument bij landbouwkundig onderzoek in ontwikkelingslanden in de praktijk pas nut hebben als de simulaties in het gebied zelf kunnen worden uitgevoerd en het onderzoek zich over langere termijn uitstrekt.

   Dit proefschrift.

2. Potentiële, slechts door weersomstandigheden gelimiteerde groei wordt niet altijd verkregen door een gesloten, gezond en onkruidvrij gewas van voldoende water en meststoffen te voorzien.

   Dit proefschrift.

3. Het economisch opbrengstpotentieel van luzerne in subtropische gebieden kan aanzienlijk worden verhoogd door veredeling op een hogere spruit/wortel verhouding.

   Dit proefschrift.

4. Voor het voorspellen van potentiële gewasopbrengsten zijn simulatiemodellen niet nauwkeuriger dan eenvoudige berekeningen.

   M.N. Versteeg & H. van Keulen. Publikatie in voorbereiding.

5. De opvatting dat door regulering van de huidmondjesopening door de CO_2 concentratie in de stomataire holte, de efficientie van het watergebruik onder praktijkomstandigheden belangrijk wordt verbeterd, is onjuist.

   Penning de Vries, 1982. Agric. Res. Rep. 918: 87-97.

6. De irrigatieëfficiëntie zal wezenlijk verbeteren als iedere boer moet betalen voor het water dat hij werkelijk gebruikt.

7. De boer en/of boerin zullen een aktieve rol dienen te spelen bij zowel de opzet als de uitvoering van "farming systems research".

8. Bij onderzoek in ontwikkelingslanden zal bij de inrichting van een proefveld vaak meer rekening moeten worden gehouden met demonstratieve aspecten en minder met overwegingen van statistische aard.

9. Het gebruik van voor-opkomst herbiciden in lage doseringen, dat het wieden slechts gedeeltelijk vervangt, is veelbelovend voor het vergroten van de productiviteit van diverse kleinschalige landbouwsystemen in ontwikkelingsgebieden.

   M.N. Versteeg, 1978. PANS 24: 327-332.

10. Door mensen met een ruime veldervaring in ontwikkelingslanden tijdelijk in Nederland te stationeren om van hieruit effectief ontwikkelingsprojecten te begeleiden, wordt de uitvoering van deze projecten sterk verbeterd en wordt tevens de mogelijkheid voor een loopbaanperspectief als ontwikkelingsdeskundige vergroot.

Door tijdens een periode van baanloosheid van meet af aan hard te werken aan het verkrijgen van nieuwe of verbeteren van bestaande vaardigheden, wordt op zijn minst voorkomen dat bij langere duur van zo'n periode de positie op de arbeidsmarkt wordt verslechterd.

Van herstel van de democratie in Peru hebben tot nu toe vrijwel uitsluitend de economisch sterkeren geprofiteerd.

De huidige Israelische regeringscoalitie van Arbeiderspartij en Likoed, de economische crisis in dat land en de toenadering tussen PLO, Jordanië en Egypte, vormen een uniek gunstige combinatie van factoren om te komen tot een bevredigende oplossing van het Palestijnse probleem.

Bossen en andere vegetaties dragen niet bij aan de zuurstofvoorziening op aarde.

Een goed gezin is het halve werk.

Een Siamese tweeling is niet altijd een Siamese tweeling.

N. Versteeg

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geningen, 16 januari 1985

ACKNOWLEDGEMENTS

The data for this report were collected at the FAPROCAF project in Peru, a cooperation between the National Institute for Agricultural Research and Extension (Peru), the Hebrew University (Israel) and the Centre for Agrobiological Research (The Netherlands). The latter institute provided the facilities for the data-processing, modelling, writing and publishing. The research was sponsored by the Directorate General of International Cooperation of the Ministry of Foreign Affairs in The Hague.

I am greatly indebted to Prof. L. 't Mannetje, who accepted responsibility to promote this study just after his appointment to the Chair of Grassland and Forage Crop Husbandry in Wageningen, despite the fact that the actual research had been finished by then. His invaluable suggestions, especially at the beginning and end of writing, have contributed much to the final manuscript.

Dr. H. van Keulen, my co-referent, carried out the simulations described in this thesis and critically read the relevant chapters, in spite of his extremely busy working schedule. I am most grateful for his time-consuming efforts.

Sincere thanks are expressed to Dr. Th. Alberda, who was always the first to comment on the draft of each chapter and who gave strong moral support during the difficult period following the return from Peru, when my family was confronted with the insecurity of becoming one of the 800 000 unemployed in the Netherlands.

The production of the results in Peru are the fruit of much teamwork and I am most grateful to all concerned. I shall always remember with pleasure the field-work and discussions with the members of the crop and water team: I. Zipori, J. Medina and H. Valdivia. Many data were skilfully produced by the laboratory team: Ms. V. Frisancho, Ms. E. Gonzalez and Ms. G. Sanz, headed by M. de Wijs and his national counterpart E. Soto. However, a good deal of the work was done by the field workers and laboratory assistents, whom I wish to thank for their support (in alphabetical order): T. Chavez, J. Gutierrez, D. Javier, A. Melgar, F. Pari, L. Ramirez, A. Yajo, M. Yajo and R. Yajo.

Thanks are due to the administrative team in Peru: Ms. M. Llerena, Ms. F. Rendón, Ms. Y. Rendón, L. Ramos and J. Montoya, and also in the Netherlands: Ms. L. Pikstra and J.M. Nonnekes, particularly for their efficiency in dealing with work of the daily leadership of the FAPROCAF project, leaving me more time for the research itself.

I am also grateful to Dr. P. Gaastra for the hospitality at CABO after the end of my contract, and to C. Esquivel for his collaborative attitude during the project.

Thanks are due to Ms. M.J. de Kock and G. v.d. Sluis, for their help with the first pot experiment installed before my departure to Peru, to W. Louwerse and J. van Kleef for the photosynthetis measurements on alfalfa swards, and to Ms. O. Nijssen, Ms. G. Kooi, I.G.A.M. Noij, H. Haitsma and W. van der Putten, for carrying out part of the experimental work for their post-graduate study at the Agricultural University.

For the critical reading of parts of the manuscript I am much indebted to K.B.A. Bodlaender, Dr. B. Deinum, K. Scholte and Dr. D.E. van der Zaag.

Acknowledgement is also due to Ms. M.F. Wulff for carefully typing the manuscript, to G. Klingenberg for his help with the word processing and to G.C. Beekhof, who always amazed me by the speed with which he accurately and beautifully drew the many figures in this report.

Thanks also to Ms. P.A. Chadwick, who quickly and accurately corrected my English, and to the Agricultural University for sponsoring the correction work. For improving the Spanish summary I am indebted to J. Boixadera.

The printing of the manuscript was carried out efficiently by Ponsen & Looijen in Wageningen.

Last, but no means least, I wish to thank all those from whom I received moral support. In particular, my wife Anne-Marijke and my daughters Maaike and Klaartje.

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1 *INTRODUCTION*

1.1 GENERAL

This thesis is the result of field research carried out in Peru, supplemented with glasshouse and modelling studies in Wageningen. The field work was part of the FAPROCAF project (Spanish acronym of "factors influencing food and fodder crop production in the desert areas of Southern Peru") and started effectively in January 1978, as a continuation of previous research on the relation between water, nutrient supply and dry matter production, in a cooperative project between Israel and the Netherlands. In this latter project, carried out in Israel between 1970 and 1975, crop growth under optimal supply of water and minerals was thoroughly studied (Van Keulen, 1975), the aim being to collect data that could be used for the improvement of agricultural practices in developing countries with similar conditions. In that respect, the dry and flat coastal areas (pampas) of south-western Peru seemed to be suitable for the following reasons:

- Precipitation is practically zero, but a limited amount of water is available, because several rivers carry water from the high Andes to the Pacific through these plains. The valleys of these rivers have been used for irrigated agriculture for a long time and from the time just before the Second World War the Peruvian Government has extended the irrigated area to parts of the pampas.
- Both Israel and the Netherlands were already supporting these irrigation extensions by means of an animal husbandry improvement program (The Netherlands) and of assistance in planning and implementation of a sprinkler irrigation system (Israel).

Because of these favourable conditions, a tripartite agricultural research project between the Netherlands, Peru and Israel was started. The project was sponsored by the Directorate General of International Cooperation of the Dutch Foreign Office which, in turn passed the responsability for execution of the project on to the Centre for Agrobiological Research (CABO) in Wageningen. The other parties actively involved in the project were the National Institute for Agricultural Research and Extension (INIPA, Peru) and the Faculty of Agriculture of the Hebrew University (HU, Israel).

An important aspect of the research programme was to that in addition to obtaining results that could be applied for the benefit of the region itself, the data could be used for the prediction of agricultural production possibilities in comparable areas elsewhere. Therefore, the programme was geared to obtain additional data that could serve to develop causal relationships and that could ultimately be used to test and improve existing simulation models.

For reasons that will be explained below, the field work covered the crops alfalfa or lucerne (*Medicago sativa*), potato (*Solanum tuberosum*), Rhodes grass (*Chloris gayana*) and maize (*Zea mays*). Simulation modelling studies were carried out for the same crops except the potato. Supplementary data for modelling purposes were obtained from glasshouse experiments with alfalfa in Wageningen.

1.2 IMPORTANCE OF IRRIGATION IN ARID AND SEMI-ARID REGIONS

Around 36% of the land surface is situated in arid and semi-arid regions, excluding another 7% of man-made desert (Fig. 1.1). According to Zonn (1977), 5.9 million km^2 are extremely arid (annual precipitation less than 50 mm), 21.5 million km^2 arid (precipitation between 50 and 150 mm) and 21 million km^2 semi-arid (precipitation between 150 and 250 mm). There are several more criteria to define these areas, but whichever one is chosen, a low and erratic rainfall is always a major characteristic. So, in general, agricultural outputs are highly variable and very low on average. Although this level can be improved without the use of supplementary irrigation (Penning de Vries & Djiteye, 1982), high and regular yields can only be obtained if additional water can be made available. If the latter condition can be met, potentially high yields can be obtained in many of the most arid regions because of their inherent environmental characteristics such as high solar radiation, favourable temperatures throughout the year and therefore long growing seasons.

In the last fifty years the total irrigated area in the world has been trebled and now amounts to approximately 240 million hectares (Malone et al., 1981; Holy, 1982). From Table 1.1 it can be calculated that almost half the total area of the world under irrigation, (about 114 million ha), is situated in the arid and semi-arid zone. Although this is only 2% of the total available land in these climates, on the basis of land in agricultural use two out of every 15 hectares under cultivation are already being irrigated. There are considerable differences among the countries involved, but in the more densely populated areas of Asia more than 25% of the cultivated area is irrigated, and this area is increasing all the time. Malone et al. (1981) stated that roughly 40% of the increase in food production in developing countries over the last decade is the result of expanded and improved irrigation facilities.

In many countries of the semi-arid and arid areas, water use for irrigation already represents a substantial proportion of the available water resources. Especially in periods of severe drought, the amount of water necessary may exceed the available resources and most of it is lost from the catchment by evapotranspiration from the irrigated fields.

Although unused fresh water resources in many areas are still considerable, some arid areas, e.g. in North Africa and the Middle East, have few undeveloped water resources left (Holy, 1982). Agricultural development in these regions should therefore place the emphasis on production increase per unit of irrigation water.

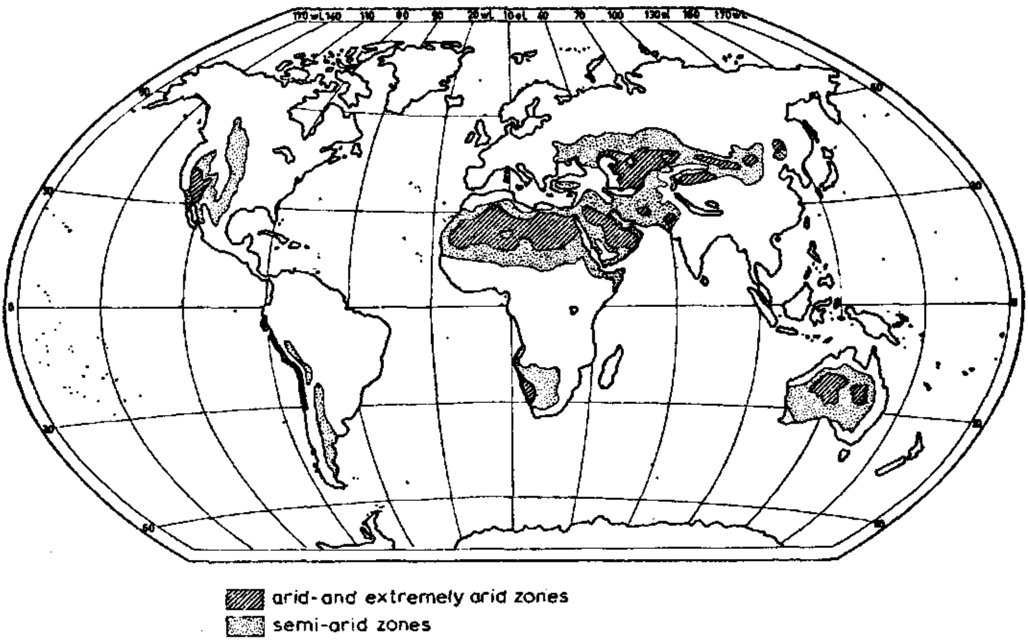


Fig. 1.1 World distribution of arid and semi-arid zones (after Skibbe, 1958).

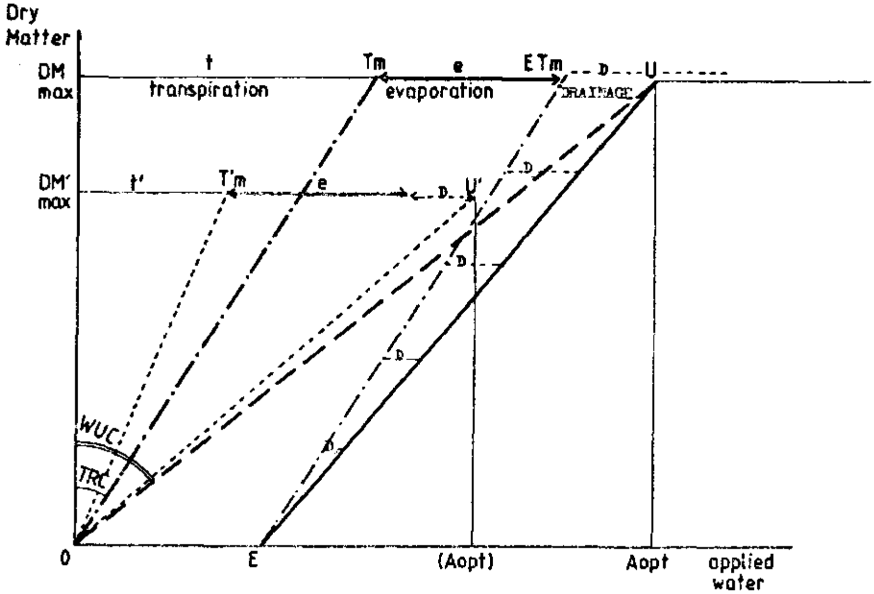


Fig. 1.2 Schematic presentation of the relation between dry matter production (DM) and the quantity of water furnished to the field. Deduced from Valdivia et al. (1982). Explanation in text.

Table 1.1 World irrigated lands in the arid and semi-arid zone (adapted from Zonn, 1977)

Country cultivated	Cultivated areas and areas under perennial crops (1000 ha)	Annually irrigated areas (1000 ha)	areas to be (%)
Kuwait	0.6	0.6	100.0
Pakistan	21700	12400	57.1
Israel	417	173	41.4
Iraq	10163	4000	39.3
Afganistan	7980	2900	30.5
Iran	16727	4360	26.0
Lebanon	316	80	25.3
India	164610	38969*	23.6
Saudi Arabia	809	131	16.1
Syria	5899	600	10.2
Yemen Arab Republic	1200	100	8.9
Turkey	26068	1724	6.6
Jordan	1300	60	4.6
Total Asia	257190	65498	25.5
Egypt	2852	2852	100.0
Sudan	7100	2520	35.4
Somali	957	162	16.8
Morocco	7900	680	8.5
Libya	2521	120	4.7
Algeria	6792	300	4.4
Senegal	5564	119	2.1
Tunis	6000	100	1.6
Mali	11600	66	0.5
Botswana	519	2	0.4
Ethiopia	13250	40	0.2
Republic of South Africa	12058	1000	0.8
Niger	15000	5	0,03
Total Africa	92113	7966	8.6
USA	191053	21489**	11.2
Mexico	27469	4200	15,3
Total USA + Mexico	218522	25689	11,8
Australia	44610	1581	3.5
USSR	232609	13437***	6.0

*Area of irrigated arid land: 16397 thousand ha.
**Area of irrigated arid land: 17600 thousand ha.
***Area of irrigated arid land: 8500 thousand ha.

Actually, about 13% of the world population lives in these arid and semi-arid regions. From Feyen's data (1979) it can be estimated that the acreage presently under irrigation in this zone alone, could produce enough food for half the world population. Such a statement is in sharp contrast to the actual situation of frequent hunger or malnutrition of many of the inhabitants of these areas. More attention to the development of the production potential of already existing irrigated areas in many countries seems, therefore, an obvious strategy for the improvement of the actual world food situation.

1.3 PRODUCTIVITY PER UNIT AREA

Although indicative data on agricultural production of different countries are easily obtained from F.A.O. Yearbooks, there is no separation in yields obtained with and without irrigation.

To get an impression of the productivity in irrigated agriculture in various countries in dry regions, data from Faki (1981), Johl (1980) and Shalhevet et al. (1979) were combined with those from the F.A.O. Yearbook 1981 (FAO, 1982) for countries with a high proportion of irrigated agriculture and for crops that are normally irrigated. As a reference, average data on "good yields" in irrigated agriculture from Doorenbos & Kassam (1979) are included (Table 1.2).

Table 1.2 Average yields (kg/ha) obtained in some irrigated crops, in various countries in dry regions

	Egypt	Israel	Iraq	Jordan	Kuwait	Pakistan	Sudan	Syria	Dem. Yemen	"good yield" reference*
Wheat	3470	4500	1060	1800	-	1640	1430	2100	1860	5000
Maize	3780	5000	2900	1100	3000	1365	740	1900	2540	7500
Rice	5410	-	3125	-	-	2560	1700	5200	-	4700
Potato	17890	35460	15600	13300	15000	10350	19230	16400	5230	30000
Seed cotton	2770	3790	1060	-	-	1040	1410	2500	1350	4500
Tomato	17400	43900	10800	17010	21070	-	11580	18050	-	55000
Water-melon	23460	14840	12650	8510	-	-	28150	9100	-	30000

*Deduced from Doorenbos & Kassam, 1979.

With the exception of Israel and Egypt, most countries obtain less than half the "good yield" values. The latter levels are certainly not exceptionally high, because experimental yields of about twice these values are reported.

As indicated in Section 1.1, land resources in arid and semi-arid regions are not in fact the limiting factor, but water. Therefore, more emphasis should be placed on the production level per unit of water.

1.4 PRODUCTION PER UNIT OF IRRIGATION WATER

Data on production in relation to the amount of irrigation water of different regions are scarce. In general, a supply between ½ to 2 liters per second (l/s) of water is needed to irrigate one hectare, if the amount of precipitation is insignificant. This equals an annual availability of 1600 to 6300 mm of irrigation water.

The efficiency of use of the available irrigation water can be evaluated in terms of the Water Use Coefficient (WUC), defined as the amount (kg) of irrigation water applied per kg of dry matter produced and the Transpiration Coefficient (TRC), defined as the amount of transpired water per kg of dry matter produced. So the TRC is an indicator of the plant's physiological characteristics with respect to water use effiency in a certain climatological environment. The WUC also depends on irrigation techniques and soil charasteristics (Zipori & Valdivia, 1982). From the difference between WUC and TRC, the magnitude of non-productive water loss can be calculated.

In the following Section an estimate will be made of the average WUC of various crops during their linear growth stage (defined as the period of maximum growth rate when the canopy is closed, green and active) for the countries listed in Table 1.2. For this purpose total dry matter production (DM) of various crops was calculated, based on an estimate of the percentage dry matter (% DMy) in the harvested material and the harvest index (HI), the ratio between economic yield and total dry matter. From these assumptions, a Yield Multiplication Factor (YMF) was calculated, that when applied to the yields given in Table 1.2, results in the total dry matter production. In addition, a certain Gross Growth Period (GGP) was assumed for each crop, defined as the number of days between sowing and harvesting in the case of direct sowing in the field.

Assuming that the average rate of dry matter accumulation during the linear growth stage (LGR) is twice the average growth rate, LGR was then calculated, using the equation: LGR = 2DM/GGP.

A summary of the parameter values for the various crops is presented in Table 1.3.

Table 1.3 Parameter values for various crops, used to estimate the average Linear Growth Rate (LGR, in kg dry matter/ha.d) of some crops in irrigated areas. See text for explanation of abbreviations.

Parameter:	% DMy	HI	YMF	GGP (days)
Crop:				
Wheat	88	0.44	2.00	110
Maize	88	0.44	2.00	150
Rice	88	0.44	2.00	140
Potatoes	22	0.80	0.28	120
Seed cotton	88	0.25	3.52	160
Tomatoes	6	0.35	0.17	140

The average linear growth rates estimated on the basis of these assumptions from the data of Table 1.2 are presented in Table 1.4. From the average LGR values for each country, the average WUC values are calculated, assuming a water supply of 1 l/s and absence of precipitation (Table 1.4).

Table 1.4 Linear growth rate (LGR in kg/ha.d) of some crops in irrigated areas of countries in dry regions, and the resulting average water-use coefficient (WUC in kg water/kg dry matter) for each country, assuming 1 l/s irrigation water supplied to the fields and no precipitation.

	Egypt	Israel	Iraq	Jordan	Kuwait	Pakistan	Sudan	Syria	Dem. Yemen	Good yield reference
Wheat	126	163	38	66	-	60	52	77	67	182
Maize	101	133	77	29	80	36	19	50	67	200
Rice	155	-	89	-	-	73	48	148	-	134
Potato	84	166	73	62	70	48	90	77	24	140
Seed-cotton	122	167	47	-	-	46	62	110	59	198
Tomato	42	107	46	41	50	-	28	43	-	133
Average LGR	105	147	62	50	67	53	50	84	54	165
Average WUC	823	588	1394	1728	1290	1630	1728	1029	1600	524

The calculations clearly indicate that in countries with a high crop production (Israel; "good yield" reference) only about one third of the amount of water is used to produce 1 kg of plant biomass than in countries with a low level of crop production. In other words, in countries with a low crop production in fact 2/3 of the scarce water is non-productive. This unused water disappears through direct soil evaporation and drainage below the root zone. The latter component can sometimes be used again in lower lying fields or to recharge the groundwater, but often this water is lost for local crop production altogether. In some cases, it may cause an undesirable rise of the groundwater table, leading to salinity problems and subsequent loss of agricultural land (Arnon, 1972). Also, when the WUC values from Table 1.4 are compared with TRC values obtained in similar regions, varying from about 150-300 for C_4 plants to 300-800 for C_3 plants (Briggs & Shantz, 1913, 1914, 1917; Meyer, 1972; Breman et al., 1982; Valdivia & Zipori, 1982), it is obvious that in many countries large amounts of water are not used by the crops.

Especially in regions where available irrigation water is relatively scarce, this results in a considerable loss of agricultural productivity, food and prosperity in general.

The options for improving the efficiency of use of applied water may be deduced from Fig. 1.2, which is a schematic representation of the results of a maize sprinkler irrigation experiment with maize during a complete growing period, carried out in Peru by Valdivia et al. (1982). Here, the slope of the line Tm represents the TRC, whereas the slope of the line U represents the WUC. In this schematic set-up direct soil evaporation is assumed constant (0 E = Tm ETm), which is not correct as soil evaporation will increase when crop growth and hence soil cover is reduced. It is also assumed that there is sufficient drainage capacity of the soil so that excess water is rapidly removed without causing aeration problems. Removing these simplifications would only reinforce the subsequent conclusions .

With an increasing amount of available water, dry matter production increases linearly until a certain maximum value (DMmax), as shown by De Wit (1958). The level of the maximum depends on crop species and environmental conditions. In the absence of pests and diseases, without interfering weeds and with an optimum supply of nutrients throughout, DMmax represents the potential dry matter production level, as dictated by available irradiance and ambient temperature regime. Application of water in excess of that necessary to reach DMmax will not result in higher production but will only waste water. At a low level of nutrient availability and hence a low level of DMmax, there is a greater tendency for excess moisture application (water lost via percolation), a phenomenon reported from many irrigated areas (Arnon, 1972; Garuthers & Clark, 1981).

Comparing line U to line Tm in Fig. 1.2 shows that more than half the water applied may not be used for transpiration by the plant, but is lost by evaporation from the soil surface and drainage below the root zone. Especially early in the growing period, when the demand of the crop for water is low, these losses can be very high. The proportion of water transpired decreases at applications below and above the amount of water (Aopt), that is just enough to realize DMmax. Hence, the first step towards improvement is optimizing the proportion of water transpired within a certain irrigation system, by the highest possible production with just enough water to reach that level. This also implies that if only a limited amount of irrigation water is available, which is insufficient to reach DMmax on the total available acreage, it is preferable in terms of dry matter production to irrigate only part of the acreage to Aopt, rather than to distribute the water evenly over the whole area and reach a lower level than DMmax and hence suffer greater relative water losses. On the other hand, several crops (cotton, sorghum, soybean, sunflower etc.) have the ability to increase the harvest index under water stress (Doorenbos & Kassam, 1979) and in those cases the distribution of a sub-optimal quantity of water over a larger area may be more efficient.

A second option to improve the efficiency of irrigation is to curtail water losses via more efficient application techniques like sprinkler irrigation and drip irrigation. With very efficient irrigation techniques WUC will approach TRC. The scope for improvement offered by this option, depends on the available irrigation system, bearing in mind environmental conditions such as climate, soil conditions, quality of irrigation water and topography. A thorough analysis of the irrigation losses, together with a cost-benefit analysis of possible improvements must be worked out by hydrologists or irrigation specialists together with economists. Such an analysis is beyond the scope of this thesis.

A possible improvement could also be obtained via plant adaptation so that a CO_2-governed stomatal regulation mechanism is induced. In that way, the transpiration may be reduced by 40 to 50%. However, dry matter production is also reduced, but only by 20 to 25%, so that the overall TRC decreases by 20 to 25% (Penning de Vries, 1982b). Although there is a good deal of speculation about the impact of such improvements (Spiertz, 1981; Penning de Vries, 1982b) it can be seen in Fig. 1.2 that the ensuing improvement in WUC is very small. It would appear that if the loss by direct soil evaporation exceeds total transpiration, as is common in natural rangelands as in the Sahel (Stroosnijder & Koné, 1982), CO_2-governed stomatal regulation is not advantageous in terms of total dry matter production. However, the possibilities for survival and seed setting increase. It may be concluded, therefore, that in areas where water is scarce, the aim should be to remove all other constraining production factors as much as possible. In such a way, the efficiency of water utilization can be optimized. The objective of the studies reported here was to develop efficient methods to produce reliable data necessary to estimate the highest possible level of production in arid regions with the aim of optimizing efficient use of the scarce, and therefore expensive, irrigation water.

To establish the scope for improvement of irrigated agriculture in arid regions, it is essential to know the technical options. In addition, however, there may be other significant constraints that prevent the realization of these options, such as lack of finance, poor credit facilities, lack of fertilizers and pesticides at reasonable prices, insecure marketing perspectives etc. In many cases these constraints must be eliminated before any technical improvement can be succesfully introduced. Efficient development planning proceeds from weighing up the different sound technical options, but it must contain efficient strategies to remove the non-technical constraints.

1.5 APPLICATION OF SIMULATION MODELS IN THIS RESEARCH PROGRAM

System analysis and simulation found their origin in the engineering sciences some 30 years ago. The considerable succes obtained with this methodology in the technical sciences, also inspired biologists and agronomists to apply the technique in their fields of interest about ten years later (Van Keulen, 1982). Simulation may be defined as the building of a mathematical model and the study of its dynamic behaviour. Models are simplified representations of systems, where a system is defined as a coherent part of reality, with well-defined boundaries. A model of a system can be developed if the relations between the relevant elements of the system can be described in quantitative terms. Dynamic simulation models of plant growth permit the analysis of real phenomena with respect to crop production.

In their analysis of crop growth models, an attractive schematization of systems of growing vegetations and crops was proposed by De Wit & Penning de Vries (1982), distinguishing four production situations:

- Production situation 1: only irradiance and temperature determine plant growth. This situation is found in well-managed irrigated agricultural systems with optimal use of nutrients, disease control, management practices etc.
- Production situation 2: as for situation 1, but soil moisture availability may at times limit growth rate. The water balance of the soil is an important part of the models describing this production situation.
- Production situation 3: as for situation 2, but the availability of nitrogen may at times also limit growth rate. Here the nitrogen balance of soils and plants is added to the model.
- Production situation 4: as in situation 3, but low availability of other nutrient elements, particularly phosphorus, may reduce growth at some stage.

The extensive knowledge available about the carbon and water balance of growing crops means that models for production situations 1 and 2 are now well developed. On the basis of their level of development, these models can be classified as comprehensive (Penning de Vries, 1982a), because the essential elements they describe are thoroughly understood and much of this knowledge is incorporated. If enough basic data of sufficient quality are available, the predictions are often good.

As soon as such a level of comprehension was reached, it was possible to simplify these models into so-called summary models. Here, only the essential aspects are considered and formulated in less detail. Because of this, summary models are more accessible to users and may be used on micro-computers.

Models describing production situations 3 and 4 can be classified as preliminary. Not all underlying concepts are clearly understood and therefore their explanatory value is limited and not very accurate. The structure of and data used in these models reflect current scientific knowledge (Penning de Vries and Van Laar, 1982). A considerable amount of experimentation is still necessary to develop these models further. Models at this level of sophistication are therefore more suitable as a research tool than for application purposes.

In this thesis, results obtained with existing plant growth simulation models, developed by the Wageningen group (De Wit, 1970; Van Keulen, 1975; De Wit et al., 1978; Van Keulen et al., 1981; Penning de Vries & Van Laar, 1982) with parameter inputs from the experimental site in San Camilo are compared with real field data and evaluated in two ways:

1. From the agricultural development planner's point of view, with emphasis on the ability to obtain quickly accurate predictions, if only a limited amount of data is available.
2. From the point of view of agricultural research, with emphasis on the ability to test hypotheses, to indicate major gaps in the knowledge and to assist in setting priorities for further research efforts.

The models used were the detailed, comprehensive BACROS - and the less detailed, but still comprehensive ARID CROP model.

The first model, developed by a group of researchers in Wageningen (De Wit et al., 1978), simulates most of the relevant physiological processes of crops, growing potentially (production level 1) on an hourly basis. It was used for maize and Rhodes grass in our situation. At the same time, it was attempted to adapt the model for situations where soil mechanical resistance interferes with optimal root development of maize.

The second model was developed for situations where only the water supply may be limiting (production level 2). It was primarily developed for Mediterranean conditions (Van Keulen, 1975; Van Keulen et al., 1981) but, with slight modifications, it appeared also applicable to Sahelian conditions (Penning de Vries & Djiteye, 1982). The model is less detailed than BACROS and simulates crop growth and related processes on a daily basis. An attemption was made to adapt the model for the simulation of alfalfa growth under San Camilo conditions, when subject to different cutting regimes.

Finally, the PHOTON model was used for simulation of canopy photosynthesis, respiration and transpiration in enclossures, in comparison to data measured with alfalfa in Wageningen. PHOTON is almost identical to BACROS, except that it uses time steps of a few minutes (Penning de Vries & Van Laar, 1982) and can therefore be used for the simulation of these types of measurements. Similar evaluations of this model have been carried out with several crops, in enclosures in the field and in the greenhouse, all in the Netherlands (Van Laar et al., 1977; Dayan & Dovrat, 1977; De Wit et al., 1978; Penning de Vries & Van Laar, 1982).

2 *DESCRIPTION OF THE PROJECT*

2.1 THE PRESENT AGRICULTURAL SYSTEM IN THE REGION

As already mentioned, the outstanding characteristic of the coastal area of Peru is the shortage of water, which is a major factor constraining crop production. Rainfall is virtually absent and irrigation water is obtained from rivers, originating in the high Andes. Traditionally, only valley areas close to the rivers could be irrigated. In the course of time, considerable improvement was obtained by the construction of dams, creating several reservoirs. In this way, the river flow downstream could be regulated so that areas at a greater distance could also be irrigated. In addition, water for irrigation was transported out of the canyon thus making possible the settlement of the desert plains (pampas).

Until recently only gravity irrigation was practised. This system causes heavy water losses from percolation, due to the sandy-stony characteristics of most of the pampas soils. For the last ten years, however, all new settlements have been making use of sprinkler irrigation.

Although the reservoirs in the high Andes are meant to ensure a regular water supply, the precipitation in the catchment areas shows such year-to-year variability that still considerable fluctuations occur in the amount of water available to the farmers.

In the traditional farming systems of the river valleys as well as in the settlements in the pampas, alfalfa is a major crop. Its efficient nitrogen fixation overcomes the limitations set by the low nitrogen content of the soil. If enough irrigation water is available, reasonable yields are obtained by farmers without the use of significant amounts of fertilizer. This is probably also because the alfalfa is generally grazed, which is less demanding on minerals than the cutting system. The importance of alfalfa within this farming system was further increased by the establishment of a milk-processing plant which stabilized farm income. Generally, after 3 to 5 years the alfalfa stand density declines considerably and the fields become infested with weeds, especially Bermuda grass (*Cynodon dactylon*) and Kikuyu grass (*Pennisetum clandestinum*). This necessitates crop rotation, so that alfalfa is replaced by arable crops, mainly potatoes, maize, onions and garlic. These crops benefit from the nitrogen accumulated in the soil during alfalfa cultivation and possibly also from improved soil physical conditions, due to residual organic material. In addition, the high financial returns of these crops justifies a labour-intensive management system aimed at the elimination of weeds. After one or two years, the rotation cycle is resumed with alfalfa.

The mixed dairy-farming system with alfalfa as a central crop has proved to be sound from an economic as well as a soil fertility point of view. Because of the reputation of alfalfa as a high water-consuming crop, special attention in the FAPROCAF project was given to this aspect in comparison to some other crops.

2.2 SCOPE AND OBJECTIVES OF THE PROJECT

2.2.1 *General outline*

It follows from the foregoing that the research project was focussed on the achievement of optimum yields with minimum water consumption. To attain this goal, two major lines of research were formulated, each being the responsibility of one guest researcher and his Peruvian counterpart:

I. Potential production: the study of growth of different crops under optimal supply of water and nutrients and the determination of the most important limiting factors to achieve this level. Those mainly responsible for this research were the present author and Jorge Medina of INIPA (Peru).

II. Water-soil-plant relationships: the response of crops to water applications, determination of different crop transpiration coefficients and the study of water losses in different pampa soils and under several different crops and irrigation systems. Those mainly responsible for this work were Isaac Zipori of HU (Israel) and Huber Valdivia of INIPA.

The data obtained in the field were supported by plant-soil-water analyses, executed in a laboratory that was installed and brought into operation within the framework of the project. Those mainly responsible for this task were Martin de Wijs (CABO) and his Peruvian counterpart Egberto Soto (INIPA).

The team in Peru received professional support from CABO in Wageningen, the Netherlands, and HU in Israel, via comments on progress reports, annual short missions and the dispatch of relevant literature, materials that were difficult to obtain locally, spare parts, etc.

2.2.2 *Experiments related to potential production*

Investigations were mainly focussed on four crops, representing C_3 and C_4 pathways of photosynthesis and annual as well as perennial crops, viz. alfalfa (C_3 perennial), Potato (C_3 annual), Maize (C_4 annual) and Rhodes grass (C_4 perennial). These crops were chosen because of their significance in the regional agriculture and because of the existing simulation experience in Wageningen and Israel. Both perennials represented extremes in this aspect: alfalfa being the very important regional crop but with practically no simulation experience available and Rhodes grass with considerable simulation experience (Dayan & Dovrat, 1977; Dayan et al., 1981a,b), but as yet of no practical value in the region.

To obtain a comparative basis for the relevant crops, first growth curves under optimal supply of water and nutrients were determined through periodic harvests. This was done to rapidly detect any unusual growth behaviour and to produce validation data for future simulation. By NPK analyses of plants, uptake curves for these elements were determined to serve for fertilization planning and to test the nutrient status of the crop. In alfalfa, maize and Rhodes grass fertilizer treatments were also given to obtain some insight into the soil-availability of NPK for the crop involved. In maize, an additional pot experiment was carried out to test possible micro-element deficiencies.

During the experiments, periodic measurements of relevant crop parameters such as leaf area index (LAI), specific leaf area (SLA) and light interception by the canopy were made. The data were used during validation and adaptation of existing simulation models.

Because alfalfa is the most important crop in the region and because of the relative lack of data under comparable conditions, extra emphasis was given to this crop by means of a crop management experiment, a cutting frequency experiment and additional pot experiments to determine data on root development and nitrogen fixation. Parallel to these activities in Peru, photosynthetis measurements of artifical swards of alfalfa in the greenhouses of CABO in Wageningen were carried out.

2.2.3 *Water-soil-plant relationships*

In order to measure crop response to water availability, experiments were carried out with alfalfa, maize and potato. This response was partially measured by means of irrigation experiments with a fixed number (5) of watering treatments, and partially by means of the so-called line source technique, in which the quantity of water is negatively correlated with the distance from a single irrigation line (Hanks et al., 1976). In addition, transpiration and dry matter production of alfalfa, maize, Rhodes grass and rye grass, grown in small containers, was measured by weighing.

Several pampa soils were compared in free drainage lysimeters for water retention capacity, leaching pattern and relative crop productivity. The leaching requirement of some soils was also determined in the field.

2.3 CLIMATE AND SOILS OF THE AREA

2.3.1 *Climate*

Most of the coastal area of Peru is characterized by the virtual absence of precipitation. If this lack of precipiation can be corrected with enough irrigation water and if sufficient fertilizer is available, crop growth is only dependent on temperature and irradiance. Along the Peruvian coast (up to 2000- 2500 m altitude), temperature and irradiance are mainly determined by altitude and latitude and do not vary much from year to year.

At the experimental station of San Camilo (16°42'S,71°11'W, altitude 1300 m a.s.l.), where most of the experiments were carried out, irradiance is high, varying between about 2000 J/cm^2.d in winter (June-July) and 3000 J/m^2.d in summer (December-January) (Fig. 2.1b).

During the year, there is little variation in the average daily maximum temperature, but the fluctuation in minimum temperature is greater as it varies between 7 °C in winter and 13 °C in summer (Fig. 2.1a).

Evaporative demand is high. Class A-pan values of between 6.3 and 8.7 mm/d were measured, which is equivalent to a range between 3.8 and 6.9 mm/d when calculated according to Penman (1948) (Fig. 2.1c).

The climatological conditions mentioned above are representative of the pampas of Majes, La Joya and Siguas, where most of the recent and future irrigation projects in Southern Peru have been planned. In low coastal regions, temperatures fluctuate somewhat more (depending on the presence of mist) around a level which is about 5 to 9 °C higher. In the higher Andes valleys, temperatures are lower and nights with frost are common during winter.

2.3.2 *Soils and irrigation water*

The pampa soils at the experimental site can be classified as sand or loamy sand with a fair amount of stones and gravel. Variability is high, root penetration is generally quite low. However, the infiltration capacity is high (30-50 mm/h). Water retention capacity is low (field capacity is about 10 cm^3/cm^3). Cation exchange capacity (CEC) is very low, because of the small amount of fine material. Other parts of the pampas have even more stones, sometimes occupying up to 30 to 40% of the soil volume and so lowering the water retention capacity even more. Virgin soils are saline and must be leached from excessive salts before the first cropping.

These characteristics can be understood from the geological history, the pampa being a basin that was filled with material, mostly sand, stones and gravel transported from the Andes (Medina, 1972; Zipori & Mena, 1982).

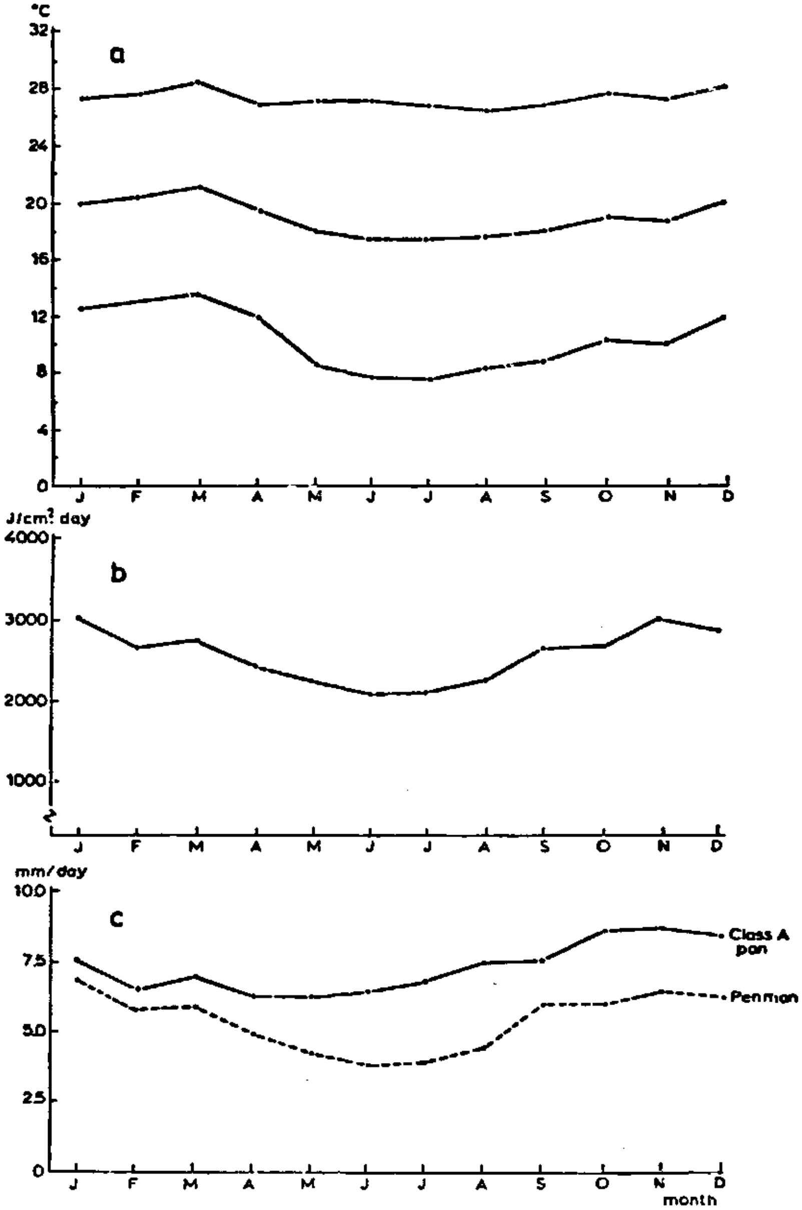


Fig. 2.1 Average monthly values (1980-'81) of different climatological parameters in San Camilo, Peru. a: Minimum, medium and maximum temperature (^{o}C); b: Global irradiance ($J/cm^2.d$); c: Class A pan and Penman evaporation (mm/day).

The water currents had varying energy levels depending on the rain intensity in the mountains, causing the formation of differently textured lenses. This resulted in the large horizontal and vertical variability of these soils. Water in the closed basin was mainly lost by evaporation, causing the actual salinity of virgin soils.

The low root permeability, low water-retention capacity in combination with a low CEC and a high water infiltration rate make these pampa soils very susceptible to loss of irrigation water and minerals by percolation. Sub-soiling (to 0.90 m) improves rooting depth and reduces these losses. The experimental fields in San Camilo, on a stone-free basis, consist on average of 90% sand, 5% loam and 5% clay and have a pH-KCl of 7.2-7.5. Most experiments were carried out on soils that had been under cultivation for more than two years. These soils had, after digestion, a total N content of 0.2 - 0.3 g/kg dry soil (Kjeldahl), an available P content of 5 mg/kg dry soil (Olsen extraction) and a K content of 170 mg K/kg dry soil (by ammonium-acetate extraction).

Valley soils generally contain much more fine material and can be characterised as loam to clay loam. The irrigation water in San Camilo contained on average 4.2 mg N/l, 0.4 mg P/l and 11.8 mg K/l.

2.4 MEASURING TECHNIQUES

- Most CLIMATOLOGICAL DATA were recorded at the station: temperature and relative humidity with a thermohygrograph, open pan evaporation with a class A pan, irradiance with a Kipp integrating radiometer and daily windrun with a cup anemometer. Other characteristics such as dew point and hours of sunshine were obtained from a meteorological station in San Isidro, 14 km from the experimental site.
- DRY MATTER PRODUCTION was obtained from a representative sample (generally between 5 and 10 m^2), that was harvested mechanically, leaving a stubble of about 5 cm and weighed in the field. Immediately a sub-sample was taken and put in a paper bag, that was subsequently enclosed in a thick plastic bag. In the laboratory, the paper bag and contents were weighed, dried in an oven at 70 °C, and weighed again to determine dry matter percentage, so that ultimately the dry matter production of the plots could be calculated.
- Sometimes, ROOT BIOMASS of alfalfa was determined by excavating a complete soil column with a cross section of 0.1 m^2 up to the deepest roots. The whole column, with the plants, was taken to the laboratory and the soil carefully washed out. Shoots were then cut at the same level as in the field and above and below ground dry weights were determined and the root-shoot ratio calculated. After multiplying this ratio by the production of the field, the below-ground biomass was obtained.
- LEAF AREA INDEX (LAI), the ratio of leaf area to soil surface area, was determined after measuring the leaf area of plant samples with an electronic surface meter. The measurement is rather time-consuming and therefore only small samples, taken from the field within frames of 0.1 or 0.5 m^2, could be handled. LAI was then calculated by direct conversion, but for some crops like alfalfa and potato, highly variable results were produced due to the size of the sample. This variability could be obtained by determining the dry weight of the leaf samples, of which the surfaces had been measured. The SPECIFIC LEAF AREA (SLA), the ratio between leaf area and leaf weight, which is much less influenced by the size of the sample, was then calculated. Using this parameter, the LAI was determined from the dry weights of the leaves, together with the above-ground dry

matter production measurements.

- LIGHT EXTINCTION in canopies was measured with a bar of 1 m length, fitted with photosensitive cells. The value obtained below the canopy was then compared with the value of the measurements above it. In this way, the relative amount of light absorbed by the canopy was calculated.
- Measurements of PHOTOSYNTHESIS, RESPIRATION AND TRANSPIRATION were carried out with alfalfa of single plants in a static assembly for routine measurements, as described by Louwerse & Van Oorschot (1969) and on artificial swards in enclosures by means of mobile equipment, described by Louwerse & Eikhoudt (1975) and Louwerse (1980). In both assemblies, the determination of CO_2 and water vapour exchange rates are based on, with an infra-red gas analyzer measured differences in, respectively, the CO_2 concentration and humidity of the incoming and outgoing airstream of the plant chamber or enclosure, simultaneously with the measurement of the corresponding flow rates.
- Laboratory determinations of NITROGEN were carried out according to the Kjeldahl method; PHOSPHORUS and POTASSIUM in plants were determined after digestion in a mixture of sulphuric and nitric acid (Schouwenburg & Walinga, 1978). Potassium in soils was extracted by an ammonium acetate solution and phosphorus using Olsen's method (Hesse, 1971). Extracts were then analysed by colorimetric techniques (P) or by flame spectrophotometry (K).
- IRRIGATION WATER SUPPLY was measured directly at the beginning of the irrigation line. In the sprinkler-irrigated fields, additional observations were obtained from rain gauges. The quantity of irrigation water to be supply was determined on the basis of a chosen k_{pan} FACTOR, defined as the ratio between water supply and cumulative Class A pan evaporation since the previous irrigation. The k_{pan} factor was chosen in relation to crop and growth stage.
- SOIL MOISTURE was routinely measured by the neutron moderation technique in 30 cm increments up to a depth of 1.20 m. First, the neutron probe was calibrated, taking soil samples for gravimetric soil moisture determinations together with simultaneous readings with the neutron probe at the same depth. From these data a linear regression equation was calculated, relating soil moisture content to the recordings of the rate meter. Fig. 2.2 shows the curve obtained for the San Camilo soil. The regression coefficient of 0.79 is not very impressive because of the high variability of the soil.
- SOIL WATER TENSION was recorded by tensiometers. The data, however, were not very reliable because of the sandy-stony character of the soils impeding contact.
- PLANT WATER POTENTIALS were measured using a Scholander pressure pump which recorded the pressure necessary to extract water from the vessels of freshly cut leaves (Scholander et al., 1965).
- Visual observations of STOMATAL APERTURE were obtained from "prints" of a mixture of silicon rubber and a hardener. A small amount of the mixture was spread on the leaf in the field. After hardening, the prints were taken to the laboratory, where positives were made by spreading transparent quick-drying material upon the prints. After drying, these transparent positives were observed under the microscope.
- Direct TRANSPIRATION measurements with a diffusion porometer were made in alfalfa and maize. The principle of these measurements is the determination of the rate of increase in relative humidity within a micro-chamber clamped upon a leaf. Because of severe calibration problems of the instrument, the results could only be used on a very limited scale. Indirectly, the transpiration of different plant species was determined by

weighing plants in containers before and after watering. Evaporation from the soil surface was reduced by a layer of gravel and further determined from containers without plants.

- IN VITRO DIGESTIBILITY was determined according to the method described by Tilley & Terry (1963) in some alfalfa, Rhodes grass and weed-samples.

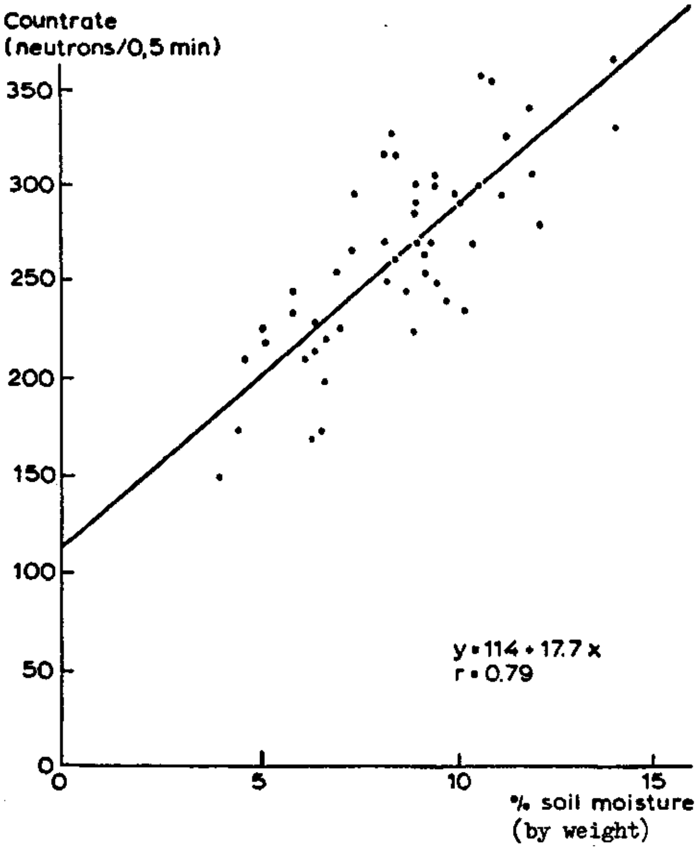


Fig. 2.2 Calibration curve for the soil of the San Camilo experimental station.

3 *GROWTH DYNAMICS OF ALFALFA*

3.1 INTRODUCTION

Alfalfa is probably the oldest cultivated forage crop; it has been used for at least 3000 years. Nowadays it is also the most extensively grown forage crop with about 33 million hectares spread between 60° N and 45° S latitude. About 2/3 of this area is situated in N and S America, of which nearly 98% can be found in the USA, Argentina and Canada. Most of the remaining area lies in Mexico, Peru and Chile (Bolton et al., 1972).

In Peru almost all alfalfa is grown west of the Andes, which is the cooler and drier part of the country. It is the most important forage in regions where dairy farming plays a major role, e.g. around Arequipa, where the majority of milk in Peru is produced, approximately 34000 ha (60% of the total arable land in the area) is cultivated with alfalfa. In the irrigated pampas around San Camilo alfalfa occupies even more than 90% of the agricultural land. Within the framework of the FAPROCAF project, it was therefore logical to start the research with this forage crop.

Alfalfa was introduced into Peru from the Mediterranean region by the Spaniards. They brought cultivars which all belonged to *Medicago sativa*. From these introductions, local ecotypes such as San Pedro in the northern regions and Yaragua, Tambo and Caravelli in the south have been developed. Boerger (1950) states that the Peruvian ecotypes are considered to be a special type of *M. sativa* described as *M. sativa var. Polia*. These ecotypes can easily be distinguished from other forms of *M. sativa*, by the dimensions of their leaves, which are 3 to 5 times longer than they are wide. Later, cultivars with genes from *M. falcata* such as Dupuits and Wairau, were also introduced. As these genotypes were more cold resistant, the alfalfa area could extend to higher altitudes such as at Ayacucho and around Puno. In the pampa region only cultivars of the *sativa* type are cultivated, so that during the FAPROCAF project all the research was centred around these cultivars and only in very few cases comparisons were made with cold-resistant cultivars.

The Spaniards also introduced the tethering system of the live-stock, which is still the most common method used by the farmers to ration the herbage. However, our investigations mainly referred to cut alfalfa, to allow comparisons with data from other sources.

The climate in San Camilo is suitable for year round alfalfa growing. Although not many countries have comparable conditions, there were some indications that very high dry matter production should be possible. For example, in Saudi-Arabia, alfalfa forage yields of 37 t/ha.yr of dry matter were recorded (Farnworth et al., 1975); in California, over a 250 day growing season, 32 t/ha was attained (Loomis & Williams, 1963) and in the Netherlands over a period of six months, 19 t/ha was produced (Sibma, personal communication). These yield levels suggested that in San Camilo higher productions than the 20 to 22 t/ha experimental yields, recorded before the start of the FAPROCAF project, should be possible.

The strategy developed in the present studies was therefore directed in the first instance towards obtaining data on growth behaviour and the production potential through growth analyses under conditions of at least one treatment of high fertilization and sufficient availability of irrigation water ($k_{pan} = 1.0$). Two more experiments were started rather early, in order to trace possible long-term effects. In the first place, much attention was paid to the influence of fertilization and to nutrient uptake, because it has become clear that nutrient availability is the determining factor governing actual crop production level in many countries

(Van Keulen & Van Heemst, 1982). A P x K fertilization experiment was established at the beginning of the project and more trials on P fertilization followed. Secondly, an experiment on management practices was set up, because it was deduced from a literature survey that this aspect was especially important for alfalfa in relation to its persistence and production.

Based on the results obtained, additional trials, measurements and observations on photosynthesis, N_2-fixation, weed competition, growth and reserve level of roots and stubble etc. were carried out, to elucidate questions such as the early decrease in forage production rate despite a green canopy and the natural capacity for N_2 fixation. Modelling studies both mid-way and at the end of the project, were used to gain more insight into the problems and for theory-testing (Section 3.5).

3.2 METHODS

3.2.1 *Growth curves*

In a well-established alfalfa field (cv. Tambo) half of a 24 m x 196 m area was fertilized with 420 kg N/ha.yr as urea, 280 kg P/ha.yr as triple super-phosphate and 420 kg K/ha.yr as potassium sulphate, applied in equal proportions at the start of each of several experimental growth curve determinations. The other half was not fertilized during the experiment. The whole field had been fertilized with 40 kg N/ha, 45 kg P/ha (both as ammonium phosphate) and 65 kg K/ha as potassium-sulphate, when the alfalfa was planted in virgin desert soil some eighteen months before the start of the experiment. Each half was divided into four equal blocks, which were further sub-divided into three sub-blocks; each sub-block was used to determine one growth curve based, on cutting eight strips of about 10 m^2 each. These cuttings were made at intervals of one week following the initial general harvest of the total field, except for the first two cuttings, which were made on days 7 and 11, respectively.

Within a given sub-block, the location of a strip for a certain cut was chosen at random. After the final sampling at eight weeks, the whole field was harvested (general harvest) and the next growth curve was determined in the second sub-block. After the third growth curve, the cycle started again from first sub-block. This rotation scheme assumes that the effects of cutting a certain sub-block periodically (on subsequent growth curve determinations) are negligible after two general harvests. An indication for the validity of this assumption, came from the coefficient of variation (7-10%) of the periodic harvests for different growth curves, which did not increase after the repetition. Harvesting was done with an Agria power-mower leaving a stubble of about 5 cm height. All harvested material was removed from the field immediately after cutting.

The first growth curve measurements started after a general harvest on September 20th, 1979. Having completed seven cycles on September 30th, 1980, three more curves were determined, but only on the fertilized half of the field. Subsequently, in March 1981, the experiment was continued on another field sown five months before, that had been sub-soiled to a depth of 0.90 m. The design of the experiment was similar to the one described above, however, instead of the two fertilizer treatments, half the field was sown with the Californian cultivar Moapa and the other half with Tambo. Initial and maintenance fertilization were identical to the fertilized half of the former field. In total, eight growth curves were determined in this field, ending May 10th, 1982.

For comparison, two growth curves, one in summer (February to March 1982) and one in early spring (September to October 1981) were concurrently determined in an established field of cv. Tambo, that had been subject to a cutting interval of 28 days for about twelve to eighteen months.

In the course of these experiments, periodically, samples were taken for the determination of LAI, relative proportion of leaves and stems, root weight and NPK concentration (see 2.4).

3.2.2 *Development and persistence experiment*

By ploughing and subsequently re-sowing half of three large plots (24 m x 60 m) in a five year old alfalfa field (cv. Moapa), a split plot experiment with three replications was initiated with old and young alfalfa of the same cultivar as main treatments. Within each main block twelve sub-plots of 3.6 m x 12 m were pegged out for a factorial combination of six management (M) and two cutting frequency (C) treatments.
The management sub-treatments consisted of:
M-1, standard fertilization with 52 kg P/ha as single superphosphate and 83 kg K/ha as potassium sulphate, given in two six-monthly applications.
M-2, higher fertilization at annual levels of 250 kg P/ha as ammonium phosphate, 200 kg K/ha as potassium sulphate and 335 kg N/ha, 2/3 as ammonium phosphate and 1/3 as urea, applied in equal portions after each cutting.
M-3, the same treatment as M-2 but with 600 kg K/ha.yr.
M-4, as M-2 but during winter (June-July) a dry rest period was applied over a complete cutting period by reducing watering to 1/3 of the normal (k_{pan} = 0.9) quantity.
M-5, as M-4, but with the same K fertilization as M-3.
M-6, the same as treatment M-4, but the dry rest period was applied during the summer period (January-February).
Cutting was either frequently (C-1), with alternating growing periods of 31 and 32 days or infrequently (C-2), every 42 days. In this way , a certain plot was either cut four (C-1) or three (C-2) times every eighteen weeks.

From the beginning of the experiment, all plots were kept free of weeds manually. However, from August 1980 till the end of the experiment weeding was discontinued on 40% of the area of each plot. Routine sampling continued in the weeded plots, but periodically (every eighteen weeks) the non-weeded part was also sampled, separating weeds and alfalfa.

Some changes were implemented in September 1980: The high K application to sub-treatments M-3 and M-5 was stopped; in addition, a wet rest period was introduced by omitting one cutting without decreasing the irrigation. This wet rest period was given either in winter (M-5) or in summer (M-3). Furthermore the urea application was omitted in the treatments M-2 to M-6 .

In all treatments dry matter production was determined and analysed for NPK concentration. In several cases, light extinction was also measured.

3.2.3 *Pot experiments in Wageningen*

3.2.3.1 Measurement of photosynthesis, respiration and transpiration of individual young leaves

During the preparation of the FAPROCAF project in 1977 to 1978, some preliminary physiological experiments were carried out in the controlled environment of the growth chambers of the Centre for Agrobiological Research (CABO) in Wageningen. Two growth chambers were set at 20 °C with a basic illumination of eleven hours at a rather low light intensity of 75 to 125

J/m^2.s. In each growth-chamber, 32 containers of eight litres each filled with sand were placed, an equal number being sown with four cultivars: Tambo, Yaragua, Caravelli (all three Peruvian in origin) and Moapa (from California). Seeds were not inoculated with *Rhizobium*, but all nutrients were supplied by irrigating with a half-strength Hoagland solution. Cutting intervals of 40 to 45 days (frequent) and of approximately 100 days (infrequent) were maintained. From May 17th to June 23rd 1978, photosynthesis of young leaves was measured in six to sixteen pots per cultivar, using the assembly summarily described in Section 2.4 (for more details see Louwerse & Van Oorschot, 1969).

3.2.3.2 Container experiment for the measurement of photosynthesis, respiration and transpiration on artifical swards

In January 1981, four alfalfa cultivars (cv. Tambo, cv. Moapa, cv. Gilboa and cv. Europe) were sown in large containers of 0.90 m x 0.90 m x 0.60 m, filled with river clay and fertilized with 15 g single superphosphate per container. Seeds had been inoculated with the appropriate *Rhizobium* (Nitragin). Water was applied at intervals of one to three days so as to maintain a water level in the container at about 15 cm above the bottom. The level was observed by means of a small transparant glass tube, that at the same time functioned as overflow (Fig. 3.1). Each container was put on a small cart.

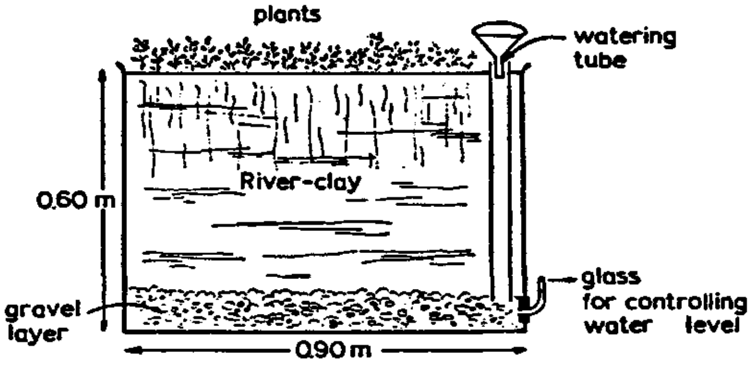


Fig. 3.1 Design of containers of 0.90x0.90x0.60m used during the measurements of canopy photosynthesis of alfalfa.

During six continuous measuring periods, covering 48 h each, photosynthesis, respiration and transpiration of swards in two containers simultaneously were determined for a total period of three weeks, following April 27th 1981. For the measurements the swards were covered with a transparant perspex chamber of 0.80 m x 0.80 m x 0.60 m, as described in Section 2.4. In each cultivar, two measurements were taken on uncut, well-developed "old" canopies (about four months) and one or two on "young" canopies, developed after a cutting two to three weeks previously. Plants were grown in greenhouses kept at a temperature of ± 20 °C, under the natural light conditions. On average irradiance inside the greenhouse was about 17% less than outside.

3.2.4 *Field experiment to determine the influence of cutting frequency on forage production, non-structural carbohydrates and regrowth in the dark*

The alfalfa field (cv. Tambo) described in 3.2.1 was also used for an experiment with the following six cutting frequency treatments:
treatment A: cutting interval eighteen weeks (for 'cleaning' purposes mainly), treatment B, C, D, E and F: cutting intervals of three, four, five, six and seven weeks, respectively. The treatments were laid out in the field in a randomized block with four replications. Plot size was 12 m x 6 m. For measurement purposes it was further sub-divided into three sub-plots:

- An area of 4.5 m x 6 m for destructive sampling to determine non-structural carbohydrate concentration in roots.
- An area of 1.5 m x 6 m in the centre of the plot to determine forage production.
- An area of 6 m x 6 m to determine reserve level from etiolated regrowth.

Non-structural carbohydrate concentration was determined in the taproot of one plant per plot, to a depth of 10 to 20 cm below the crown. After August 22nd 1981, only the upper 5 cm was taken of the taproots of two plants per plot; these were divided into phloem and xylem for separate determinations. After drying (72 hrs at 65 °C) and grinding, the carbohydrate concentration was determined after hydrolysis according to the method described by Schaffer and Somogyi (McDonald & Foley, 1960). In addition, non-structural carbohydrates were further separated into soluble sugars and starch, by first extracting sugars with 40% alcohol before hydrolysis.

Determination of forage production in the central part of the plot was identical to that described in 3.2.1.

Etiolated regrowth potential without light was determined every two weeks in the course of the experiment, by covering two areas of 0.1 m^2 each with closed wooden cases. Before covering the area, the alfalfa was cut. After two weeks of regrowth in the dark, the etiolated shoots were harvested and their dry weight determined.

3.2.5 *Determination of the influence of cutting frequency on root growth in pots*

140 pots, filled with 7 kg of dune sand on top of a "root barrier" of gravel, separated from the sand by a disc of metal gauze, were sown with alfalfa and placed as closely as possible to establish an artificial sward. At least two rows of pots in all directions were maintained as border during the experiment. After two months of establishment, a cutting frequency of four weeks was maintained, starting January 25th 1982. Following the second cutting, nine pots were chosen at random and destructively sampled to determine the above and below-ground biomass. Immediately after removal of the nine selected pots, the remainder were regrouped together to maintain the artificial sward. A total of nine dry matter determinations were carried out; during the last four, crowns and roots, separated into phloem and xylem, were weighed and the carbohydrate concentration separately determined for each fraction according to the method described in 3.2.4.

3.2.6 *Fertilization experiments*

As mentioned in Section 3.1, a P x K fertilization experiment in alfalfa was established at the beginning of the project. After about one year, was concluded that rapid responses could not be expected in the experimental field. However, some doubts remained, especially concerning the phosphorus situation of the farmer's fields in the region, as symptoms of P deficiency in cows were regularly reported. A trial in a field, where such a P-deficient animal had been observed, certainly proved that the P situation could also be critical for the alfalfa production level. Based on this observation some more P experiments were carried out in the farmer's field. These experiments are described in 3.2.6.2.

3.2.6.1 P x K fertilization experiment

The experiment was set up in a field that had been under alfalfa for three years. This field was ploughed, sub-soiled and resown with *Rhizobium*-inoculated seed of cv. Tambo on July 3rd, 1979. The whole field received a starter fertilization, as described in 3.2.1. After 95 days, the field was cut and fertilizer treatments, consisting of 0, 250 and 500 kg P/ha.yr as triple superphosphate and 0, 250 and 500 kg K/ha.yr as potassium sulphate, were applied in equal portions after each cutting. Generally, the cutting interval was five weeks, but in each winter period the interval was extended once or twice to six or seven weeks. A complete 3^2 factorial design was applied with four replications using plots of 3.60 m x 12 m. During the first eight cuttings an additional 960 kg (urea)-N/ha.yr was also given, distributed in equal portions together with the P and K fertilization; this was gradually lowered to zero, applying after the eighth and ninth harvest two-thirds and one-third of the former portions, respectively. However, for check, the high N fertilization was maintained in one of the borders of the field. Dry matter production was determined per plot and from the sixth harvest onwards, plants were also analysed for N, P and K concentration according to the methods described in 2.4.

3.2.6.2 Experiments to determine the critical phosphorus level

In unfertilized fields, belonging to farmers, a total of three experiments were carried out to investigate critical phosphorus levels in alfalfa. Dry matter production and plant-NPK concentration were determined according to the methods described in 2.4.

The first experiment was carried out in a five year old alfalfa stand, in the neighbourhood of San Camilo (settlement 6), where low P availability was suspected because of a cow suffering from *Haemoglobinuria puerperales*, a disease related to a low P level. Two P (0 and 250 kg P/ha.yr as triple superphosphate) and two K treatments (0 and 250 kg K/ha.yr as potassium sulphate) were given in a factorial design with four completely random replications. Plot size was 3 m x 3 m.

The second experiment was set up in the neighbourhood of the previous site in an alfalfa field sown five months earlier on virgin soil, where low P concentrations (about 0.20%) in the plants had been detected. A split-plot experiment was set up, with two main treatments (0 and 42 kg K/ha as potassium sulphate) and eight sub-treatments (0, 6, 12, 24, 48, 96, 144 and 192 kg P/ha as triple superphosphate), with two complete replications. All fertilizer was given in one application at the start of the experiment (August 22nd 1981). Three experimental cuttings were made on September 15th, October 20th and November 30th 1981.

Both experiments were irrigated by the farmer, according to general practice.

The third experiment was adjacent to the second one. The main difference was that in this case irrigation was under our control, in an attempt to avoid variability and influence of possible deficient irrigation

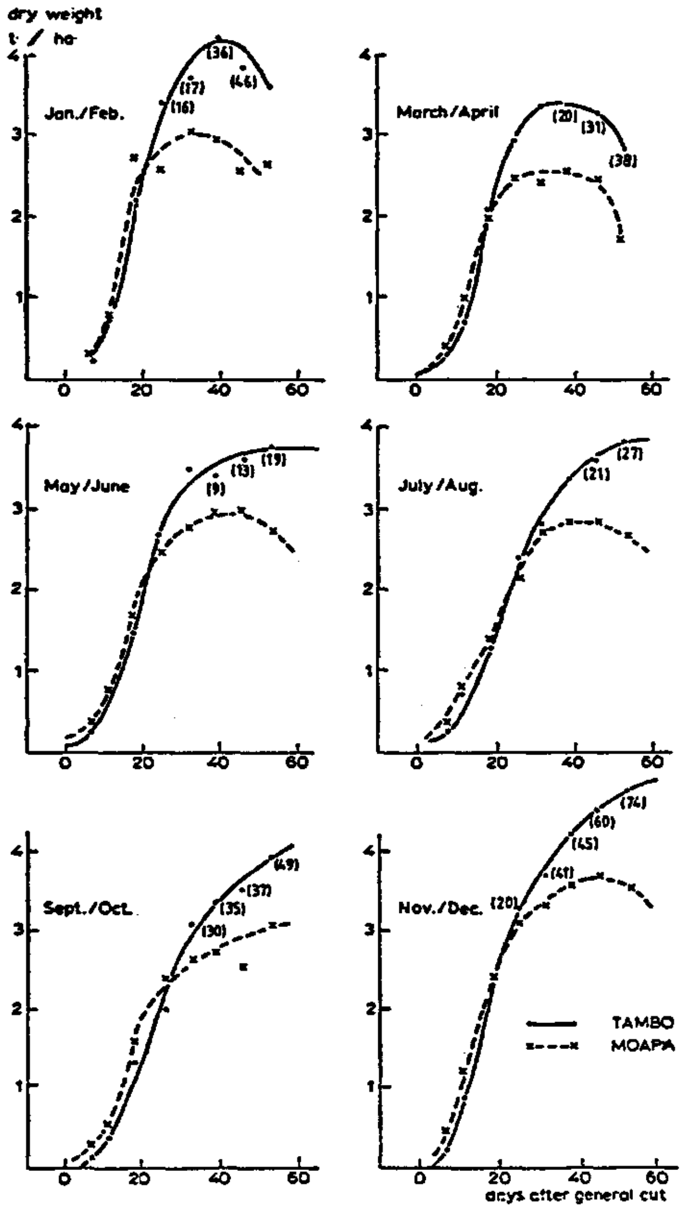


Fig.3.2 Growth curves of established irrigated alfalfa at different times of the year. Between parenthesis: percentage of flowering stems.

by the farmer on the results. Four P fertilization levels (0, 10, 20 and 40 kg P/ha.cutting as triple superphosphate) were applied in a random block design with four replications. This experiment was given a controlled sprinkler-irrigation on the basis of k_{pan} = 1.0. Plot size was 3 m x 3 m. The whole experimental field received an overall application of 200 kg K/ha.yr.

3.2.7 *Trial to identify the source of natural inoculation in San Camilo*

Twenty-six pots of five litres were filled with sterilized soil from a field that had never been under alfalfa. There were four treatments:

a. Sowing with *Rhizobium* inoculated seed and watering with common irrigation water;
b. Seed not inoculated, sterile (boiled) irrigation water;
c. Sterilized seeds, normal irrigation water;
d. Sterilized seeds, sterile irrigation water.

The pots were placed in holes in virgin dry desert soil without any vegetation.

After three months, the alfalfa in each pot was harvested separately and the dry weight of above and below-ground biomass was determined. In addition, nodules were counted from ten randomly chosen plants from each pot.

3.3 RESULTS

3.3.1 *Growth curves*

3.3.1.1 Above-ground dry matter production

Above-ground growth of alfalfa cv. Tambo (2½ years average) and of cv. Moapa (data from one year only) for the six two-monthly periods of the year, is presented in Fig. 3.2. All curves show that during the first seven days after cutting practically no growth occurred, after which the growth rate rapidly increased until day 11, when the maximum linear growth rate was attained. This rate varied between 125 kg (July to October) and 190 kg (January to February) dry matter/ha.d. These growth rates were generally maintained only during a relatively short period of 10 to 20 days. After that forage growth rates declined rather rapidly, in many cases to such an extent that total above-ground dry matter remained constant or even declined towards the time of the final harvest, thus exhibiting "ceiling yields". The degree of decline in growth rate varied with cultivar as well as the time of year. At all times, cv. Moapa exhibited very pronounced early ceiling levels. On the other hand, the growth rate of cv. Tambo between July and December diminished only gradually and no ceiling level was reached. However, in the period from January to July (months of declining day lengths in Peru) this cultivar also reached a clear ceiling and during the first four months of the year total above-ground biomass declined from day 32 to 40 until the final harvest (day 53).

Cv. Moapa had slightly better initial growth, but this was always reversed after two to three weeks. The cumulative dry matter production of the six growth curves presented in Fig. 3.2 is 24.0 and 18.2 t/ha for cv.

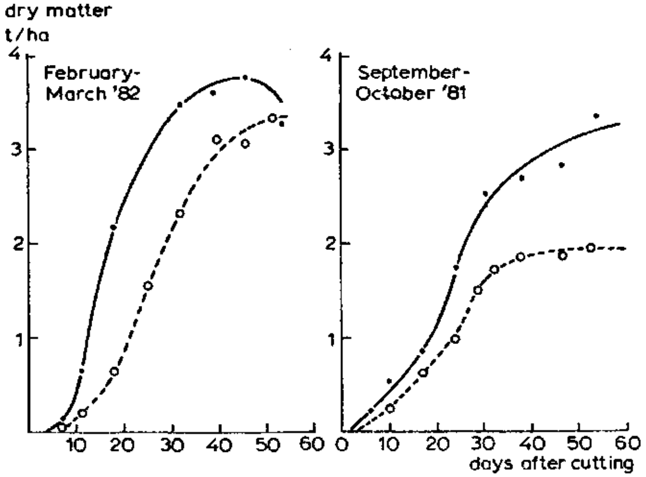


Fig. 3.3
Growth curves of alfalfa cv.Tambo, after harvesting at cutting intervals of 53 (•——•) and of 28 days (o----o) in two different seasons.

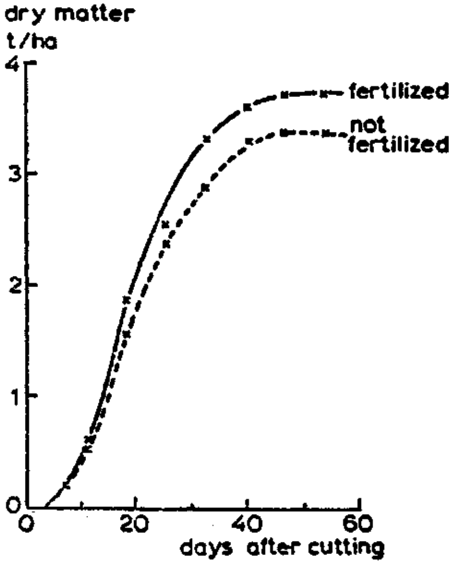


Fig.3.4 Average growth curves (one year) of alfalfa cv. Tambo with (×——×) and without (×----×) NPK fertilization.

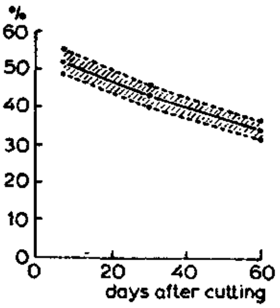


Fig. 3.5
Leaves as percentage of total dry forage of alfalfa cv.Tambo during complete growth cycles.Upper limit: winter-;lower limit: summer values.

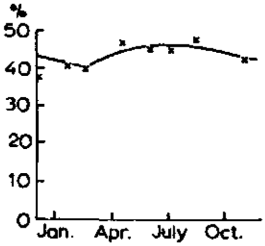


Fig. 3.6
Annual fluctuation of percentage of leaves (of total dry forage) on day 30, of alfalfa cv.Tambo.

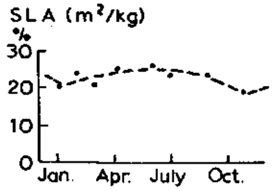


Fig. 3.7
Annual fluctuation of specific leaf area (SLA) of alfalfa cv.Tambo.

Tambo and cv. Moapa, respectively, obtained over a period of 318 days. To obtain the average production over a complete year, the numbers cited above must be multiplied by 365/318. This gives annual dry forage yields of 27.6 t/ha for cv. Tambo and 21.9 t/ha for cv. Moapa.

Fig. 3.3, shows a comparison between growth curves of cv. Tambo in fields previously cut every 28 days and every 53 days during summer (February to March) as well as at the end of the winter period (September, October). In both periods, initial growth was reduced by the short cutting interval, causing on day 30 about 50% less accumulated dry matter in the frequently cut treatment. During winter, that difference was maintained until the end of the growing period, but during summer the difference largely disappeared, mainly because of a more pronounced decline in growth rate in the low frequency treatment.

During the first year of the experiment, seven growth curves were determined from the heavily fertilized plots as well as from the non-fertilized alfalfa. There was a consistent and statistically significant difference ($P < 0.001$) between the treatments, of approximatelv 13.5% dry matter in favour of the heavily fertilized alfalfa (Fig. 3.4).

3.3.1.2 Leaf area development and light interception

The younger the alfalfa, the higher the proportion of leaves in the forage (Fig. 3.5), varying from an average of 52% on day 11 to 34% on day 53. The share of leaves was higher during the colder winter months (May to August, Fig. 3.6). Thinner leaves were produced then, resulting in specific leaf areas (SLA) of 23 to 25 m^2/kg, compared to summer values of 20 to 22 m^2/kg (Fig. 3.7). Measurements taken during periodic harvests, showed variations in SLA between 17 and 25 m^2/kg, without showing any systematic pattern. In contrast to leaf percentage, SLA and dry matter production, the leaf area index (LAI) values did not show much difference between summer and winter (Fig. 3.8).

Cultivar differences in both leaf area development and light interception were in accordance with dry matter production: a more rapid initial leaf expansion and light interception for Moapa, but after approximately thirty days Tambo had more leaf area and a slightly better light interception, which lasted to the end of the growing period (Fig. 3.9).

When leaf area was plotted against light interception, there was no difference between cultivars (Fig. 3.10).

3.3.1.3 Measurement of non-harvested biomass (roots, crowns and stubble)

The total non-harvested part of the biomass (roots, crowns and stubble) showed an overall tendency to increase with age of the stand. In general a decline was observed during winter. The highest observed value was 17 t/ha, measured thirty months after sowing (Table 3.1).

Table 3.1 Total weight of non-harvested part of dry matter (roots, crowns and stubble) in t/ha

Month of sampling	April	June	August	November	February	January
Number of months after sowing	7	9	11	14	17	30
cv. Tambo	8.0	10.4	6.4	10.8	11.3	17.0
cv. Moapa	9.8	12.1	8.4	9.5	13.0	

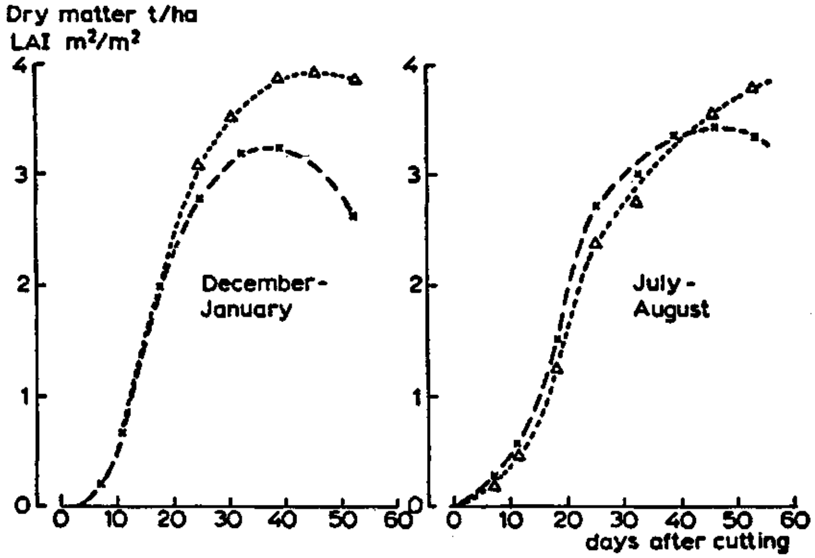


Fig.3.8 Course of leaf area index (LAI,×---×) and dry matter production (△-----△) of alfalfa cv. Tambo.

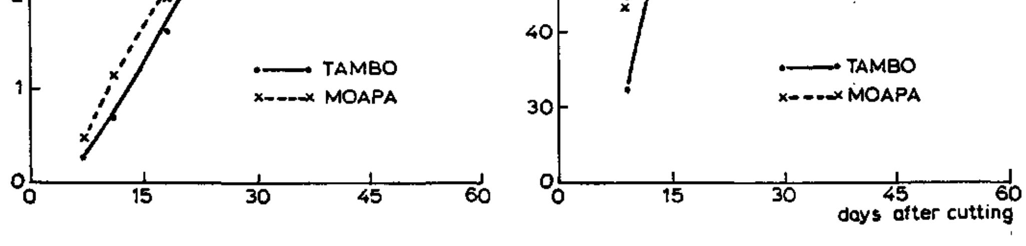


Fig. 3.9 Comparison of leaf area index (LAI) and light interception of alfalfa cv.Tambo and cv.Moapa (average of five growth curves).

In most cases Moapa had more non-harvested biomass than Tambo (the January sampling of Tambo was carried out in a different field). After sampling in November, the total amount of crowns plus stubble was measured separately from the roots, resulting in 0.64 t/ha and 1.15 t/ha crowns plus stubble for Tambo and Moapa, respectively.

3.3.1.4 N, P and K concentration in the tissue

The average N, P and K concentrations of NPK fertilized alfalfa over more than two years are presented in Fig. 3.11. During periods with high growth rates, as in summer, the nutrient concentration was lower than in periods with low growth rates, as in winter. Leaves of plants not fertilized with N had an average N concentration of 3.8%. Differences in fertilization, as practised in the first year, showed up most clearly in the P concentration, only slightly in K and were virtually absent in N (Fig. 3.12). Average P and K concentrations of Moapa (0.44 and 3.61% respectively) were slightly but significantly higher than those of Tambo (0.42 and 3.23%, respectively). There was no statistical difference in N concentration (4.0%) between the cultivars.

3.3.2 *Development and persistence experiment*

3.3.2.1 Forage production

Fig. 3.13 presents average daily growth rates of the two cutting frequencies (every 4½ and 6 weeks) of young (½ to 2½ yrs) and old (5 to 7 yrs) sward of cv. Moapa during 1980 and 1981. The results obtained in the beginning of the trial until March 1980, were probably still influenced by the history of the field before the treatments were imposed. After this period, the stand subject to the short cutting-interval showed larger fluctuations in growth rates with very low values during winter (June to September) in both years. These recovered from December to April and especially from January to March 1981 when average growth rates in the short cutting interval swards were significantly higher than those obtained in the longer interval swards. Total forage production over the two years was not significantly different between both cutting frequencies. The young stand always attained higher growth rates than the five year older alfalfa, but only during the second year was the difference statistically significant.

The annual forage production was negatively affected by the summer resting period, particularly by the dry period (Table 3.2). Winter resting periods and fertilization treatments did not have any significant effect.

3.3.2.2 Plant density

Plant density was influenced very significantly by age and only slightly by cutting frequency (Fig. 3.14); it was not affected by either cutting treatment, or by weeding intensity. The very strong decrease in plant density of Moapa during the first two years after sowing, from 75 plants/m^2 one year after establishment to 12 plants/m^2 at the end of the second year, was remarkable.

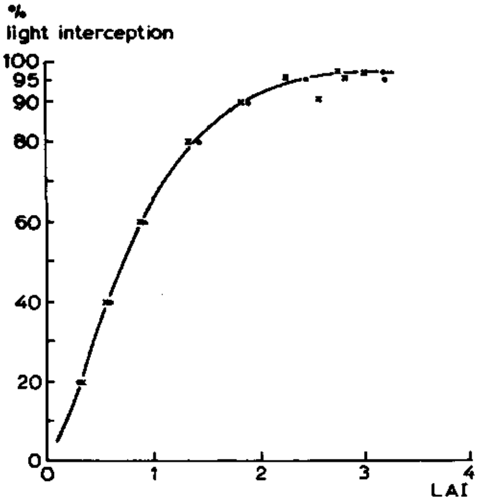


Fig. 3.10

Relation between leaf area index (LAI) and percentage of light interception for alfalfa cv.Tambo (•) and cv. Moapa (×).

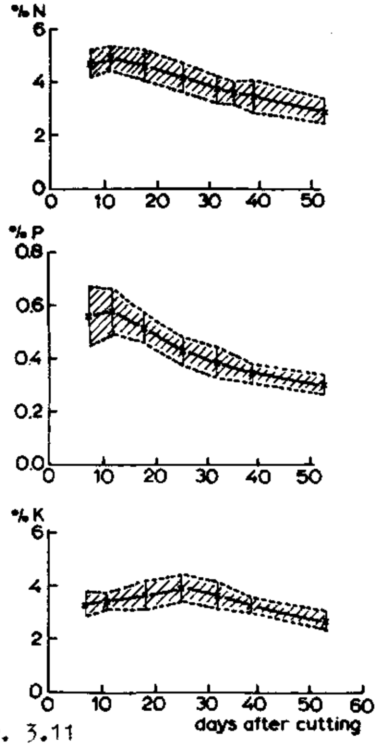


Fig. 3.11

Average NPK percentage (two years) in alfalfa cv. Tambo. Hatched area limits values between standard deviations.

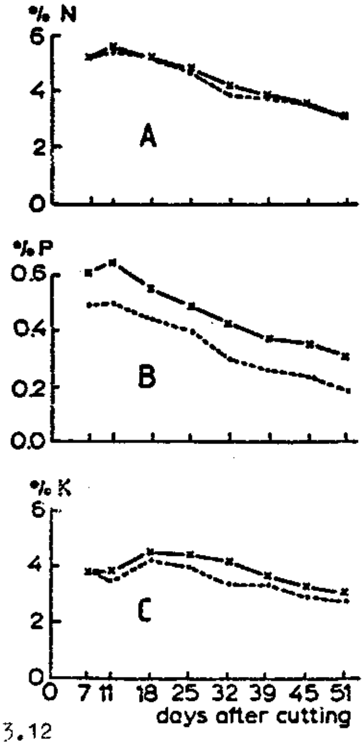


Fig. 3.12

Average NPK percentage (three cropping periods from March to August) in alfalfa cv.Tambo with (×——×) and without (•-----•) NPK fertilization.

Table 3.2 Average (two yrs) annual dry matter yield of alfalfa cv. Moapa under different management treatments (significant difference if no letter in common, according to Duncan at 0.05 level)

Treatment M-5, high NPK fertilization and humid winter resting period	13.68 t/ha a
Treatment M-1, low PK fertilization without resting period	13.31 t/ha ab
Treatment M-4, high NPK fertilization and dry winter resting period	13.06 t/ha ab
Treatment M-2, high NPK fertilization without resting period	12.85 t/ha ab
Treatment M-3, high NPK fertilization and humid summer resting period	12.15 t/ha bc
Treatment M-6, high fertilization and dry summer resting period	11.11 t/ha c

3.3.2.3 Effect of weed infestation

The biomass of alfalfa and weeds, harvested on several dates, (from August 1980 onwards) in the non-weeded plots, and the alfalfa biomass in the weeded plots, are presented in Fig. 3.15. In all cases the total biomass of alfalfa plus weeds exceeded that of the amount of pure alfalfa in the weeded plots. In most cases, the alfalfa component was virtually identical and only in May 1982 was the amount of alfalfa in the non-weeded plots significantly less than in the weeded ones. *In vitro* digestibility of the weed mixtures determined according to the method described by Tilley and Terry (1963) was 61-64% in the high frequency cutting regime plots and 50-54% in the low frequency cutting regime ones (three determinations). These values were about 0.9 and 0.8 times the digestibility of the alfalfa from the same treatments. Palatability observations with dairy cows indicated that rations of alfalfa mixed with up to 40% weeds were accepted just as well as pure alfalfa.

3.3.2.4 N, P and K concentration in the tissue

In general, plant-NPK concentrations (Table 3.3) were comparable to those obtained in the P x K experiment (Fig. 3.23). All concentrations were higher under shorter cutting intervals. Neither N fertilization, nor age of the stand influenced N concentrations. The low P fertilization of the M-1 treatment (52 kg P/ha.yr) was sufficient to maintain the P concentrations at the same level in corresponding months in subsequent years. The high P dose (250 kg/ha.yr) strongly increased the P concentrations. Low K fertilization (83 kg/ha.yr) was not sufficient to maintain the K concentrations in the plants, whereas even the high K fertilization (200 kg/ha.yr) was only able to maintain K concentrations in the old alfalfa swards.

Table 3.3 Comparison of average plant-NPK concentrations in above-ground dry matter of different fertilizer treatments for old (5 to 7 yrs) and young (½ to 2½ yrs) alfalfa swards, cv. Moapa. C_1, C_2: cutting intervals of 31 to 32 and 42 days, respectively.

	YOUNG		OLD	
	C_1	C_2	C_1	C_2
N_0 -1980	3.7%	3.2%	3.5%	3.2%
-1981	3.6	3.2	3.6	3.1
N_{225}-1980	3.7	3.2	3.6	3.2
-1981	3.6	3.1	3.7	3.2
P_{52} -1980	0.32	0.29	0.29	0.21
-1981	0.34	0.28	0.37	0.29
P_{250}-1980	0.44	0.42	0.44	0.43
-1981	0.50	0.47	0.54	0.51
K_{83} -1980	3.1	3.0	3.1	2.8
-1981	2.5	2.5	2.9	2.7
K_{200}-1980	3.3	3.2	3.3	3.0
-1981	3.1	2.8	3.3	2.9

During 1980, P and K concentrations in the young alfalfa were generally higher than those in the old alfalfa, whereas this was the reverse in 1981 (the latter at $P < 0.05$).

The extra high K fertilization at the start of the experiment (treatment M-3, M-5) had no effect on either yield or persistence. It only increased the K level of the plant tissue.

In general, the presence of weeds did not affect the average mineral and N concentration of the total herbage (Table 3.4). The weeds had about the same P and K concentrations, and although the N concentrations were about 20 to 25% lower, this was compensated because the proportion of weeds in the mixture was usually lower than 25% and the alfalfa component in the mixtures had an approximately 7% higher N concentration than in pure stands.

Table 3.4 NPK percentage in both weeds and alfalfa, in weeded and weed-free plots, with cutting intervals of 31 to 32 days (C_1) and 42 days (C_2)

Nutrient	N		P		K	
Cutting interval	C_1	C_2	C_1	C_2	C_1	C_2
Alfalfa, weed-free	2.99	2.67	0.52	0.50	2.85	2.41
Alfalfa, with weeds	3.23	2.84	0.49	0.49	2.68	1.93
Weeds	2.55	2.12	0.49	0.49	2.82	2.50

3.3.3 *Container experiments carried out in Wageningen*

3.3.3.1 Measurement of photosynthesis, transpiration and dark respiration of individual young leaves

Average maximum, net assimilation rates of attached individual leaves (measurements on four pots) reached values of 30 mg $CO_2/dm^2.h$ for cv. Tambo and Moapa, and of 28.5 mg $CO_2/dm^2.h$ for cv. Caraveli and one pot of cv.

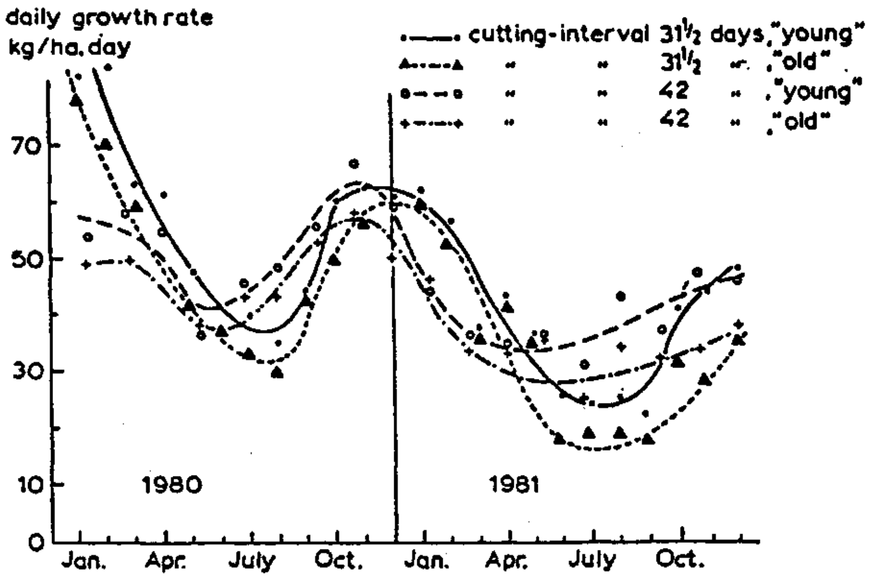


Fig.3.13 Average daily growth rates of old (5 to 7 yrs) and young (½ to 2½ yrs) stands of alfalfa cv. Moapa, submitted to two cutting intervals .

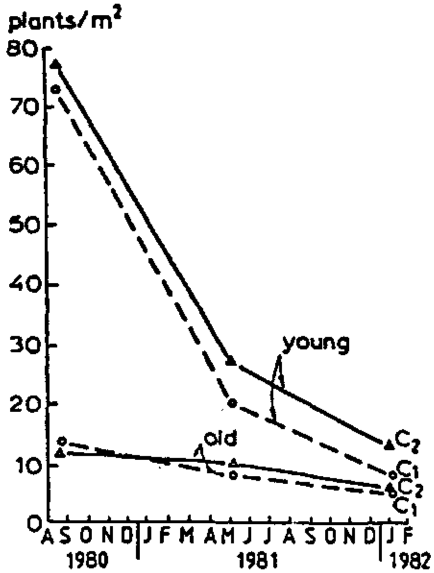


Fig. 3.14
Decline in time of stands of young (1-2½ yrs) and old (5½-7 yrs) alfalfa cv.Moapa, submitted to cutting intervals of 31 to 32 (C_1) and 42 (C_2) days.

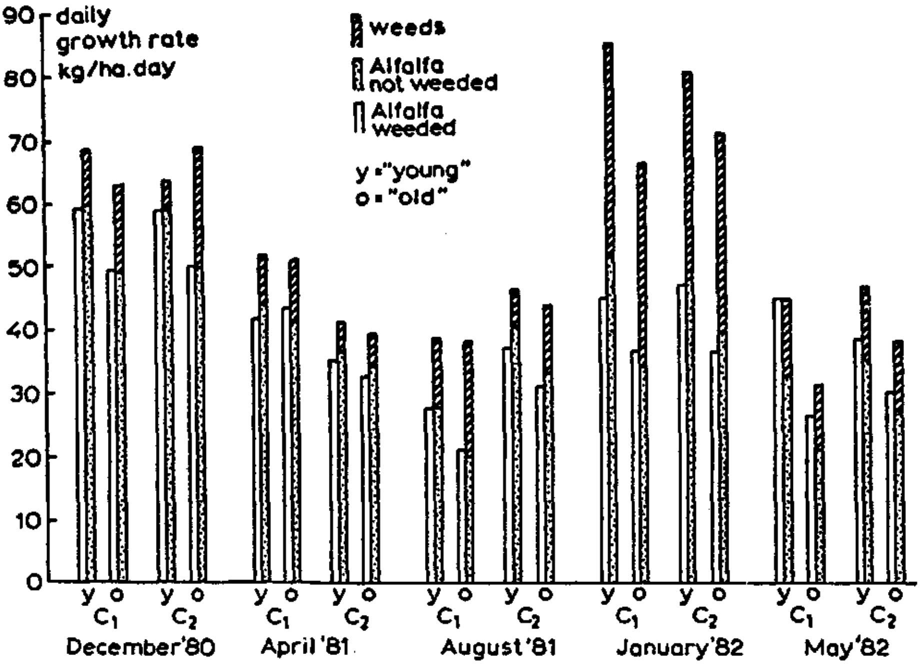


Fig.3.15 Average daily growth rates of old (5 to 6 yrs) and young (1 to 2 yrs) alfalfa cv.Moapa and of weeds, in plots with and without weeding, submitted to cutting intervals of 31 to 32 (C_1) and 42 (C_2) days.

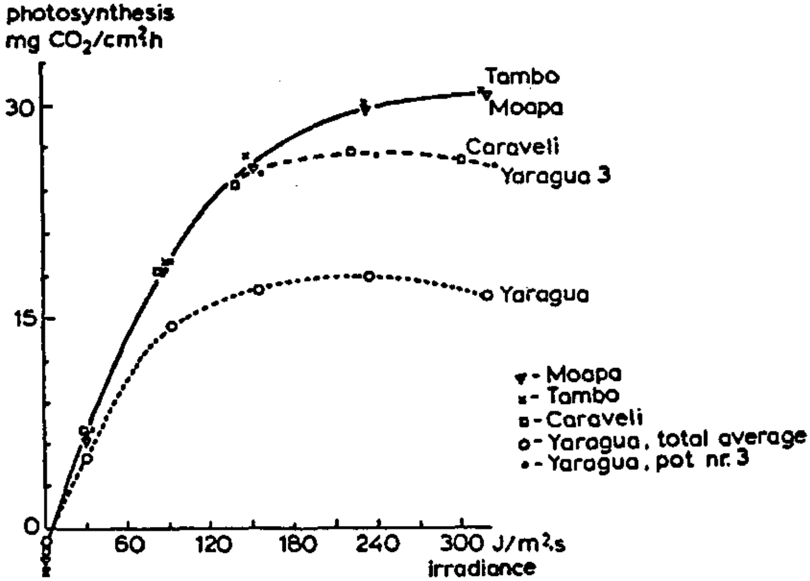


Fig.3.16 Net assimilation rate of young leaves of four cultivars of alfalfa at different light levels.

Yaragua, at light intensities of 240 to 300 $J/m^2.s$ (Fig. 3.16). All these results were produced with about the same efficiency of 0.23 mg $CO_2/dm^2.h$ per $J/m^2.s$. The other three pots of cv. Yaragua reached maximum net assimilation rates of only approximately 15 mg $CO_2/dm^2.h$ with an efficiency of 0.165 mg $CO_2/dm^2.h$ per $J/m^2.s$. Values of dark respiration were between 1.5 and 3.2 mg $CO_2/dm^2.h$, the lowest values corresponding to the lowest assimilation rate at light saturation.

Measured transpiration reached values of about 4 g water/$dm^2.h$ for cv. Tambo, cv. Caraveli and for one pot of cv. Yaragua at the higher light intensities; cv. Moapa transpired somewhat less (3 g water/$dm^2.h$) and the three other pots of cv. Yaragua levelled off at around 2.5 g water/$dm^2.h$. Converting these values into transpiration coefficients (TRC) by dividing grams transpired water by grams CO_2 x 0.62 (conversion to structural material according to Brown et al., 1972), resulted in the lowest values of about 180 to 270 g water/g dry matter at light intensities of 140 to 240 $J/m^2.s$ for all pots (Fig. 3.17). At low light intensities, higher TRC values were obtained and the same occurred (with the exception of cv. Moapa) at the higher irradiance level of 300 $J/m^2.s$.

3.3.3.2 Photosynthesis, dark respiration and transpiration measured on artificial swards

Photosynthesis of undisturbed (not cut since sowing four months previously) and regrowth canopies (2½ to 4 weeks after cutting) of four alfalfa cultivars, is presented in Fig. 3.18. At high light intensities net CO_2 assimilation reached values of 55 to 110 kg CO_2/ha.h, with corresponding efficiencies of 0.40 to 0.65 kg CO_2/ha.hr per $J/m^2.s$, depending mainly on the values of the LAI in the container. Dark respiration, varying from 5 to 18 kg CO_2/ha.h, was also related to LAI.

TRC values, calculated as in 3.3.3.2 for different irradiance levels, showed no significant differences, neither among cultivars, nor between age of canopies (Table 3.5). TRC remained constant (about 260 g water/g dry matter, based on total, below and above-ground biomass) at light intensities higher than 150 $J/m^2.s$; at lower intensities TRC values became increasingly higher.

Table 3.5 TRC (g water/g dry matter) based on total, below and above-ground, biomass) of four cultivars of alfalfa, in relation to light intensity and age of the canopy. Y.C.: young canopy; O.C.: old canopy.

Light intensity $J/m^2.s$	cv. Tambo		cv. Moapa		cv. Gilboa		cv. Europe		mean
	O.C.	Y.C.	O.C.	Y.C.	O.C.	Y.C.	O.C.	Y.C.	
300-350	245	261	-	241	238	234	248	220	241
250-300	266	274	248	231	-	285	245	263	259
200-250	287	267	279	224	290	-	253	-	267
150-200	255	258	-	237	265	264	245	282	258
100-150	337	279	364	294	298	319	283	294	309
50-100	376	352	342	345	347	363	336	365	353
0- 50	930	1001	1184	1173	753	858	844	1000	968
mean	385		406		366		368		380

mean O.C.: 377, Y.C.: 382

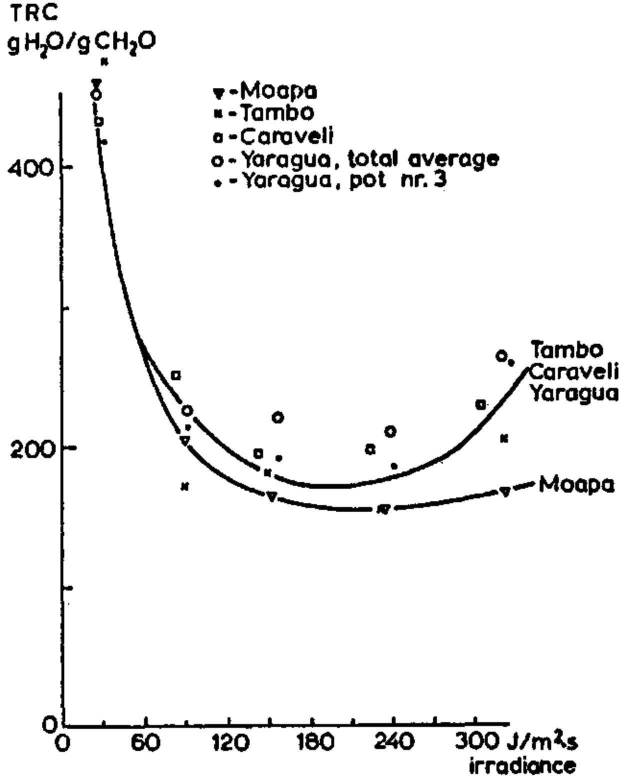


Fig. 3.17
Calculated transpiration coefficients (TRC) of young leaves of four cultivars of alfalfa at different irradiance levels.

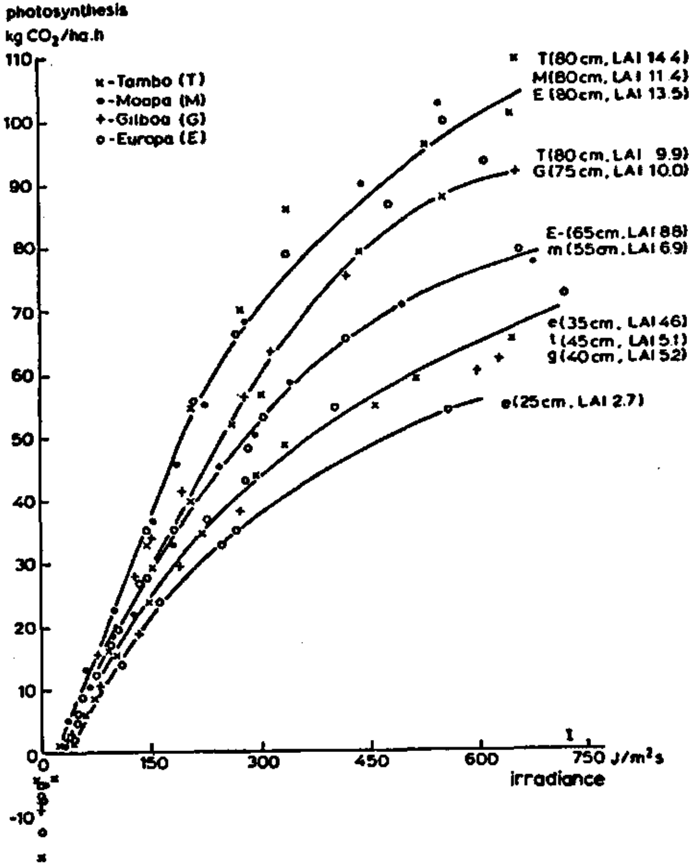


Fig.3.18 Net photosynthesis rate of canopies of four alfalfa cultivars, grown in large containers. Capitals: undisturbed canopies; small letters: canopies of regrowth. In parenthesis: crop height and leaf area index (LAI).

3.3.4 *Influence of cutting frequency on forage production, plant density, non-structural carbohydrates and regrowth in the dark*

3.3.4.1 Above-ground dry matter production

The influence of cutting frequency on the average growth rate of above-ground dry matter of cv. Tambo is illustrated in Fig. 3.19. During the winter months, growth rates of the frequently cut alfalfa amounted to only 10 to 20 kg/ha.d, which was about 25% of the values obtained with cutting intervals of five weeks or longer. Around January, however, the swards subject to longer cutting-intervals showed lower average growth rates. As the treatments with the short intervals recovered at that time, about the same rates of around 45 kg/ha.d were then obtained for all cutting regimes.

3.3.4.2 Plant density

Plant density was determined in September 1981 and February 1982. Average results are presented in Table 3.6. Differences between cutting treatments were small and did not reach significance.

Table 3.6 The influence of cutting interval on plant density (plants/m^2) of three to four year old alfalfa, cv. Tambo. Average of twelve counts.

Cutting interval (weeks)	Plant density (plants/m^2)
3	37
4	39
5	39
6	43
7	43
18	41

3.3.4.3 Total non-structural carbohydrates

Total non-structural carbohydrate (TNC) concentrations in phloem and xylem of the upper 5 cm of primary roots over seven consecutive weeks, for different cutting frequencies starting 48 weeks after initiation of the treatments, are presented in Fig. 3.20. Considerable fluctuations in TNC were observed, without any discernable pattern. Generally, TNC in the phloem was lower than in the xylem. The average TNC concentration in xylem and phloem of all seven samplings of the extremely long cutting interval of eighteen weeks, was significantly higher than all other means, with the exception of that obtained in the xylem of alfalfa, cut every seven weeks. Most other frequencies did not show any significant differences in TNC of either xylem or phloem. The only exception was the low average TNC concentration in the phloem of alfalfa cut every five weeks, which was significantly lower than the corresponding result from the three and seven weeks cutting interval.

3.3.4.4 Measurement of etiolated regrowth

Although the variability among individual values of etiolated regrowth was quite high, averages over periods of about two months showed clear differences among the various cutting intervals, as shown in Fig. 3.21. Over

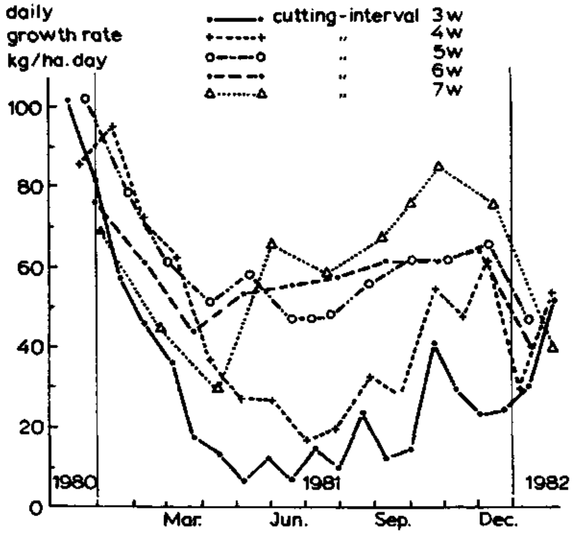


Fig. 3.19
Average daily growth rate of alfalfa cv. Tambo submitted to different cutting intervals.

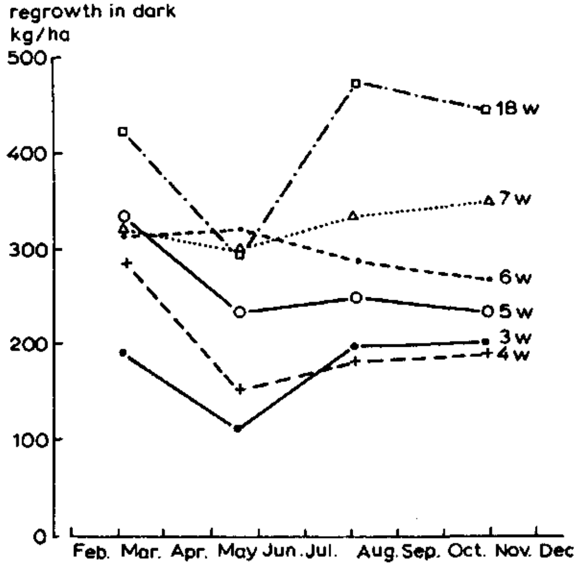


Fig. 3.21
Etiolated regrowth from alfalfa cv. Tambo for two weeks in different times of the year. The sward had been subject to six different cutting intervals of three to eighteen weeks.

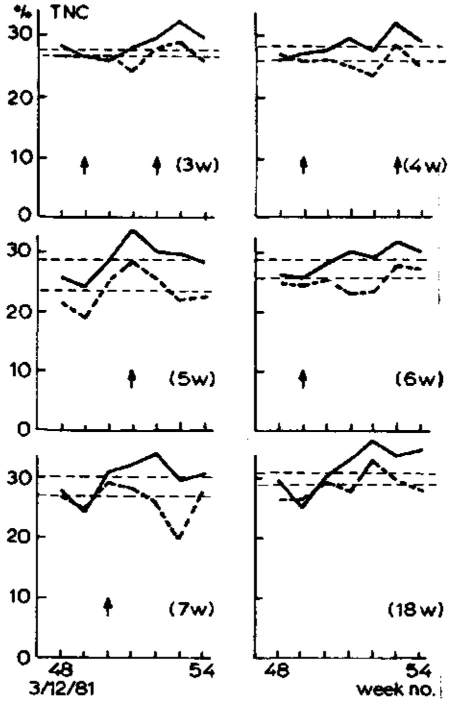


Fig. 3.20
Course of percentage of phloem (- - - - -) and xylem (———) of tap roots of alfalfa during seven succesive weeks from week 48 after starting different cutting intervals of 3 to 18 weeks. ↑ : moment of cutting; — — —: average TNC level of xylem (upper line) and phloem (lower line).

a period of ten months, the average regrowth values were 175, 200, 261, 298, 328 and 409 kg/ha for cutting intervals of three, four, five, six, seven and eighteen weeks, respectively.

When the regrowth measurement was started two weeks after a harvest, a lower regrowth was usually obtained, although the differences were not significant (Table 3.7).

Table 3.7 Average etiolated regrowth (kg dry matter/ha), produced in two weeks under wooden cases, placed at harvest (I) or two weeks after harvest (II).

Cutting interval	I	II
3 weeks	169	140
4 weeks	193	183
5 weeks	218	218
6 weeks	396	258
7 weeks	413	298
Mean	278	219

3.3.4.5 Non-harvested biomass (roots, crowns and stubble)

Total non-harvested biomass was determined during the winter months (June/July) of 1982, when cutting frequencies had been maintained for eighteen months. The results indicate that the amount of non-harvested biomass was very strongly related to the cutting frequency, increasing from 2.5 t/ha at cutting intervals of three weeks up to 20 to 25 t/ha when the interval was longer than seven weeks (Table 3.8).

Table 3.8 Non-harvested dry matter (roots, crowns and stubble) in cv. Tambo in June/July 1982, after different cutting regimes maintained over eighteen consecutive months.

CUTTING INTERVAL:	3	4	5	6	7	18	weeks
DRY MATTER ROOTS + CROWNS + STUBBLE	2.5	4.2	10.1	7.4	19.9	25.1	t/ha

3.3.5 *Determination of root growth dynamics in pots*

The results of nine consecutive weekly determinations of above and below- ground biomass of alfalfa cv. Tambo, grown in pots and submitted to a four-weekly cutting regime, are presented in Fig. 3.22-A. After harvesting, total dry matter of roots and stubble obviously decreased in the first week, but successive samplings demonstrated a steady increase up to the next cutting, followed by a new decrease.

During the last four periodic harvests, stubble, root-phloem and root-xylem were determined separately, as well as TNC in root-phloem and root-xylem (Fig. 3.22-B and C). Xylem and phloem dry matter both decreased and recovered as total non-harvested biomass, but the stubble dry matter remained almost constant. The TNC level in root-phloem and root-xylem also decreased after each harvest, but in this case recovery only occurred after the second week.

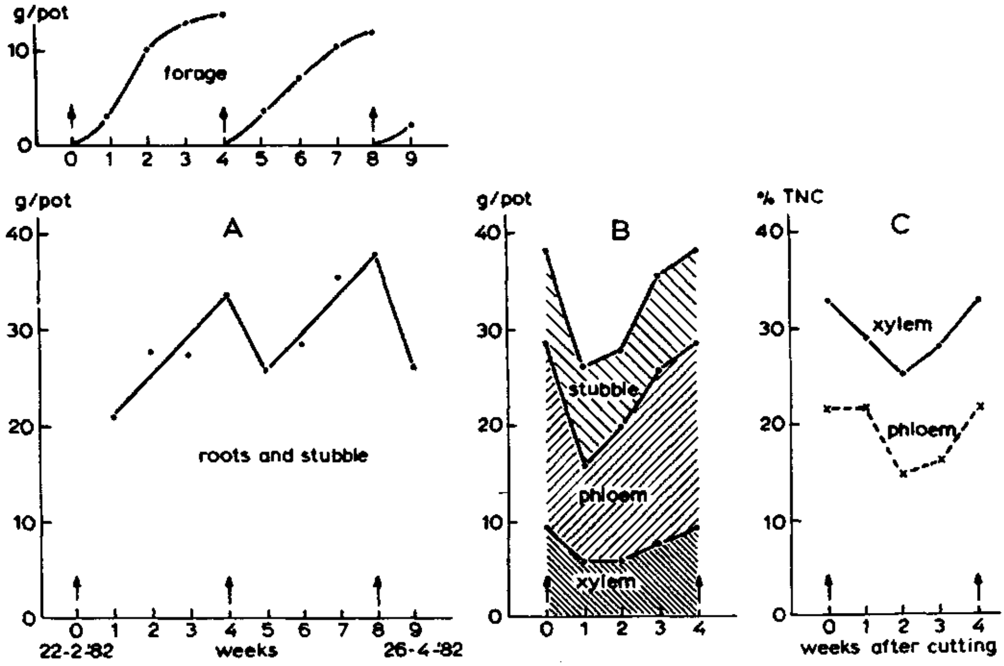


Fig. 3.22

Dry matter and non structural carbohydrate (TNC) percentage in relation to cutting of alfalfa cv. Tambo in pots. ↑ : moment of cutting

A: Dry matter of forage (upper part) and roots + stubble (below part).

B: Cumulative distribution of roots (xylem and phloem) and stubble between cuttings.

C: TNC percentage of xylem and phloem between cuttings.

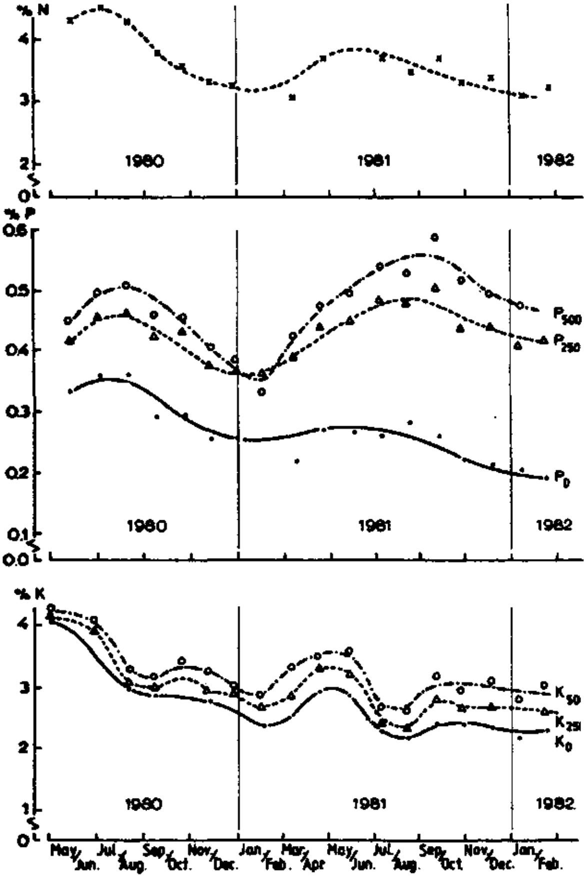
3.3.6 *Fertilization experiments*

3.3.6.1 The P x K fertilization experiment

From the end of 1979 up to March 1982 (24 harvests) generally no response to fertilizer application was obtained in above-ground dry matter production, with the exception of one harvest in February 1981, when P_{500} plots produced significantly more dry matter than P_0 plots. Also, when separate harvests were grouped into winter and summer results, only those from December 1980 to March 1981 gave a significant P response, due only to the results of February 1981. However, when total fresh weight was analysed, significant P responses of 11 to 15% ocurred in five individual harvests.

During the last harvest a significant response in fresh weight was also obtained from K fertilization, but this difference was also non-significant in terms of dry weight.

Contrary to the almost total absence of influence on production level, fertilizer applications caused responses in P and K concentration, especially for the former (Fig. 3.23). During the course of the experiment, the level of P in the P_0 treatment and to a lesser degree the level of K in the K_0 and K_{250} treatments, decreased. The K level in the K_{500} and the N level remained more or less constant, whereas the P levels in the P_{250} and P_{500} treatments clearly increased. The fluctuation in N, P and K concentration during the year is quite remarkable. The patterns of N and P are similar but that of K is somewhat different.



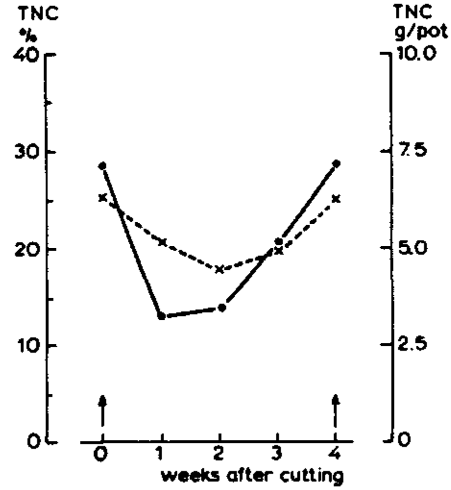


Fig. 3.24
Course of TNC of alfalfa roots, expressed as percentage of dry matter (x - - - x) or as weight (g/pot, •———•) between two succesive harvests.

Fig. 3.23
Course of NPK percentage in forage of alfalfa cv. Tambo after annual fertilizations of 0, 250 and 500 kg P and K per hectare.

3.3.6.2 Experiments to determine the critical P level

The results from both cuttings of the first trial carried out in a farmer's field, showed a very clear response to P fertilization, in terms of both forage production and P concentration (Table 3.9). K fertilization gave no response, neither in forage, nor in tissue-K concentration.

Table 3.9 Average dry matter production and tissue-NPK percentage obtained in a factorial trial with fertilizations of 0 and 250 kg P/ha.yr and 0 and 250 kg K/ha.yr.

	Dry matter/cutting	% N	% P	% K
P_0	1.73 t/ha	3.35	0.21	3.24
P_{250}	2.34 t/ha	3.40	0.32	3.47
K_0	2.03 t/ha	3.52	0.27	3.28
K_{250}	2.04 t/ha	3.50	0.27	3.34

In the next farm-experiment on a young stand of alfalfa, no effect on dry matter production was obtained, neither from P, nor from K fertilization. However, there was a clear effect of P fertilization on tissue-P concentration (Table 3.10).

Table 3.10 Average dry matter production and tissue-P percentage in an experiment with eight levels of P (0-6-12-24-48-96-144-192 kg P/ha) with farmer's irrigation (average of three cuttings).

Treatment	P_0	P_6	P_{12}	P_{24}	P_{48}	P_{96}	P_{144}	P_{192}
Dry matter/ cutting (t/ha)	1.94	2.13	1.85	1.76	1.97	1.92	2.13	2.16
% P	0.17	0.18	0.20	0.21	0.22	0.22	0.23	0.28

Also in the last experiment (same site, but controlled irrigation) no effect on dry matter production was obtained, despite again a clear effect on tissue-P concentration (Table 3.11).

Table 3.11 Average dry forage production and tissue-NPK percentage, obtained in an experiment with levels of 0-10-20 and 40 kg P/ha.harvest and experimentally controlled irrigation (average of two harvests).

	Dry forage/cutting (t/ha)	% N	% P	% K
P_0	2.75	3.17	0.22	3.41
P_{10}	2.80	3.17	0.23	3.60
P_{20}	2.71	3.21	0.26	3.60
P_{40}	2.80	3.33	0.28	3.45

3.3.7 *Rhizobium inoculation source*

The results obtained (Table 3.12) indicated that, in spite of soil sterilization and different treatments with respect to irrigation water and seed manipulation, all pots produced well. Biomass production was favoured by seed inoculation, but only the differences in root biomass were significant ($P < 0.025$).

Table 3.12 Average number of nodules per plant, dry matter of roots and tops (g/pot) of different seed and irrigation water treatments.

TREATMENT	number of nodules	dry matter tops	dry matter roots
seed inoculated, normal irrigation water	29	9.3	8.6
seed not inoculated, sterile irrigation water	25	7.9	6.0
sterilized seeds, normal irrigation water	28	7.9	5.4
sterilized seeds, sterile irrigation water	23	7.9	6.1

3.4 DISCUSSION

Based on the results described in the previous Sections, the following main conclusions may be drawn:

- Alfalfa, cut every 53 days, produced about 27 t dry matter/ha.yr, during the twelve months growing season in San Camilo. The lowest rate of production occurred in winter and was about 70% of the highest production reached during late spring. Active forage growth was maintained for a relatively short period, subsequently a pronounced decrease or even a stop in the rate of above-ground dry matter accumulation took place, probably due to a strongly increased translocation of the assimilates to the root system.
- In a pattern idential to forage production, LAI developed up to low maximum values of only 3.3 to 3.5. Variation in LAI throughout the year was almost absent due to adaptations of both the SLA and the proportion of leaves in the above-ground dry matter. The rather low LAI was compensated for by an efficient light interception.
- Assimilation measurements on Peruvian and other cultivars showed similar values as those found elsewhere, and did not indicate a pronounced decline shortly after cutting, as observed for the forage dry matter growth.
- The assimilaton measurements also showed, that the relation between net CO_2 assimilation and transpiration was identical for all cultivars and independent of the leaf area development.
- High N fertilization produced a small (7 to 13.5%) but statistically highly significant increase in forage production, presumably because of the higher respiration requirements of biologically fixed N.
- N_2 fixation of a good alfalfa field in San Camilo, was estimated at about 700 kg N/ha.yr or about 2 kg/ha.d. This rate is comparable to results obtained in regions with shorter growing seasons.
- Decrease in plant density was mainly related to cultivar and age. The small effect of the cutting frequency seems largely due to mechanical damage to the crowns during the harvesting operations.
- In San Camilo, alfalfa growth was hardly related to non-structural carbohydrate concentration in the roots, but was strongly related to root mass.
- In the region around San Camilo, response to fertilization with P or K will be rather exceptional, under the prevailing grazing system.

The above conclusions will be discussed in the following Sections.

3.4.1 *Undisturbed above-ground dry matter accumulation*

The average annual dry matter production, calculated from the growth curves, of around 27 t/ha (cutting interval 53 days) with the local cultivar Tambo, was also obtained in an irrigation experiment with ten cuttings per year, using the same cultivar (Zipori & Valdivia, 1982). These yields were of the same order of magnitude as reported by others (Section 3.1) and were about 25 to 30% greater than the higher yields recorded so far for the region. Optimum irrigation management and careful crop management are the key factors to reach these productions.

The undisturbed above-ground dry matter accumulation in San Camilo showed clear differences in maximum production level between the different periods of the year (Fig. 3.2), ranging from 3.5 to 5.0 and from 2.5 to 3.5 t/ha for cv. Tambo and cv. Moapa, respectively. Although the initial growth of Moapa was somewhat faster than that of Tambo, both cultivars maintained a maximum above-ground growth rate (between 125 and 225 kg/ha.d) for a relatively short period of two to three weeks. A decline in growth rate was then observed, which was most pronounced during the period of decreasing day lengths (from summer to winter) and in the cultivar Moapa. In many cases, this led to above-ground dry matter accumulation reaching "ceiling yields". This decline was caused by leaf fall during the warmer period of the year. Especially in Moapa, leaf senescence was sometimes considerably accelerated by attacks of leaf miners (*Liriomiza* spp.), which were difficult to control.

The growth pattern described here suggests a possible influence of cultivar, photoperiod and temperature. A photoperiod effect is generally more pronounced in dormant, winter-hardy cultivars than in non-dormant cultivars (Holt et al., 1975; Hesterman & Teuber, 1981), to which both Moapa and Tambo belong. However, in an experiment in a controlled environment at different photoperiods and two levels of light intensity, there was also a significant effect of photoperiod on total dry weight, average leaf size, specific leaf weight and shoot dry weight in the non-dormant cultivar Moapa. Hesterman & Teuber (1981) showed that the latter parameter was only affected by photoperiod and not by light intensity. Photo- period sensitivity in alfalfa is still poorly understood. In alfalfa growth modelling photoperiod-dependent forcing functions have been used, significantly influencing the growth rates of stems, leaves and the storage rate of total non-structural carbohydrates (TNC) (Holt et al., 1975; Fick, 1981). All these functions caused very drastic changes as soon as photoperiods started decreasing or increasing. However, the functional relationships were generally deduced from the results of sensitivity analyses with the model and are not based on independent data.

In temperate regions, the spring production is in general much higher than in San Camilo and reaches 6.5 to 7.5 t/ha for one cut (Nelson & Smith, 1968; Woodward & Sheehy, 1979; Sibma, unpublished results). Subsequent yields, however, decline rapidly until the autumn harvest, to approximately one third of the spring level (Nelson & Smith, 1968; Singh and Winch, 1974; Gosse et al., 1982; Sibma, unpublished results). These differences between spring and summer production are mainly caused by differences in the duration of the maximum linear growth rate (in these regions about 100 to 150 kg/ha.d), rather than in the growth rate itself. Several authors indicated the importance of the temperature influence for this phenomenon. The higher temperatures during the summer months later in the growing season, accelerate flowering and senescence of the leaves and so shorten the length of the growing period. As the crop growth rate in the linear stage remains about the same, it is the shorter duration that causes the yield reduction (Singh & Winch, 1974; Field et al., 1976). During late summer and autumn at these higher latitudes, the above-ground growth rate in the linear stage also clearly decreases due to the influence of photoperiod (Gosse et al., 1982), lower irradiance and sub-optimal temperatures. The lower yields from January to April in San Camilo, are probably comparable to the lower mid-summer productions at higher latitudes, whereas those from May to

September in San Camilo are more comparable to the late summer and autumn yields.

Results from pot experiments in Canada (Nielsen et al., 1960) and the Netherlands (Sibma, unpublished results), suggest that soil temperatures have a comparable significant effect on both the weight of above-ground and below-ground dry matter. A rise in soil temperature from 15 °C to 20 °C increased root weight by 35 to 65% and shoot weight by 22 to 100%. Therefore, the decrease in average temperature from about 20 °C in summer to about 17,5 °C in winter in San Camilo, may significantly affect total dry matter production. This winter decrease occurs despite an optimal air temperature for photosynthesis and growth during the day, because soil temperature in most of the rooted layer remains close to the colder seasonal average.

Similar short periods of maximum growth rate to those found in San Camilo, were also observed in California (Loomis, unpublished results). A striking phenomenon at both sites is that these maximum growth rates were produced during a period in which the light interception was still incomplete, whereas the decline in growth rates occurred when virtually all the light was intercepted. As growth rate has often been found to be an almost linear function of the amount of absorbed irradiance (De Wit, 1965; Scott & Wilcockson, 1978; Bean & Allen, 1981), one would expect growth rates to increase rather than decrease. The results in San Camilo showed also that the magnitude of this unexpected decline in growth rate was strongly cultivar dependent and clearly less pronounced for Tambo than for Moapa.

Several possibilities for the early decline in growth rates can be put forward:

1. rapid decline of canopy photosynthesis with age;
2. use of assimilates for N_2 assimilation;
3. nitrogen deficiency due to insufficient N_2 assimilation;
4. investment of assimilates in growth of below-ground biomass;
5. high respiration rates, mainly because of below-ground biomass.

Some of these aspects will be discussed below.

1. Rapid decline of canopy photosynthesis. Our photosynthesis measurements in Wageningen (Figs. 3.18), as well as measurements elsewhere (King & Evans, 1967; Sheehy et al., 1979; Sheehy and Popple, 1981; Loomis, unpublished results) do not indicate a significant decline in canopy photosynthesis with age.
2. Nitrogen assimilation costs. This process does not seem to offer a plausible explanation for the pronounced decline in growth rate, as the heavy N fertilization treatment during the first year of the growth curve experiment demonstrated the ceiling yield phenomenon to the same extent, although a 13.5% increase in total dry matter was obtained (Fig. 3.4). This aspect is further discussed in Section 3.4.2.3.
3. Nitrogen deficiency. Taking into account the small response of dry matter production to heavy N fertilization (420 kg N/ha), concomitant with the virtual absence of response in plant N concentration, this possibility also seems unlikely.
4. Investment in below-ground parts. The results shown in Tables 3.1 and 3.8, indicate that large quantities of root mass were built up (up to 25 t/ha) when alfalfa was harvested with long cutting-intervals and, consequently, canopy photosynthesis continues for a fairly long period. Other data on root production of alfalfa are scarce, but recently high yields of root-mass (up to about 8 t/ha) of alfalfa cut at 10% flowering, have also been reported by Abdul Jabbar et al. (1982) in New Mexico. These data are comparable with our data from alfalfa at a cutting interval of five

to six weeks (Table 3.8). So it would seem that large amounts of assimilates are invested in the extension of the root system, hence large quantities of assimilates may eventually be necessary for maintenance respiration.

5. Respiration rates. With the already mentioned extensive below-ground system, these may be very high. Assuming a relatively low relative rate of maintenance respiration of ca. 0.01/d for the roots, crowns and stubble and of about 0.02/d for the protein-rich forage, then collectively this may require about 300 to 350 kg carbohydrates/ha.d at the end of a (long cutting interval) growth cycle. Such a value is comparable with the measured total growth rate of another C_3 crop in San Camilo: the potato (Chapter 4). King and Evans (1967) also reported high respiration rates for alfalfa of 68 to 70% of gross assimilation. Using data from Woodward and Sheehy (1979) it can be calculated that at the end of a growth cycle of 69 to 78 days, up to 91 to 95% of the carbohydrates produced (equalling 500 to 600 kg CH_2O/ha.d) were used for respiration and translocation below-ground. Therefore, it can be concluded that although available data are scarce, strong indications exist that the build up and maintenance of below-ground tissue offer a good explanation for the observed growth pattern in San Camilo.

3.4.2 *Discussion of some growth-related parameters*

3.4.2.1 Leaf area development and light interception

In the course of the growth cycle, the proportion of leaves in the above-ground dry matter decreased, whereas the proportion of stems increased (Fig. 3.5). This is a common phenomenon in most crops. Less common are the relatively low LAI values of 3.3 (summer) to 3.5 (winter), compared to values of 6 to 7 reported for alfalfa from temperate regions (Nelson & Smith, 1968; Koter, 1977; Woodward & Sheehy, 1979; Sheehy & Popple, 1981). Under the low light conditions of growth chambers or greenhouses, LAI values as high as 12 to 14 were obtained (King & Evans, 1967; our measurements Section 3.3.3.2). However, low values of 2.0 to 3.2 are also reported from temperate regions, especially during late summer and autumn (Nelson & Smith, 1968; Gosse et al., 1982). Compared to these data from the literature, LAI patterns during different seasons in San Camilo are quite constant. The LAI during the winter period is even somewhat higher than in the summer period, because of the increased relative share of leaf dry matter (Fig. 3.6) and the production of thinner leaves, i.e. somewhat higher SLA values (Fig. 3.7).

There was again a clear cultivar difference between Moapa and Tambo in leaf area development. As with dry matter production, initially the formation of leaf area was faster in Moapa, although eventually (after about 30 days) Tambo produced a higher LAI (Fig. 3.9). In spite of the low LAI, light interception was very efficient and even at an LAI of 2.5, 95% of the light was intercepted. The LAI- light interception relation was the same for both cultivars (Fig. 3.10). Data presented by Wilfong et al. (1967) demonstrated that in field situations, more than 95% light interception no longer increased photosynthesis. This fraction of light interception is generally reached at LAI values of 3 to 5, although for seedling-alfalfa in spring a value of 2.4 has been reported (Wilfong et al., 1967; Gosse et al., 1982), probably because of a more favourable leaf geometry of the still regularly distributed stand.

In San Camilo, during the first 30 to 40 days the numerical values of LAI were about the same as the number of tons per hectare of dry forage production (Fig. 3.8). This rule of thumb also gave a reasonable approximation of the LAI obtained in growth curves reported by Nelson &

Smith (1968), Woodward & Sheehy (1979) and Sheehy & Popple (1981). After that period LAI mostly does not increase further or declines due to leaf drop.

The SLA values found in San Camilo of 20 to 25 m^2/kg were about half of those reported by Woodward & Sheehy (1979) and Sheehy & Popple (1981) for temperate regions, although in early regrowth and in the top layers of the canopy values similar to those in San Camilo were recorded. SLA-data from Loomis (unpublished results) were, in general, around 17 m^2/kg, so even lower than in San Camilo. Wolf and Blaser (1972) found that SLA increased mainly because of lower light intensities, as occur deeper in the canopy. Above an SLA of 22 m^2/kg, simultaneously the photosynthetic capacity decreased. These findings agree with the SLA values obtained in the greenhouse in Wageningen, where the low light intensities during winter resulted in SLA values of around 48 m^2/kg in all four cultivars, including Moapa and Tambo. It seems that under such conditions, the lower photosynthetic capacity per unit area at light saturation is well compensated for by the development of high LAI values. In that situation, light is distributed over a larger leaf area, so that most of the leaves do not reach the saturation level and, in total, high canopy photosynthetic rates are produced.

3.4.2.2 Leaf and canopy photosynthesis, respiration and transpiration

The relations between irradiance and photosynthesis of individual leaves showed little difference between the cultivars, with the exception of three pots of the Peruvian cultivar Yaragua. Photosynthesis reached values of 28 to 30 mg CO_2/dm^2.hr, which is somewhat below maximum values of about 33 to 36 mg CO_2/dm^2.hr measured by Brown et al. (1972); Sheehy et al. (1979); Sheehy and Popple (1981) and Loomis (unpublished results). Data from Wolf and Blaser (1972) suggest that the low levels of irradiance in the growth chambers in which the plants were grown, may be a cause of this reduced photosynthetic potential. A supportive indication was that SLA of the measured leaves was 33 to 40 m^2/kg, considerably higher than the SLA values of 20 to 25 m^2/kg generally found for the newly expanded leaves in canopies in the field. The reason for the low photosynthetic values obtained for three out of four measurements of cv. Yaragua is not clear. There may be number of reasons, such as light environment of the particular leaves or cultivar characteristics. Pearce et al. (1969) and Sheehy et al. (1980) found a large variability in leaf photosynthesis rates among different genotypes, ranging from 15 to 82 mg CO_2/dm^2.hr, but the data reported by Foutz et al. (1976) and Sheehy et al. (1980) clearly show that these values are not correlated with dry matter production and that genotypes with a low leaf photosynthetis accumulate dry matter as fast as, or even faster than those with a high leaf photosynthesis. However, dry matter accumulation was positively correlated with photosynthesis when expressed on a per plant basis by multiplying the leaf photosynthesis by the leaf area per plant. Delaney & Dobrenz (1974) found the same, but the correlation with yield was even higher for dark respiration per plant. Foutz et al. (1976) and Sheehy et al. (1980) concluded that, in fact, morphological characteristics such as leaf area/plant and leaf weight/plant alone were equally good, and often more reliable, indicators of alfalfa production capacity than physiological characteristics such as photosynthesis on a per plant basis.

Photosynthetis measurements of artificial swards showed a very high assimilation rate for the older undisturbed canopies due to their very high LAI (Fig. 3.18). The effect of the latter was so pronounced because of the effect of illumination of the sides of the enclosure. The absence of any difference among cultivars, despite the completely different environment in their place of origin, was remarkable. After correcting for the side illumination (Section 3.5.2.2), maximum net canopy photosynthesis at the highest irradiance level (about 650 $J/m^2.s$) was simulated to be around 55 kg CO_2/ha.hr; somewhat lower at an LAI of fourteen than at an LAI of five.These values are reasonably comparable with the data obtained by King & Evans (1967) with artificial communities of alfalfa plants, grown under the low light intensities of environmentally controlled growth chambers. In the field, measured maximum net canopy photosynthesis of alfalfa, reported by Wilfong et al. (1967) and Sheehy et al. (1979), varied between 60 and 75 kg CO_2/ha.hr, thus somewhat higher than the corrected values from our greenhouse measurements. These results emphasize the major influence exerted by the environment in which the plants were grown before measurements started. It means that the absolute values from the measurements in Wageningen cannot be extrapolated directly to the field situation in Peru. Nevertheless, the results strongly support the idea that photosynthesis does not decline significantly in older canopies and hence cannot be the cause of the decreasing dry matter growth rates about four weeks after cutting in San Camilo. Data from Wolf & Blaser (1981) referring to field measurements in spring in Virginia, also do not indicate either a reduced photosynthetic rate with age, neither per unit of soil surface, nor per unit of leaf area.

The measured values of above-ground dark respiration were well within the range found elsewhere (Sheehy et al., 1979; Brown et al., 1972 and Loomis, unpublished results).

Similarly as for the canopy photosynthesis, no cultivar differences were noted with respect to transpiration per unit of dry matter produced (Table 3.5), which is in agreement with results reported by McElgunn & Heinrichs (1975), who tested fifteen alfalfa genotypes of *Medicago sativa*, *M. media* and *M. falcata* origin. Although differences in transpiration per day existed between the genotypes, this was due to differences in growth rate and not in transpiration per unit of dry matter produced.

The results presented in Table 3.5 do not seem to agree with the average quantities of 650 and 850 g transpired water per g dry herbage produced by cv. Tambo and Moapa, respectively, in San Camilo reported by Valdivia and Zipori (1982). However, these values are not comparable, because the calculated results of Table 3.5 do not take into acount transpiration during the night. Moreover, the values of Table 3.5 are based on total dry matter and not on herbage alone. To take night transpiration into account, the photosynthesis and transpiration of Tambo and Moapa, measured on clear days during the experiment in Wageningen, were accumulated over an uninterrupted period of 24 hours. This resulted in TRC values of 433 and 416 g water/g dry matter for Tambo (LAI 14.4) and Moapa (LAI 13.5), respectively. If the herbage to total dry matter ratio may be assumed equal to the average ratio for various cultivars reported by McElgunn & Heinrichs (1975), average values of 561 and 584 g water per g herbage would result for Wageningen; these values are comparable to those found in San Camilo by Valdivia & Zipori (1982). The difference between Tambo and Moapa in San Camilo is probably the result of a different distribution of dry matter among herbage, roots and crowns for both cultivars.

The TRC calculated from the photosynthesis measurements of the artificial swards appeared independent of the LAI in the range of 2.7 to 14.4, which is in agreement with the results of King & Evans (1967), who found only a distinct increase in evapotranspiration with increased LAI up to a value of about three, with a similar increase in photosynthesis.

3.4.2.3 Influence of N fertilization and some aspects of N_2 fixation

Figure 3.4 demonstrates, that high NPK fertilization increased dry forage production on an annual basis by about 13.5%. This difference, although not very large, was consistent in every growth curve determination and was highly significant ($P < 0.001$). Although the average P and K concentration of the tissue at 10% flowering was increased by the fertilization from 0.28 to 0.40 and from 3.4 to 4.0%, respectively, the lower values from the non-fertilized plots were still far above values measured later in the P_0 and K_0 treatments of the PK fertilization experiment (Section 3.3.6.1), in which no response in dry matter yield was obtained. Moreover, critical nutrient concentrations reported in the literature are well below the values obtained in non-fertilized herbage (Nelson & Barber, 1964; Rhykerd & Overdahl, 1972). At first, the N application seemed not to be the cause of the difference in forage yield either, as tissue-N concentration in both treatments was almost identical and the value in the non-fertilized treatment at 10% flowering (3.8%) was well above the critical value of 3.0% reported by Nelson & Barber (1964).

However, Christiansen-Weniger, as early as 1923, reported for several legumes increases of 11 to 13% in total dry matter, following fertilization with ammonium-nitrate. The response in above-ground dry matter was much stronger than in roots. For alfalfa, increases of 13, 18 and 4% were found for total dry matter, tops and roots, respectively. When light was reduced, reponse was much lower and at low light it was absent. Christiansen-Weniger (1923) explained the differences from the difference in energy requirement between N_2 fixation and mineral N-assimilation.

A similar small but significant response ($P < 0.025$) of 7% extra above-ground dry matter production was obtained in San Camilo in a strip of alfalfa, adjacent to the PK fertilization experiment, fertilized with 1000 kg N, 250 kg P and 250 kg K, compared with plots that received no N, but otherwise the same amount of P and K fertilizer. Halva & Lesak (1977) and Sibma (personal communication) also reported alfalfa forage production responses to N fertilization of 9% and 6% respectively. In contrast to these results was the absence of any response to mineral N fertilization in cv. Moapa in the development and persistence experiment. However, there the yield level was quite low. Apparently, at sub-optimal growing conditions for the plants, the available amount of mineral N is relatively higher and, therefore N_2 fixation is more reduced (McAuliffe et al., 1958). The same interpretation can also be given for the previously mentioned absence of response from N fertilization under low light conditions, reported by Christiansen-Weniger (1923).

Christiansen-Weniger (1923) estimated the energy costs of N_2 fixation for alfalfa from a nitrogen balance of the pots, resulting in 7.2 g dry matter/g N fixed, which was estimated by Phillips (1980) to be about 2.9 g C/g N fixed. Ryle et al. (1979b) measured photosynthesis and respiration simultaneously in plants of three legumes (soybean, cowpea and white clover) growing without nodules on a nutrient solution and depending completely on NO_3 uptake, and in plants of the same species, that were effectively nodulated and completely dependent on N_2 fixation. In all three species, plants fixing N_2 respired 11 to 13% more assimilated carbon than comparable plants lacking nodules and utilizing NO_3-N. In N_2-fixing plants, average respiratory losses for the three species varied between 6.3 and 6.9 g C/g N. These costs represent the total respiration, including maintenance respiration of the root (Ryle et al., 1979a). Uncertainties with respect to the separation of root and nodule respiration have recently been elucidated using a new technique for the direct measurement of the respiratory costs of symbiotic N_2 fixation (Minchin et al., 1983). From those data an average value was estimated of 4.5 g C/g N, which was also used by Sheehy (1983) for soybean.

The high forage production of alfalfa, without any N fertilization in San Camilo, resulted in a first estimate of 900 to 1000 kg fixed N/ha.yr in San Camilo (Versteeg et al., 1982). This estimate was based on a tissue-N concentration of 3.8 to 4.0% and a dry matter production of 30 t/ha.yr. In due course, however, it appeared that the high N levels were prevalent especially in the winter season and, that on an annual basis an average value of about 3.4% would be more acurate. Moreover, root-N concentration was lower at about 2%. A more accurate estimate may be obtained from the first year alfalfa production of a virgin desert soil, where the influence from N mineralization in the soil can be neglected. The first year production of above and below-ground dry matter was 19 and 8 t/ha respectively, in which 0.034 x 19000 + 0.02 x 8000 = 806 kg N was present. From this quantity, N in irrigation water (about 80 kg) and the starter fertilization (40 kg) have to be substracted, but only for 80%, as at least an estimated 20% has percolated with the surplus irrigation water below the rooting zone. So, in total 96 kg N have to be substracted, which results in an estimated fixation of 710 kg N/ha.yr.

This value is still appreciably higher than the range of 50 to 465 kg N/ha.yr reported in the literature (Burton, 1972; Nutman, 1976). The high N_2 fixation in San Camilo is mainly the result of the length of the growing season that lasts twelve months. On a daily basis, almost 2 kg N/ha are being fixed, a value that is similar to N fixation rates, calculated during favourable growth periods in Minnesota, measured directly in the field by the ^{15}N isotope dilution technique (Heichel et al., 1981). Sibma (personal communication) reported that alfalfa in the Netherlands absorbed, over a period of three years, a total of about 1300 kg N/ha. Substracting from this value the amount of N absorbed by an N_0-treatment of ryegrass on the same site, fixation was estimated at about 1000 kg N/ha, over a period of three years. Taking into account that the growing season for alfalfa was about six months/yr, again fixation amounted to 2 kg fixed N/ha.d. So, it may be concluded that on average alfalfa is able to fix about 2 kg/ha.d under favourable conditions. There are indications that this rate could be further enhanced. For example, Barnes et al. (1981) reported that by selection the N_2 fixation rate of the cultivar Saranac was increased by an extra 36%.

In San Camilo, a significant number of farmers do not inoculate seeds prior to sowing alfalfa. There were, however, no visible indications of a lower production compared with inoculated fields. At the experiment station, there was a slight retardation during the first four to six months after establishment, when seeds were not inoculated. After that period, the production of inoculated and non-inoculated fields was at about the same level, as was the tissue-N concentration. Root samples from both types of fields showed the presence of effective nodules, indicating an efficient inoculation by effective strains of *Rhizobium* naturally present on the site. This was confirmed by the results of the inoculation source pot trial in San Camilo (Table 3.12). Here, after three months, only significant differences in root weight between the different treatments were obtained. The question regarding the sources of the natural inoculation, was not solved completely, but it became evident that the dust from surrounding alfalfa fields, in combination with sprinkler-irrigation, gives an efficient inoculation. The question whether the irrigation water itself is also a potential source of inoculant, remained, at least for the San Camilo situation, still an academic question.

3.4.3 *Production in relation to management*

3.4.3.1 Plant density

One of the most important problems associated with alfalfa cultivation, is the inability of an established stand to replace lost plants, contrasting markedly with other pasture species, that in many cases regenerate within the ageing sward either vegetatively or from seed, or both. Consequently in alfalfa cultivation, detrimental effects of management, pests and diseases are much more critical for alfalfa than for most other pasture legumes and grasses (Leach, 1978). Probably the most important management tool for the preservation of a good and productive alfalfa stand, is the choice of the correct cutting or grazing regime.

The results obtained in San Camilo clearly demonstrate that long cutting intervals of five to seven weeks result in higher production during the colder period of the year (May to October), but that shorter intervals are clearly more favourable from January to April (Figs. 3.13 and 3.19). The latter phenomenon is the result of the pronounced declining growth rates during the second part of the growth periods obtained in these months (Fig. 3.2).

Generally, farmers in the San Camilo area graze the alfalfa when about 10% of the stems are flowering, which leads to an exploitation interval during winter of about six weeks and a shorter interval in summer of about 30 to 35 days. Hence, farming practice agrees with recomendations resulting from the experiments in San Camilo.

Such advantageous use of shorter exploitation intervals during the warmer months of the year could not be demonstrated in South Australia, another region where weather conditions would permit year-round alfalfa cultivation (Judd & Radcliffe, 1970; Leach, 1978). In regions with shorter growing seasons a more frequent cutting regime during summer often decreased forage production substantially (Feltner & Massengale, 1965; Robison & Massengale, 1968). This phenomenon has been defined as "summer slump" in regions where day and night temperatures are very high during the summer growth period, causing a depletion of stored reserves (Feltner & Massengale, 1965; Robison & Massengale, 1968). In San Camilo, temperatures in summer are close to optimum and such growth behaviour was not observed during that season.

A common phenomenon reported in combination with the lower production, is a decrease in plant density in the field (Robison & Massengale, 1968; Judd and Radcliffe, 1970). Up to a certain minimum plant density, the alfalfa stand can maintain its production level by compensating losses in stand density by yield per plant. Apparently, these critical plant densities are not identical for all cultivars used and values from 30 (Leach, 1979) to 55 plants/m^2 (Offutt, 1979) have been reported. Mullen et al. (1977) reported that below these critical densities the same number of stems/m^2 could be obtained, but that nevertheless production declined, because of a decrease in the average weight per stem.

In San Camilo, the effect of cutting frequency on plant density was not very pronounced (Fig. 3.14, Table 3.6). Zipori & Valdivia (1982) measured the density in an irrigation experiment which was cut every 35 days and was sown the same date and adjacent to the "development and persistence" experiment. They found that treatments with less irrigation generally showed a reduced decrease in plant density. In their experiment, plant density of Tambo was 2.4 times as high as that of Moapa. Another striking observation was that the plant density of Moapa in the irrigation experiment was nearly twice as high as in our experiment, even at a cutting interval that was one week shorter. In hindsight it was then found that in our development experiment the strips, that had been harvested for sampling by the Agria power mower, were cut the same day again with a tractor-driven Taarup harvester, in the cleaning operation for the rest of the field. In the irrigation trial, the experimental plots were cleaned by hand only, because of the installed measuring devices. Hence, possibly the mechanical damage of the crowns had a marked influence on the stand decline of alfalfa. This could also explain why the smaller and more deeply situated crowns of cv. Tambo were clearly less susceptible to such harvest damage than cv. Moapa.

3.4.3.2 Reserve level

Forage production, as affected by different cutting intervals, has been related to the total non-structural carbohydrate (TNC) level in the roots (Møller Nielsen et al., 1954; Feltner & Massengale, 1965; Robison & Massengale, 1968). A low level of TNC in the roots at the moment of cutting results in a slow recovery of the canopy and, consequently, in a low dry matter production. Smith (1962) studying the carbohydrate levels in roots during the growing season in Wisconsin, observed that after the alfalfa was cut, the TNC concentration declined for two to three weeks, and then increased until full flowering or the next cut, whichever came first. At full flowering, plants had accumulated about 35 to 38% TNC in the roots, which dropped after cutting to about 15 to 20%. Several levels of fluctuations were reported. In Finland, Pulli (1980) registered fluctuations from 40 to 10% in 1973, and in the next year from 50 to 40%. Cralle & Heichel (1981) in Minnesota reported a fluctuation in TNC percentage from 15 to 5%; Cohen et al. (1972) in Israel from 24 to 20% and Loomis (unpublished results) in California from 17 to 11%. The implication from these results is, that the interval between two cuttings should be long enough to enable restoration of the TNC concentration in plant roots, and to enhance forage production and survival (Robison & Massengale, 1968). However, observed trends of TNC concentrations in the roots of cv. Tambo under different cutting frequency treatments in San Camilo did not demonstrate any relation to the moment of cutting, neither in phloem, nor in xylem (Fig. 3.20). Average TNC concentrations in the roots under the different cutting intervals of three to seven weeks varied slightly, generally without reaching any significant difference. However, etiolated regrowth was positively related to the reserve level in the same experiment (Fig. 3.21, Table 3.7). This result indicates that "reserves" certainly played a significant role in the regrowth of alfalfa, but apparently the TNC concentration was not an adequate parameter, at least not for the alfalfa growing in our fields.

An alternative hypothesis could be that carbohydrates for regrowth and maintenance may also be mobilized from a part of the root system which result in dying of these roots. In that way, the absolute amount of carbohydrates available to the plant could be considerable, without affecting the TNC concentration in the remaining roots to any extent. A positive indication for such a hypothesis could be derived from the results of root weight determinations in the field used for the cutting frequency experiment. Root weights were substantially lower following a frequent cutting regime (Table 3.8). In a subsequent pot experiment with alfalfa, which still had a relatively small number of young roots, both root weight and TNC concentration showed a distinct cyclic pattern. However, also with these results a more pronounced picture emerged when TNC is presented as weight per pot (Fig. 3.24). As early as 1939, Harrison (1939) and Hildebrand & Harrison (1939) found a very distinct response in root weight in a pot experiment, with cutting intervals from one week to one month. Photographs of washed roots clearly showed the dying roots in the frequently cut alfalfa. Root weight responses to cutting are also presented by Smith & Nelson (1967); Chatterton et al. (1974), and by Cralle & Heichel (1981). Reynolds (1962) used the same reasoning to explain the absence of a relationship between regrowth and TNC concentration in the storage organ of some grasses, the stem base.

In addition to TNC level and cutting frequency, the cutting height and the remaining leaves in the stubble may also influence regrowth. A tall, leafy stubble (10-15 cm) only gave superior regrowth under very frequent cutting, probably partly because such stubble can develop high photosynthetic rates. However, when sufficient reserves are available, as is the case with not too frequently cut alfalfa, leaf area is restored so rapidly that the contribution of stubble leaves will be of no advantage (Hodgkinson et al., 1972).

3.4.3.3 Some other aspects of management

A winter resting period in San Camilo gave some improvement in subsequent average growth rates, but total annual productivity remained the same because of the loss in production during the resting period (Table 3.2). A summer resting period, especially when combined with water stress, showed a slight, but still significant, negative response. The absence of a clear response to a winter resting period shows that in San Camilo alfalfa was very flexible with respect to cutting, which agrees with results reported by Leach (1978) in Australia. Wolf & Blaser (1981) also reported that early spring cutting of alfalfa in Virginia resulted in a lower yield in the subsequent hay harvest, but that the total forage yield during the season remained the same.

The indication that weeds may constitute a considerable portion of the total dry matter production (Fig. 3.15) and still do not significantly decrease the overall digestibility, palatability and mineral composition of the sward (Table 3.4) is in agreement with the results of McKinney (1974) in Australia. He even obtained higher live-weight gains of ewes in pastures containing a significant proportion of annual grasses, compared to almost pure alfalfa swards or pastures containing mostly annual grasses. Also the results from 't Mannetje (in Leach, 1978), who compared pure alfalfa stands with alfalfa combined with a sown perennial grass (*Cenchrus ciliaris* or *Panicum maximum*), alone or with Siratro (*Macroptilim atropurpureum*) are indicative. The mixtures always produced more than pure alfalfa swards, especially when there was no irrigation. Decline of the alfalfa stand in the mixtures was the same (with irrigation) or less (dryland conditions) than in pure alfalfa swards. Also in San Camilo the alfalfa death rate was not influenced by weeds in general, altough especially Bermuda grass (*Cynodon dactylon*) and Kikuyu grass (*Pennisetum clandestinum*) certainly crowded out the alfalfa plants.

3.4.4 *Aspects of crop requirements for and concentrations of P and K*

The results of the fertilization experiment with P and K in San Camilo have indicated that good alfalfa production on the pampa soils can be obtained for several years without fertilization. Nevertheless, a crop of alfalfa yielding 25 t/ha.yr absorbs annually the considerable amounts of about 50 to 60 kg P/ha and 600 to 700 kg K/ha. Consequently P and K concentration of forage from unfertilized plots decreased significantly (Fig. 3.23), but apparently not to critical levels (i.e. concentration of nutrients in the dry matter, below which a significant yield depression occurs). Yet the concentration in the above-ground dry matter at the end of the project period (0.20 and 2.20% for P and K, respectively) are already within or close to the ranges of critical values of 0.11 to 0.23 for P and 0.44 to 2.0% for K (Gerwig & Ahlgren, 1958; Kresge & Younts, 1962; Nelson & Barber, 1964; Bingman, 1965; Ulrich & Ohki, 1965; Rhykerd & Overdahl, 1972 and Malakondaiah et al., 1981). Another indication that a P response could be expected soon, is the fact that fresh forage yields in P-fertilized plots were sometimes significantly higher. Apparently the fresh weight in the P_0 plots is slowed down earlier than the dry weight. Such a phenomenon was also recorded for N shortage in wheat and poppies (*Papaver somniferum*) by van Dobben (1961), who ascribed it partly to accumulation of carbohydrates in the tops. This explanation is supported by the observation of Alberda (1965) that at lower NO_3 concentrations in the nutrient solution, TNC and crude fibre percentages in Ryegrass increased before the dry matter production was affected.

With regard to the critical concentrations in the tissue, several aspects are noteworthy. In the first place, the ranges are quite wide. The optimum nutrient concentration in plants varies with the season (Kresge & Younts, 1962; Fig. 3.23) and also with physiological age (Sallee et al., 1959; Rhykerd & Overdahl, 1972; Fig. 3.11 & 3.12). Also significant differences were observed between cultivars and between stands of different age.

The results on P and K fertilization of an alfalfa-orchard grass mixture in Japan, reported by Drake et al. (1977) and by Oohara et al. (1981), are also illustrative of the variability in critical nutrient levels. Fertilization with 250 kg K/ha.yr increased the average annual production of the alfalfa component (over the period 1970 to 1979) by a factor of thirteen, from only about 0.14 t/ha to 1.8 t/ha. When in addition to K, an extra 44 kg P/ha.yr was given, the production increased as much as sixteen times, up to 2.3 t/ha.yr. The measured nutrient concentration ranges in the forage of the unfertilized control were 0.9 to 2.1% K and 0.13 to 0.23% P, respectively, compared to ranges of 1.7 to 3.6% K and of 0.19 to 0.31% P for the fertilized treatments. So, even these extreme responses (partly caused by competition effects of the orchard grass), coincided with tissue nutrient concentration ranges in the fertilized treatments and in the unfertilized control that often overlapped.

It can be concluded, therefore, that apart from the nutrient supply to the crop, many other factors, like month of sampling, cultivar, age and history of the stand, influence the nutrient concentration in the plant. Therefore, the definition of a critical range such as that proposed by Kresge and Younts (1962), may be more valuable, even for a specific region. In addition, for a correct judgement more data, such as the actual and potential production level and the season and physiological stage at the moment of sampling, are necessary.

Taking all this into account, it was not so surprising that no clear critical P level in our experiments in the farmer's field was found. In the first experiment, a stand where the P concentration in the non-fertilized situation was 0.21%, 36% extra forage yield after P fertilization was obtained (Table 3.9), whereas no response to P fertilization was found in the second and third experiments, despite tissue-P concentrations in the unfertilized plots of 0.17 and 0.22%, respectively (Table 3.10 and 3.11).

Results of Sallee et al. (1959) suggest that for P, less variable results are obtained that can be interpreted easier, when only mid-stem tissue is analysed, obtained by cutting out the middle third of the stem and stripping the leaves. Sampling should only be done on 10% flowering plants.

The results obtained in San Camilo indicate that even with an application of 250 kg K/ha.yr, the K concentration in the harvested material could not be maintained at a constant level (Fig. 3.23), whereas a relatively low application of 52 kg P/ha.yr in the "development and persistence" experiment could maintain the P percentage at its starting level (Section 3.3.2.4). When alfalfa is grazed, as is generally the case in Southern Peru, practically all the P can be recycled. Noij (unpublished results) estimated that in San Camilo, about 50 kg of P/ha.yr. returns to the field when only 40% of the manure production is recycled in the same alfalfa fields and the P in the irrigation water is added. In that case, the system is practically in balance for P. Grazing is also the major factor in the recycling of K, although somewhat greater losses can be expected by percolation below the roots, as the element is more mobile in the soil. On the other hand, few problems are to be expected in the near future in San Camilo for K, because of weathering of parent rock material and the relatively greater contribution by the irrigation water, provided the same grazing system is maintained.

3.5 MODELLING ACTIVITIES WITH ALFALFA

3.5.1 *Introduction*

Despite a voluminous literature on the subject, many quantitative aspects of alfalfa growth as dependent on environmental and management factors are poorly understood. This may be partly due to the wide variability in genetic and environmental resources. In addition, the perennial nature of the crop that leads to repetitive removal of above-ground organs, followed by regrowth, is an additional source for yield variations, that makes the quantitative understanding of this crop more troublesome.

In the previous Sections it was shown, that in San Camilo the growth of alfalfa did show only moderate fluctuations throughout the year. Under proper management, well-established fields produced forage yields (per cutting) of 1.5 to 2 t/ha during winter and of 3 to 3.5 t/ha in summer, under a regime of ten cuttings per year (Zipori & Valdivia, 1982). This is a much smaller fluctuation than in the strongly seasonal temperate regions, where cuttings in spring generally give much higher yields of up to 7 t/ha, and successive cuttings are significantly reduced to about 2.5 t/ha in autumn (Nelson & Smith, 1968; Woodward & Sheehy, 1979). Evidently, the difference can largely be explained by the relatively small fluctuations in weather conditions in summer and winter in San Camilo. However, the phenomenon of "ceiling-yields", the rather sudden decline in forage growth rate of a still green canopy under favourable growing conditions, is difficult to explain. Observations did not indicate a relation to phenological development of the crop. Similar behaviour was also noted in California (Loomis et al., unpublished results). Another poorly understood aspect of alfalfa growth, is the regrowth after cutting. Several authors have related it to the carbohydrate concentration in the roots (Smith, 1962; 1972; Hodgkinson, 1970), whereas others consider the number of shoots resuming regrowth as the most important parameter (Leach, 1968; 1970). On the other hand, Langer & Steinke (1965) regarded the residual leaf area as the major factor controlling regrowth. On the basis of these three factors, Fick (1977) developed a model that predicted reasonably well several observed regrowth patterns. However, a simplified model that did not use root and shoot reserves as state variables gave similar results. Fick (1977) emphasized that more quantitative knowledge about basal buds and root reserves is necessary for a proper understanding of the regrowth.

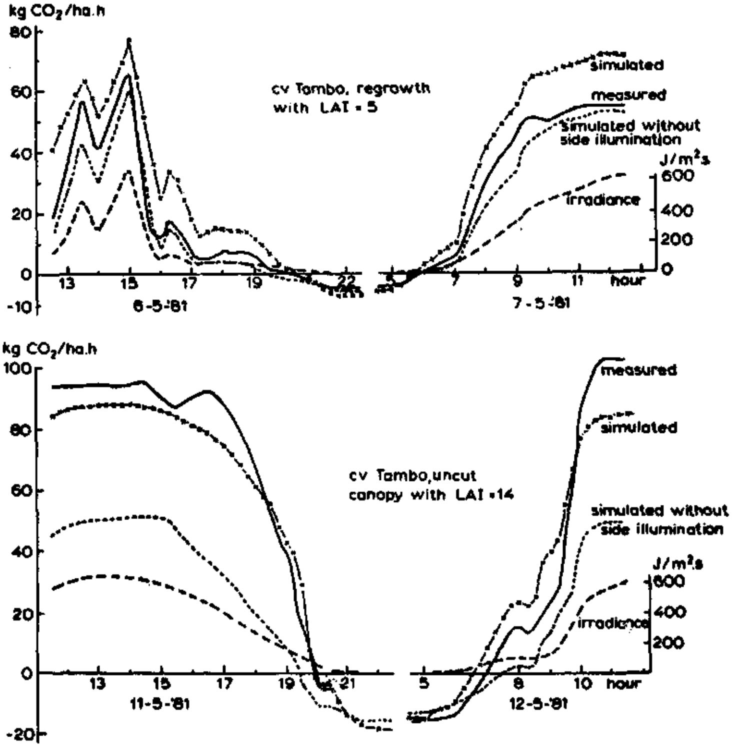


Fig. 3.25

Net photosynthesis of canopies of alfalfa cv. Tambo in enclosures in the greenhouse. Above: uncut, LAI = 14;below: regrowth, LAI = 5; ——— : measured; ×-×-×-× : simulated; .... : simulated for conditions without ilumination from the sides.

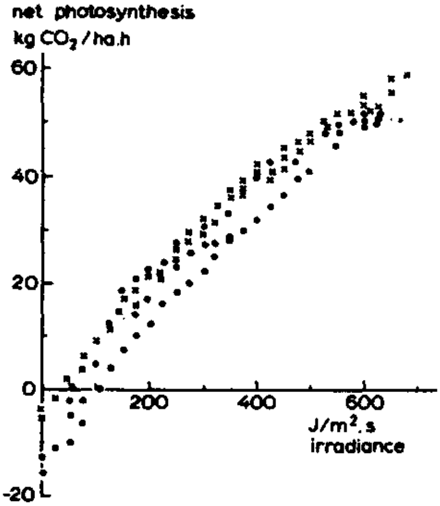


Fig. 3.26

Response of net photosynthesis to irradiance, as simulated for the enclosures in the greenhouse, without advantage of illumination from the sides. ooo : uncut,LAI = 14; xxx : regrowth, LAI = 5.

A first attempt to describe alfalfa growth in San Camilo in a quantitative way was made in 1980 by Van Keulen & Zipori (unpublished results), on the basis of an adapted version of the crop growth simulation model ARID CROP (Van Keulen, 1975; Van Keulen et al., 1981). Levelling-off could be achieved by assuming concurrently a declining photosynthetic capacity of the canopy with age and an increasing allocation of assimilates to a reserve pool below-ground. Regrowth after cutting was assumed to be produced by translocation of reserves from the roots to the above-ground parts, in dependence of reserve level and sink size. These assumptions, and the values of several parameters in the model, were mainly based on intelligent guesswork, derived in part from calibration* of the model on the 1980 summer growth curve. Without further adaptation, the model predicted the measured growth during winter fairly well.

On the basis of these results, further experimentation was directed to obtaining additional data on the revealed knowledge gaps. That information, described in the previous Sections of this Chapter, was used in further modelling activities. The main objective was at this stage, to develop a descriptive model that would realistically predict alfalfa yields, measured under different cutting regimes.

3.5.2 *Simulation of photosynthesis, respiration and transpiration in crop enclosures in the greenhouse*

3.5.2.1 Introduction

Measured exchange processes of artifical alfalfa swards in enclosures (see Section 3.2.4) were simulated with the model PHOTON (De Wit et al., 1978), which has basically the same structure as the model BACROS (see Section 5.4.2 for a brief description). The main difference is that time steps of only a few minutes are used; the exact time step at any moment is determined by the model itself in relation to the rate of change of the fastest process.

Simulations were carried out for two sets of measurements with the Peruvian cultivar Tambo, one with an established sward with an LAI of 14, the other with a four-week old regrowth with an LAI of about 5. The measurements were carried out in a greenhouse in the Netherlands, on reasonably sunny days at the beginning of May.

The basic simulations were carried out without correction for the illumination of the sides of the enclosures, but the effect of the glasshouse roof was always corrected. However, some runs were executed correcting for the side illumination, to mimick a normal field situation.

The original calculation of the maintenance respiration was slightly modified to include the maintenance of the photosynthesizing tissue (leaves) during the night, when there is no surplus energy from the photosynthesis process.

3.5.2.2 Results and discussion

For both sets of measurements, the calculated photosynthesis deviated often significantly from the measured results (Fig. 3.25). One problem was that the deviations for the two sets of measurements were generally in opposite direction: the simulated values for the young sward were

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*Model calibration or curve fitting is the process of running a simulation program several times at different parameter values, in order to choose those which give the best fit with the measured data.

consistently higher and those for the old one mostly lower than was measured. For this reason, adaptations in the model such as use of different maximum values of net photosynthesis for single leaves at light saturation or modified fractions of diffuse and direct light, did never result in better predictions of both enclosures at the same time. A possibility could be that correction for the side illumination of the enclosure should be smaller for the young, and greater for the old sward. However, no theoretical basis for such an effect could be found and it was therefore not attempted. In contrast to the net photosynthesis, the simulated dark respiration approached the measured values reasonably well for both types of canopy.

As in the simulation program no decrease in photosynthesis of older leaves was assumed, the observed deviations between measured and simulated photosynthesis of the old sward are contrary to what one would expect if such an age effect would be present in reality. Therefore a declining photosynthesis in older alfalfa swards seems unlikely.

Taking into account the magnitude and the direction of the deviations of measured and simulated photosynthesis, it was decided to simulate also the photosynthesis of young and old alfalfa swards without side illumination. The objective was to obtain an idea about the difference in the photosynthetic behaviour of the two types of swards in field-like situations. These simulated assimilation rates in the absence of side illumination are also presented in Fig. 3.25. In addition these rates are plotted against irradiance in Fig. 3.26. The results show, that in the field situation the "heavy" old sward would have a slightly lower level of net photosynthesis, mainly because of the higher maintenance respiration burden. The temperature-sensitivity of that process explains the larger variability in net photosynthesis at similar irradiance levels in the old sward. This effect was most striking at corresponding light levels in the lower morning and higher afternoon temperatures. Maintenance respiration also caused greater differences in net assimilation between the two swards at lower irradiance levels, when in the old sward a larger proportion of the leaves is in dark conditions, where they have to rely for their maintenance on assimilation products made elsewhere.

The results presented in Fig. 3.26 confirm our earlier impressions from the results of the enclosure measurements and the evidence found elsewhere (e.g. King & Evans, 1967; Sheehy et al., 1979; Loomis, unpublished results) that the photosynthetic capacity of older alfalfa swards does not decline significantly. The slightly lower value for the older sward is probably negligible in real field situations, where such large canopies were not found. There is still a possibility that the calculations, such as those for the additional side illumination, were too pessimistic for the old and too optimistic for the young canopy. Also King and Evans (1967) did not measure a decrease in photosynthesis in alfalfa swards up to an LAI of 11.

The PHOTON simulations proved usefull for several reasons. First, the comparison of the accurate assimilation measurements and the simulated results showed that these types of comprehensive, physiologically based simulation models can still not account for all phenomena observed. Secondly, the calculations confirmed the absence of a strong decline in assimilation rate of older alfalfa swards. Finally, the model could be improved once an error had been detected, mainly through the excessive amount of photosynthesizing tissue present in the older sward.

3.5.3 *Simulation of alfalfa growth in San Camilo under different cutting regimes*

3.5.3.1 Some general aspects

The model ARID CROP, the basis for the present simulation study, was developed for the simulation of growth of natural vegetation in a semi-arid environment, growing under conditions where water availability is determined by rainfall and soil physical properties, but where nutritional and phytosanitary conditions are considered optimal. The choice for this model in a first alfalfa growth simulation study (Van Keulen & Zipori, unpublished results) was based on the consideration that future simulations would require different soil and water conditions. Although these aspects are not relevant to the present study, the model has the advantages of being relatively simple and of requiring a limited amount of information. Moreover, it uses a relatively small amount of computer time, which is especially relevant when modelling is still in its preliminary stage. A short description of the concepts of ARID CROP, summarized from Van Keulen et al. (1976) follows.

The model ARID CROP describes the growth of an annual vegetation under optimal mineral and nitrogen supply, in dependence of weather conditions and available moisture. The main plant state variables are the weight of leaves, stems, and roots, the leaf area and the rooting depth. To monitor moisture availability, the model uses several soil state variables, the most important being the water content (up to a depth of 2 m and subdivided in compartments) and the soil temperature.

The rate of growth of the vegetation is determined by the actual transpiration rate and the water use efficiency (defined as the ratio of potential growth rate and potential transpiration rate). The actual transpiration rate is determined by the potential crop transpiration and moisture availability in the soil.

Potential crop transpiration is calculated from the evaporative demand of the atmosphere, determined by irradiance intensity and the combined effect of windspeed, air humidity and the leaf area of the canopy.

For the description of the moisture status of the soil, the total soil depth is divided into an arbitrary number of compartments. In each compartment a moisture balance is described comprising infiltration, evaporation and water uptake by the roots. Infiltration into the soil follows from precipitation (corrected for the influence of run-off and run-on) and actual evaporation is calculated from the Penman equation, taking into account the distribution of energy between canopy and bare soil and the reduction due to drying of the upper soil compartment. Moisture availability to the vegetation depends on the actual moisture content of the soil and the vertical extension of the rooting system. It is assumed that a "root front" moves down at a temperature-dependent rate when the moisture conditions are favourable. Growth stops when the roots reach a dry soil compartment. The root system is considered homogeneous in horizontal direction, so that the moisture uptake is governed by the average moisture content of each compartment that is reached.

Potential crop growth rate follows from the rate of gross photosynthesis, taking into account the losses due to maintenance respiration and due to conversion of primary photosynthates into structural plant material (growth respiration).

The leaf area of the vegetation, important for both the calculation of potential transpiration rate and potential crop growth, is calculated from the leaf weight, assuming a leaf area ratio dependent on air temperature.

Fig. 3.27
Specific leaf area (SLA) pattern over the year.

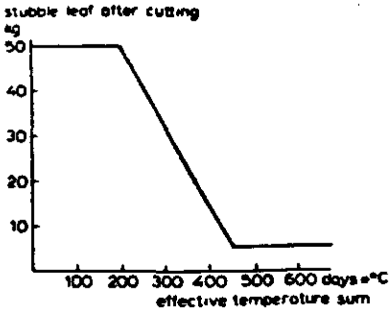


Fig. 3.28
Remaining leaf after cutting in relation to accumulated temperature in the previous growing period.

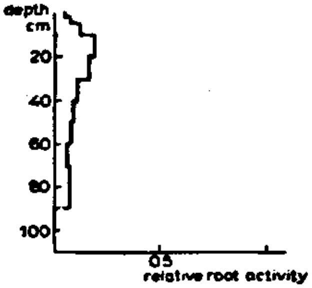


Fig. 3.29
Activity profile of the root system.

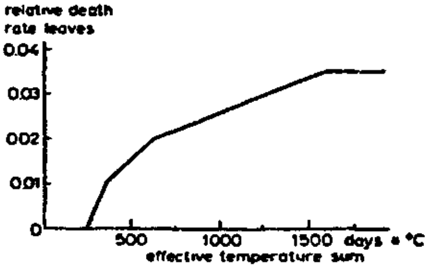


Fig. 3.30
Relative death rate of the leaves as a function of accumulated temperature.

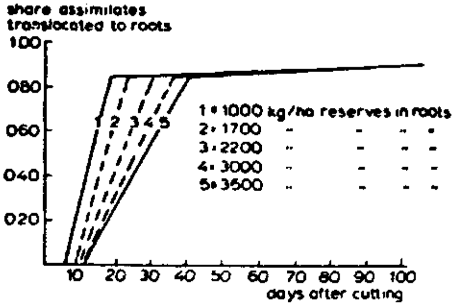


Fig. 3.31
Proportion of assimilates translocated to the roots as a function of reserve level and age of the regrowth.

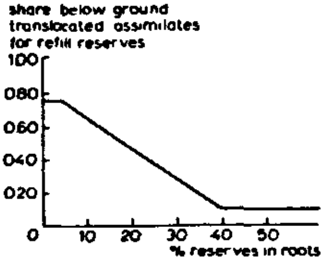


Fig. 3.32
Proportion of assimilates translocated to the root system for refill of reserves, as a function of reserve level in the roots

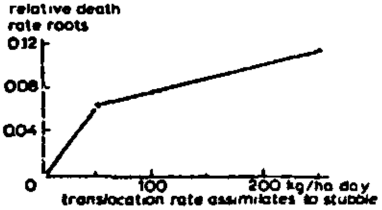


Fig. 3.33
Relative death rate of the roots as a function of the rate of upward translocation of assimilates.

The development pattern of the canopy, characterized by the rate and order of appearance of vegetative and generative organs, is only treated superficially. The development stage is calculated by dividing the accumulated temperature by a total temperature sum necessary for complete maturity. The development stage influences the potential transpiration rate (being reduced from 1 to 0 between development stage 0.75 and 1) and the partitioning of newly formed material to the roots (less at a higher development stage). It is assumed that during growth, plant material is continuously dying at a relative rate of 0.005 to 0.1/d, depending on maturity stage or the occurrence of severe water stress.

As ARID CROP was developed for an annual vegetation, it contains a germination section. Germination proceeds when the moisture content in the upper 10 cm of the soil is above wilting point and is completed when these conditions continue until a temperature sum of 150 degree-days above zero has accumulated. Growth then starts with an initial biomass that has to be provided as input. The model is executed with time steps of one day, employing the simple rectilinear integration method.

Compared to BACROS (Section 5.4.2), ARID CROP employs less detailed descriptions for the determination of crop photosynthesis, respiration and transpiration. It also uses a simpler, more descriptive formulation for the calculation of the root/shoot ratio. The necessary plant variables for BACROS of category 1 (must always be provided) and category 2 (necessary for simulations of specific experiments), listed in Table 5.1, are also relevant to ARID CROP. Additionally, this model requires precipitation and soil characteristics such as field capacity, wilting point, run-off fraction (all category 1) and soil evaporation characteristics (category 2). An additional plant variable for ARID CROP is the recovery rate after water stress (category 3: supplementary variables for accurate simulation).

Adaptation of the preliminary alfalfa growth model of Van Keulen & Zipori (unpublished results) was carried out in two stages. In the first stage undisturbed growth was first calibrated using one data set of measurements. Thereafter other available data sets were used for validation. During the second stage the undisturbed growth model was adapted to impose a cutting regime and first calibrated against the measured growth curves of alfalfa that had been cut every 53 days. Subsequently also data sets of other regimes with cutting intervals varying from 21 to 53 days were used for validation as well as further calibration.

In the next Section, the most important modifications of the ARID CROP model for simulation of alfalfa growth under different cutting regimes are described.

3.5.3.2 Adaptations of ARID CROP to an alfalfa cutting management model

a. Initialisation

ARID CROP was developed for an annual vegetation, starting from germination. As alfalfa growth was simulated from an established stand, the germination process was omitted and it was assumed that at the onset of the simulation 75 kg/ha above-ground material was present in the field, consisting of 70 kg of stems and 5 kg of leaf material. These values hold for a sward that has been subjected to a cutting regime of 53 days for a prolonged period. From the leaf weight the initial leaf area was calculated, applying an SLA, defined as a function of the cutting date (Fig. 3.27).

The roots were initialized at a total dry weight of 7500 kg/ha, consisting of 5400 kg structural root material and 2100 kg (28%) of reserves. These values, deduced from field observations of commercial alfalfa fields (cut about every 35 days) in San Camilo, include crowns and lignified stubble (basal parts of old stems below cutting height).

It was assumed that the roots extend over a depth of 90 cm in a sub-soiled soil profile that is maintained at field capacity during the growing period. Appropriate parameters defining the water-holding capacity of the soil have been introduced.

b. Re-initialisation after cutting

After each cutting the total dry matter of the remaining green biomass (buds, leaves and young shoots) was reset at 75 kg/ha. In the field it was observed that the amount of leaves escaping the cutting bar could be about ten times greater at shorter cutting intervals than at longer ones, especially during colder periods. Although the reason for this phenomenon is not clear, it has important consequences. Therefore, it was introduced into the model by a function, relating the residual leaf weight to the accumulated effective temperature sum (sum of average daily temperatures above a threshold value of 5 °C) over the preceding growing period (Fig. 3.28). In this way, the effects of both, cutting interval and temperature were incorporated, resulting in leaf weights of 30 to 35, 15 to 30 and 5 to 15 kg/ha for intervals of 21, 28 and 35 days respectively. The higher values of these ranges belonged to the cooler periods of the year (lower temperature sum). After longer cutting intervals leaf weight was always 5 kg/ha. From the leaf weight, the leaf area was, calculated as described in the previous paragraph.

c. The dynamic part

In this section of the model the equations that were executed repetitively at each time interval of one day are defined. The most important adaptations are also discussed.

c-1 Root water uptake

Contrary to the definition in the original model, where roots were either present or absent, but otherwise equally active irrespective of their position in the profile, in this version a root distribution function was introduced based on field observations (Fig. 3.29). The formulation applied postulates that a fraction of the total potential transpiration of the canopy, defined by the relative root activity must be supplied by the roots in a particular soil compartment. When the water content in a compartment falls below the minimum value for unrestricted uptake (Van Keulen, 1975; Fig. 46), the rate of moisture withdrawal from that compartment is reduced, and hence total actual transpiration and consequently the photosynthesis of the crop. It could be argued that in such a situation compensatory uptake from other compartments would take place. That phenomenon was not further pursued because the soil profile was assumed to be kept continuously at field capacity. The model is, however, in principle also applicable for simulation of alfalfa growth under limited water availability.

c-2 Potential transpiration

The calculation of potential crop transpiration was essentially identical to that applied in the original version of the model. The standard value for minimum stomatal resistance used by Van Keulen & Zipori (op. cit.), i.e. $5 * 10^{-6}$ d/cm (= 0.43 s/cm) was maintained.

c-3 Assimilation

The potential rate of gross CO_2-assimilation was calculated as in the original model, i.e. the algorithm of Goudriaan & Van Laar (1978) was applied.

The light-saturated value of gross CO_2-assimilation for individual leaves was set at 40 kg CO_2/ha (leaf).hr and the initial light use efficiency at 0.5 kg CO_2/ha.hr per J/m^2.s, identical to the value used for other C_3 species like wheat and the natural vegetation in the Israeli situation.

The extinction coefficient for the calculation of light interception by the leaves, was changed from 0.8 to 0.9, on the basis of the measured light interception in San Camilo (Section 3.3.1.2, Fig. 3.10).

The decrease in photosynthetic capacity of the leaves by 10% per day after an effective temperature sum of 450 °Cd had been accumulated, was eliminated, because no experimental evidence for such a phenomenon was found.

The actual rate of gross CO_2 assimilation is calculated from the potential rate by multiplying it by the ratio of actual and potential transpiration rate. The requirements for maintenance respiration, were based on values of 0.02 and 0.0115 g CH_2O/g dry matter per day for shoot and root structural material respectively. The balance of gross assimilation and maintenance respiration provided the assimilates for growth and storage.

c-4 Partitioning of assimilates

In the model, four sinks for carbohydrates are distinguished: leaf blades, stems, structural root material and root reserves. Partitioning of the available assimilates among the various sinks is of prime importance for the simulated growth pattern.

The root growth observations both in field and pot experiments in San Camilo showed that a large proportion of the assimilates was transported to the root system. However, a substantial part was not converted into structural material, which suggests that the root system functions partly as a storage pool for reserves. The observations further suggest that this process started rather early after regrowth, which is in accordance with the results of $^{14}CO_2$ studies in the greenhouse, reported by Hodgkinson (1969). On this basis, the description in the model is such that already shortly after cutting a large part of the assimilates is translocated to the root system, partly for storage as reserves and partly for formation of structural root tissue. Moreover, if the quantity of reserves stored in the roots is small, translocation to the roots is promoted. This description is shown in Fig. 3.31, where the proportion of assimilates translocated to the root system is shown as a function of time after cutting and the total amount of stored reserves. The translocation functions shown belong to five different levels of stored reserves; values between these levels are obtained by interpolation.

The distribution of assimilates translocated to the root system between reserves for storage and formation of structural root material was related to the existing reserve level in the roots (Fig. 3.32). From the allocated assimilates for root structural material, root growth was calculated, taking into account the efficiency of conversion of primary photosynthates into structural material (growth respiration).

The distribution of assimilates allocated to the roots between leaves and stem material was defined as a function of the phenological development of the crop, characterized by the accumulated temperature sum. It was assumed that leaves started to die slowly after a temperature sum of 240 °Cd was reached, increasing up to a maximum relative death rate of 3.5% per day at a temperature sum of 1600 °Cd (Fig. 3.30). This relation was deduced from the measured LAI patterns.

At longer cutting intervals, large quantities of structural root material are produced, requiring large amounts of assimilates for maintenance, whereas assimilate availability is reduced due to dying of leaves. As a result, above-ground growth ceases and in the period between 120 and 150 days a negative carbon balance results. Under such conditions, in the model roots start dying and reserves stored in these roots are made available to support maintenance.

Lack of reliable quantitative data is the reason that the descriptions used for partioning of assimilates were obtained to a large extent by calibration and are therefore highly speculative. They must thus be considered as an hypothesis, that produces reasonable descriptions of growth, both below and above-ground, whereas the simulated reserve percentages also generally remained within the range of observed values.

c-5 Mobilization of reserves after cutting

It is widely accepted that translocation of carbohydrates from the root system is essential for regrowth after cutting. The results of our experiments about regrowth in the dark, are also in agreement with that hypothesis (Section 3.3.4.4 and Table 3.7). Direct evidence for such a mechanism was reported by Hodgkinson (1969), who showed with $^{14}CO_2$ that this remobilization is important for shoot growth, especially during the first ten days after cutting. In addition, our data and those of Harrison (1939), Hildebrand & Harrison (1939), Hodgkinson (1969) and Chatterton et al. (1974) indicate clear responses in root dry matter during this period. In the model both phenomena are therefore taken into account.

In the model, all reserves stored in the root system above a minimum concentration of 0.1 kg/kg are available for translocation to support regrowth of leaves and stems. However, the rate of reserve utilization is proportional to the above-ground biomass present, up to a value of 650 kg/ha. This formulation expresses the assumption that directly after cutting sink size limits the rate of translocation. Omission of such limitation leads to unrealistically fast regrowth of the vegetation.

Remobilization of root reserves and upward transport is assumed to cease as soon as the downward flow of assimilates starts (Fig. 3.31), which is sooner after regrowth if a small amount of root reserves is present. In such a case (as with frequently cut alfalfa) both a smaller quantity of root reserves is available and the period of supply is shorter.

Translocation of reserves to the above-ground plant parts is accompanied by decay of structural root material. The relative death rate of the roots is a function of the rate of upward flow of assimilates (Fig. 3.33), to a maximum value of 150 kg/ha.d. This decrease in structural root material modifies the fluctuations in root reserve concentration, increases

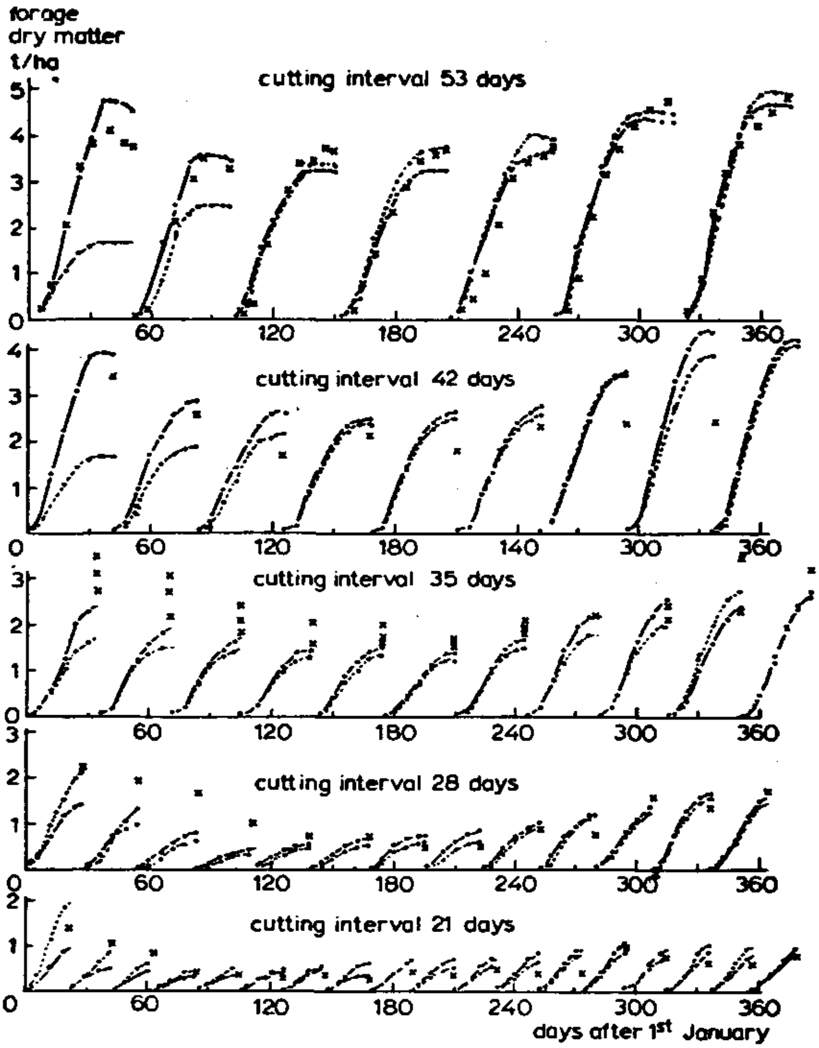


Fig.3.34 Simulated and measured dry forage weight in relation to cutting interval. × : measured; .... : first year, ——— : second year simulation.

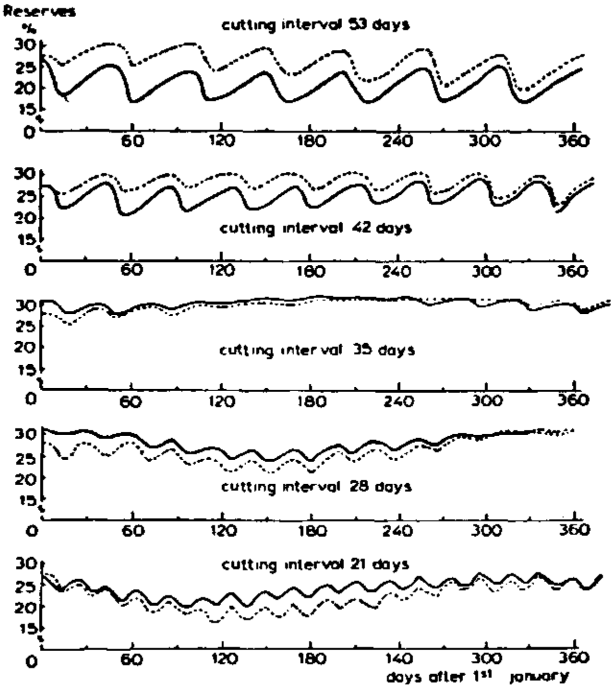


Fig. 3.37 Simulated reserves as percentage of total below-ground dry matter, in relation to cutting interval. •------•:first year simulation;•———•:second year.

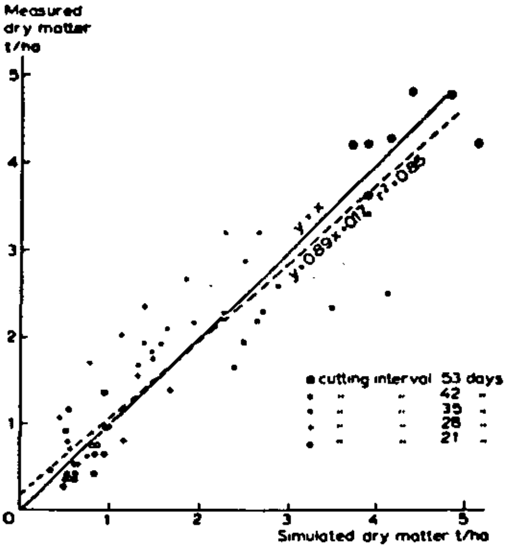


Fig. 3.35 Relationship between simulated and measured alfalfa forage yields.

the amount of assimilates available for remobilization and relieves the maintenance requirements.

3.5.3.3 Model performance, results and discussion

In Fig. 3.34 the time course of simulated forage production for different cutting regimes is presented for a continuous period of two years. Simulated values are those present at the cutting date, but do not include the leaves that died during the growing period. Measured values of final yields and in some cases of intermediate harvests are also indicated.

For most periods during the year the differences between first and second year simulations were small. Clear exceptions were the simulations of the first two periods, especially for the longer cutting intervals, caused by the fact that for all cutting regimes the model was initialized in an identical way. For the longer cutting intervals those conditions were different from the "equilibrium" values that were attained after a prolonged period with a constant cutting regime. In the field it was also observed that the first yields after a decrease in cutting frequency, were lower than subsequent ones, but this effect was less pronounced than the model prediction.

The fit between measured and simulated results is reasonable. When the simulated final yields (average of first and second year simulations) of each cutting interval are plotted versus the corresponding measured yields (with the exception of the two first simulations mentioned above), the resulting regression equation is: $Y = 0.89\ X + 0.17$ (X = simulated, Y = measured yield), with a coefficient of determination (r^2) of 0.85 and a slope and intercept not very different from the values 1.0 and 0.0 pertaining to an ideal prediction (Fig. 3.35).

It is remarkable that for the 42 day cutting interval the model consistently overestimated yield prediction and for the 35 day interval consistently underestimated it. The measured data from the cutting frequency experiment (21, 28, 42 and lowest values of 35 days) were obtained from a rather old stand, which may have caused a negative influence on its yield potential. The underestimation of forage yield for the 35 and for the 28 day cutting interval during the summer months, could probably have been improved by assuming more stubble leaf present after cutting at these intervals. Such adaptations are, however, highly speculative without experimental evidence from the field situation.

The simulated values of root biomass (Fig. 3.36) show a very wide range, from about 3.5 t/ha to 21 t/ha for the cutting intervals of 21 and 53 days, respectively. The few available field measurements showed a similar range. The simulated patterns between successive cutting dates are comparable to those measured in a pot experiment in San Camilo (Fig. 3.22). In the field these fluctuations between cutting dates are difficult to establish experimentally. However, the combined effects of a substantial translocation of assimilates to the root system, soon after the start of regrowth, and of root decay during translocation of reserves to the shoot, resulted in simulated ranges in root weight that were often close to the field measurements for the different cutting treatments. Similar strong influences of cutting interval on root development were also found in pot experiments reported by Hildebrand & Harrison (1939) and by Langer & Steinke (1965).

The simulated reserve levels (Fig. 3.37) are within the range reported in the literature (e.g. Smith, 1962; Cohen et al., 1972; Pulli, 1980). Compared with the results measured in San Camilo (Fig. 3.20), the simulated level for the 53 day interval is somewhat too low and that for the 35 day

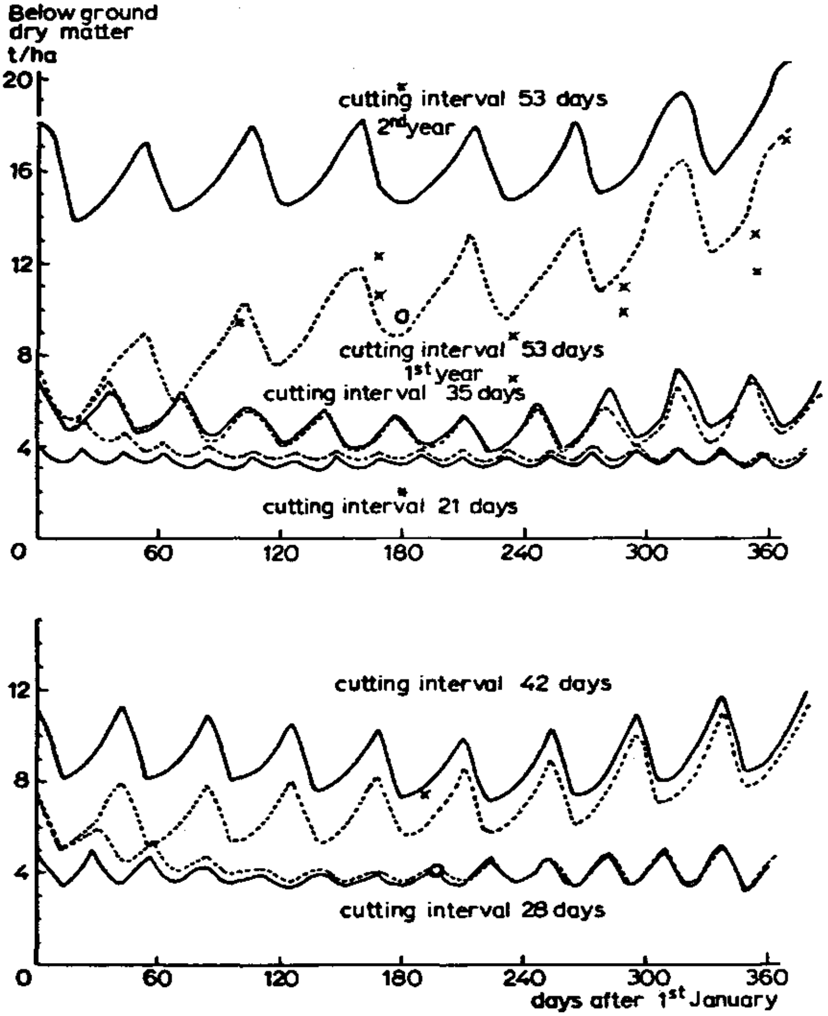


Fig. 3.36 Simulated and measured root dry matter in relation to cutting interval. ••••••••: first year, ———: second year simulation.
× : measured with cutting intervals of 53 and 42 days.
○ : measured with cutting intervals of 35 and 28 days.
✱ : measured with cutting interval of 21 days.

interval somewhat too high. The fluctuations between successive cutting dates could not be established in our field measurements, but others (e.g. Smith, 1962; Feltner & Massingale, 1965; Cohen et al., 1972) reported patterns similar to the ones simulated.

The model predictions are to a large extent the consequence of both root dynamics and reserve dynamics. The formulations in the model are to a large extent descriptive, as the physiological principles underlying these processes are not understood and quantitative data are scarce. Because of this descriptive character and the fact that the experimental data were also used for calibration of the model, the comparison between measured and simulated results should be judged cautiously. During calibration it was often noticed that changes in the functions and parameters applied in the model significantly influenced the simulated results. For example the value of above-ground dry matter, below which the sink size limits translocation of reserves after cutting (in the model 650 kg/ha), strongly influenced the initial regrowth and the subsequent growth. This also holds for the functions describing transport of assimilates to the root system (Fig. 3.31), which were mainly the result of intelligent guesswork. Furthermore, the rate of decay of roots after cutting and the distribution of assimilates in the root system between storage and increase in structural root weight, were obtained by trial and error. These calibrations were carried out mainly with the two extreme cutting intervals (21 and 53 days). Hence, the predicted growth patterns are influenced significantly by a small number of functions that were established by calibration. This remains a major weakness of many models. Also in the alfalfa models described by Holt et al. (1975) and Fick (1981) such calibrations were used. In our case some check against unrealistic calibrations was obtained by the availability of five data sets for different cutting frequencies. Despite this weakness, the model in its present state was able to integrate most of the relevant data obtained in San Camilo and many data from the literature and predicted realistically the widely differing results of the various cutting frequencies. The hypotheses incorporated in the model accounted for observed phenomena such as "levelling off", the large quantities of roots measured and the fluctuations in reserve levels.

The importance of stubble leaf area after harvest, when short cutting intervals are practised, indicated by the model, was remarkable. It would suggest, that the larger amount of stubble leaf area that escaped the cutting bar in the higher frequency cutting regimes in San Camilo, was essential for survival of the stand. A strong positive influence from a leafy stubble on regrowth was also observed in pot experiments by Hildebrand & Harrison (1939) and Langer & Steinke (1965). In the field, the response was usually less strong (Smith & Nelson, 1967; Robison & Massengale, 1968) or even insignificant (Leach, 1970). The latter author suggests that genotypic differences may also cause variable responses. Hodgkinson et al. (1972) reported a very rapid recovery of the photosynthetic capacity of older stubble leaves soon after cutting. No reports were found on the LAI remaining in the field directly after cutting. The relation introduced in the model is a schematization of only a few measurements during the summer period and some observations during colder periods. More attention to this aspect during different growing seasons is necessary and may give a more realistic model description. Ultimately this may lead to a more optimal cutting management during different seasons.

For a comparison with other alfalfa modelling studies that of Fick (1981) seems to be most relevant, as other reported studies only deal with separate single growing cycles, where each time new (often measured) initialisations of stem, leaf and root weights (Holt et al., 1975) take place or where a leaf area forcing function is used (Gosse et al., 1982; 1983). Fick's level 2 ALSIM model (Fick, 1981) can also be used with variable cutting frequencies. It simulates the growth of the above-ground parts, the total amount of stored reserves and the quantity of basal buds; the latter is an important state variable in its description of regrowth. The model predicted above-ground dry matter production of locally grown alfalfa with reasonable accuracy, but at extreme cutting frequencies the simulations seemed less realistic than the present model. Also the prediction of reserve level was less satisfactory and no calculation of root dry matter was included.

As a conclusion of the modelling activities on the basis of the present project, it may be stated that several hypotheses could be quantified in such a way, that reasonable agreement was obtained over a range of measured results. These hypotheses may also be useful for the explanation of similar phenomena observed elsewhere. However, as in so many other modelling efforts, it must be concluded that for a complete description of the production process, several functional relationships had to be estimated on the basis of incomplete information. The indication of these knowledge gaps is the major result of the exercise and could be used for setting priorities in future alfalfa research.

It was shown in this study that the ARID CROP model could be adapted rather easily to an alfalfa cutting management model for conditions prevailing in Southern Peru. This seems to confirm the conclusion of Van Keulen (1982), that ARID CROP in its general outline is applicable to different ecological conditions, provided that water is the major production-determining factor. Similar flexibility was also shown in the adaptation for Sahelian conditions (Penning de Vries & Djitèye, 1982). For agricultural research objectives the model appears to offer a workable compromise, giving enough information for the detection of major constraints in crop production, but without the very detailed sophistication of the BACROS and PHOTON models, which proved to be difficult and expensive for specific application.

4 *GROWTH DYNAMICS OF THE POTATO*

4.1 INTRODUCTION

The potato is the fifth largest crop in the world in terms of energy production (Van der Zaag, 1983) and in Peru it is the third after rice and maize (FAO, 1983). The major area of the primary centre of origin of this crop is also located in Peru.

In the region around Arequipa, potato is often the first crop grown after alfalfa. In this way the potato crop uses the residual N from the alfalfa and also provides the farmer with enough income to rid the field of established noxious weeds.

Despite the importance of the crop, potato yields in Peru are generally very low. Under irrigated conditions the average tuber yield of 10.9 t/ha (on a fresh weight basis) in the region of Arequipa (Anon., 1980a) is about 20% higher than the national average under the same conditions (Anon., 1976). However, this level is still only one third of the commercial yields in Northern Europe and the USA and only one eighth of experimental yields obtained in these regions (Sale, 1973b; Van der Zaag & Burton, 1978).

Because of these large yield differences, and the local importance of the crop, it was considered worthwile to investigate the regional yield potential and its major influencing factors. The characteristics of a rather productive Peruvian cultivar "Revolución" of the sub-species *andigena*, were therefore compared with those of the Dutch cultivar Désirée of the sub-species *tuberosum* (Hawkes, 1956), which has shown high yields in several places, such as the Middle East, Chile and also Peru (Wiersema & Booth, 1981).

4.2 METHODS

4.2.1 *Preparation of seed tubers*

Seed tubers of the potato cultivars, Revolución and Désirée were pre-sprouted in a roofed structure with walls of mosquito-netting, to make sprouting in diffuse light possible. Average tuber weight was about 70 g for Désirée and 45 g for Revolución. A trickle irrigation line on top of the corrugated zinc roof dripped water continuously to cool the roof and to wet the netting. "Revolución" was brought from Cusco (above 3000 m a.s.l.) and kept in the pre-sprouting house for two and a half months. For Désirée this period was only three weeks, as the cultivar had already sprouted on arrival due to delays at the border of Peru. Before putting this cultivar into the pre-sprouting house, the largest etiolated sprouts (> 1 cm) were removed. Both cultivars were planted in the field on 3rd October 1981.

4.2.2 *Field preparation and experimental design*

The sandy soil had been sub-soiled and cropped with maize. The field was subsequently disc-ploughed and harrowed and low ridges of about 15 to 20 cm height were made in N-S direction. Twenty three days after planting, the ridges were raised to a height of 30 cm.

Phosphorus (90 kg/ha P as triple superphosphate) was incorporated during ploughing; N (as urea) and K (as potassium sulphate) were applied by injection through the sprinkler irrigation system during the growing season. In this way, weekly applications of 10.5 kg K/ha were given over a period of 22 weeks, totalling 231 kg K/ha. The weekly applications of N varied: during

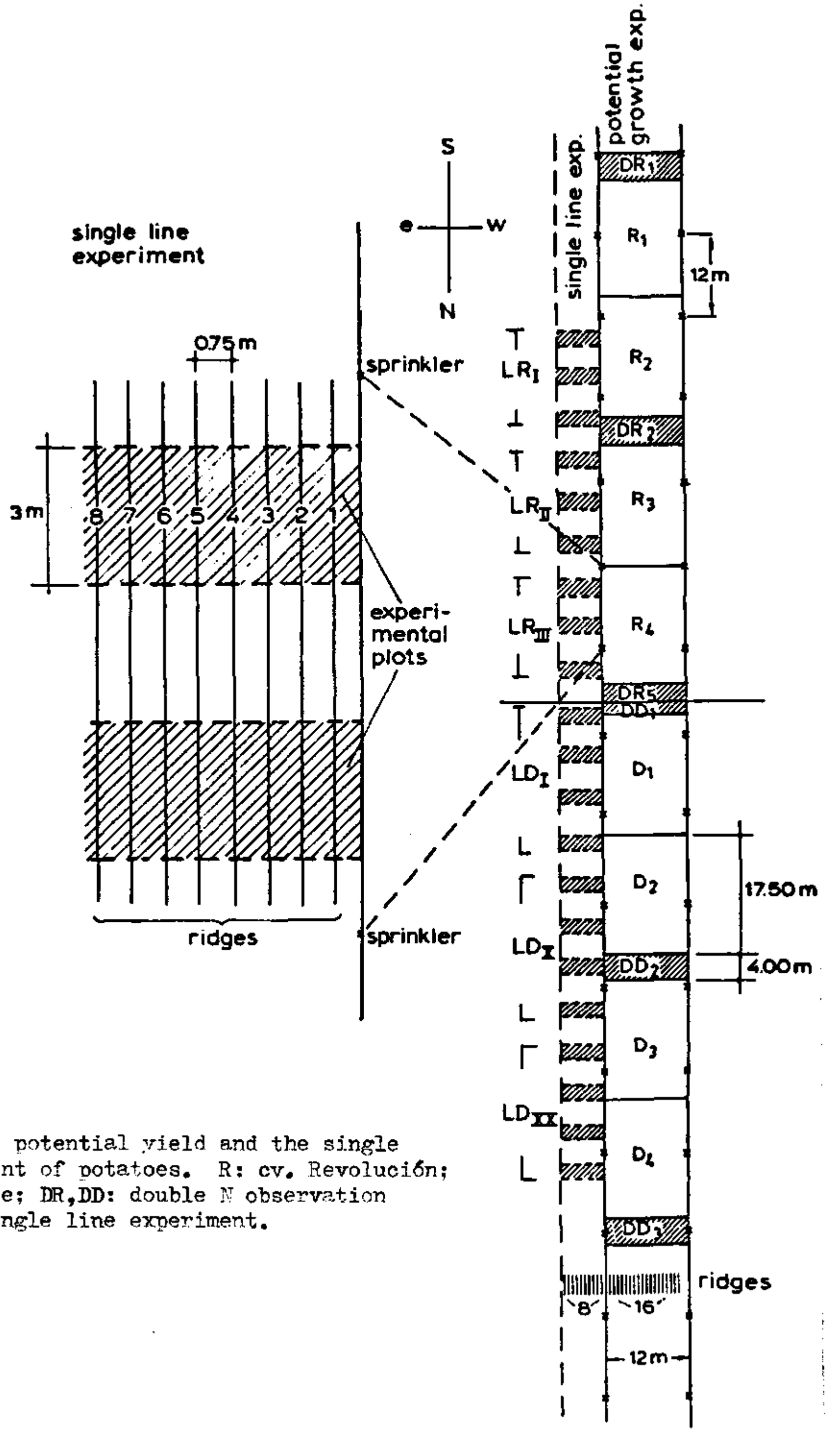


Fig. 4.1

Set-up of the potential yield and the single line experiment of potatoes. R: cv. Revolución; D: cv. Désirée; DR,DD: double N observation strips; L: single line experiment.

the first three and the final ten weeks 12.5 kg N/ha.wk was injected, while from week 4 till 12 the rate was doubled, thus totalling 388 kg N/ha.

The experimental area was sprinkler-irrigated with two parallel irrigation lines in the same direction as the potato ridges at a distance of 12 m. The distance between sprinklers on each line was 12 m. The area between the lines was used to determine the growth potential of the two cultivars under conditions of optimal water and nutrients and optimal phytosanitary management (potential growth experiment). Alongside the eastern irrigation line, a strip of 6 m was used to investigate the response to different amounts of irrigation water (single line experiment). The field design is shown in Fig. 4.1.

4.2.3 *The potential growth experiment*

Both cultivars were grown separately; the northern half of the experimental field was planted to cv. Revolución and the southern part to cv. Désirée. The distance between rows was 0.75 m, between plants in the row 0.25 m (53 300 pl/ha). Each half was sub-divided into 4 blocks of 17.50 m x 12.0 m. In each block eight and nine periodic harvests were carried out for Désirée and Revolución, respectively. Harvests took place were (from planting) on days 42 and 63 and subsequently with intervals of two weeks until the end of the experiment on day 147 and 161 for Désirée and Revolución, respectively.

At the northern and southern border of each cultivar, as well as between blocks 2 and 3, strips of 4 m x 12 m received an additional weekly fertilization of 12.5 kg (urea-) N, to test whether the plants within the blocks had received enough N (see Fig. 4.1, strips DD and DR). In these plots, a control harvest was made on day 135.

From planting until full emergence of both cultivars (on day 21), a daily sprinkling of 10 mm water was given, with the exception of the first day, on which the irrigation was 20 mm. After day 21, the field was irrigated twice a week, for three successive weeks, according to $k_{pan} = 1.0$. During the remainder of the experiment, the field was irrigated every other day according to $k_{pan} = 1.2$.

4.2.4 *The single line experiment*

Alongside the eastern irrigation line, eight ridges were planted with the same cultivar as in the neighbouring potential growth experiment. Because of shortage of seed tubers, the distance between the plants was 0.33 m. Given the gradually diminishing amount of irrigation water with inreasing distance east from the line (because of water coming from only one side), the water distribution pattern was first determined by means of 56 regularly distributed rain gauges. Experimental main plots of 3 m x 6 m were then laid out perpendicularly to the irrigation line, so that at the centre of each ridge the distance to the closest sprinkler was one third of that of the second nearest (Fig. 4.1).

Because of the limited amount of seed tubers, the planted area could only contain nine main plots of Revolución and twelve of Désirée. These main plots were grouped into three blocks, each containing three or four plots of Revolución or Désirée, respectively. Within the blocks, each main plot was used for one periodic harvest, on days 78, 121, 134 for Revolución and on the same days plus an additional harvest on day 97 for Désirée.

The decreasing amount of irrigation water at increasing distance from the irrigation line also resulted in lower amounts of N and K fertilizer applied. For N, a correction was made by applying additional urea to each

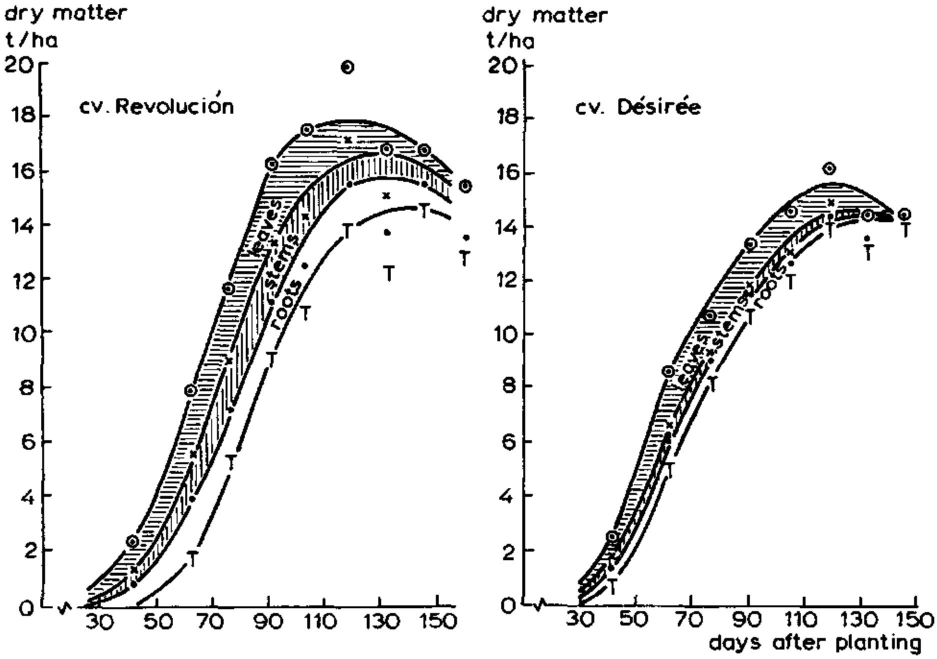


Fig.4.2 Cumulative dry weight of tubers (T), roots (•), stems (×) and leaves (= total crop: ⊙), for two potato cultivars grown in San Camilo.

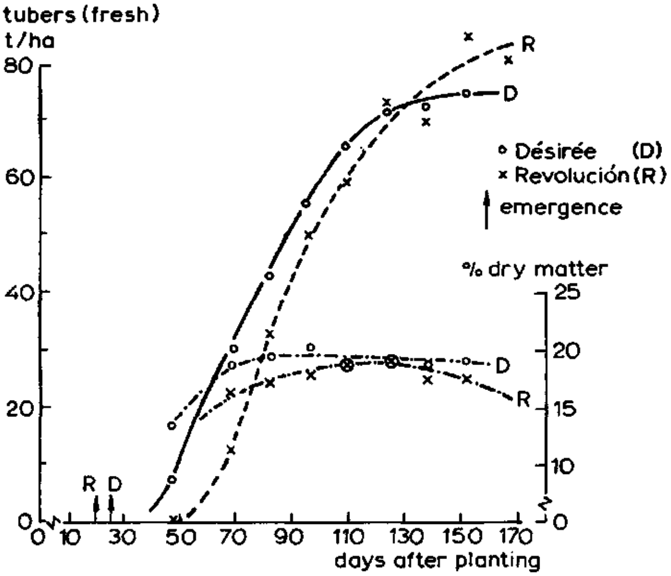


Fig. 4.3 Fresh weight (———) and percentage dry matter (—•—•—) of the tubers, of two potato cultivars grown in San Camilo.

ridge by hand, in proportion to the irrigation deficit. However, this fertilization correction was stopped after ten weeks, when serious leaf burning was observed, particularly in the drier ridges of cv. Désirée.

4.2.5 *General provisions and additional measurements*

At planting, the tubers were protected against insect damage by applying malathion 2.5% to the planting holes. Weekly sprayings of insecticides (Ambush) and fungicides (first three weeks with maneb/zineb, and subsequently with a maneb/fentin-acetate mixture) were applied from day 29 till the end of the growth period.

LAI was determined in the potential growth experiment, on the basis of one representative plant per harvest per plot. For further details, see Section 2.4.

Light interception was measured periodically for the first eighty days using a bar mounted with a number of photocells, as described in Section 2.4. Three readings were taken per replicate:
a. at the base of the plants, the bar parallel to the ridges;
b. perpendicularly to the ridges, the middle of the bar between two plants;
c. as b, but the bar at the base of one plant.

The light interception values calculated from readings b and c were too low when crop cover between the rows was still incomplete, because the bar was 25 cm longer than the distance between plant rows and hence the open space was overrepresented. Therefore, the relative quantity of intercepted light (i) from readings b and c was corrected:
for values of $i \geqslant 0.50$: according to $i' = 1.333\ i$
for values of $i < 0.50$: according to $i' = 0.667\ i + 0.3333$

After correcting the b and c values, the final percentage of light interception by the crop was calculated according to: $p = 50\ a\ (b + c)$. Because of problems with the instrument, the measurements could only be carried out up to 81 days after planting.

At each sampling, plants were separated into leaves, stems, tubers and roots (including stolons) and fresh weight was determined. Sub-samples were dried at 65 °C in forced air ovens to determine dry weight and subsequently analysed for N, P and K according to the methods described in Section 2.4.

In addition newly expanded leaves were sampled periodically, from which petioles were separated, dried and analysed for NO_3-N concentration, according to the xylonol method, described by Horwitz et al. (1975).

4.3 RESULTS

4.3.1 *Growth and development*

Both cultivars reached maximum total dry matter weight on day 119 after planting (Fig. 4.2). At that sampling date 19.9 t/ha was recorded for cv. Revolución, of which 70% was present in the tubers (13.9 t/ha) and 22% in the foliage (4.4 t/ha). After that date, tuber dry matter yield stabilized around 14 t/ha, whereas foliage decreased to about 1.7 t/ha or approximately 10% of the maximum total dry matter produced. Désirée reached a maximum dry weight of 16.1 t/ha, also on day 119, but by then 86% (13.8 t/ha) had already been invested in the tubers and only 1.9 t/ha foliage (12% of total dry matter) was present. After that date tuber yield no longer increased but foliage weight decreased to less than 1.5% of the total dry matter. Thus, although the two cultivars differed greatly in total dry matter production, their tuber dry weight was virtually identical.

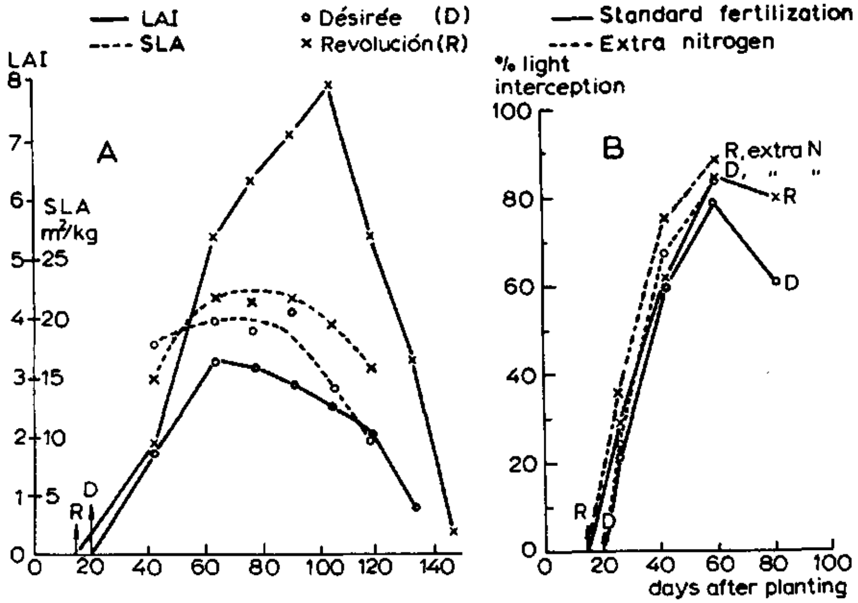


Fig. 4.4 Leaf area index (LAI) and specific leaf area (SLA) (Fig. A) and percentage of light interception (Fig. B) as a function of time after planting, for two potato cultivars grown in San Camilo.
↑ : emergence.

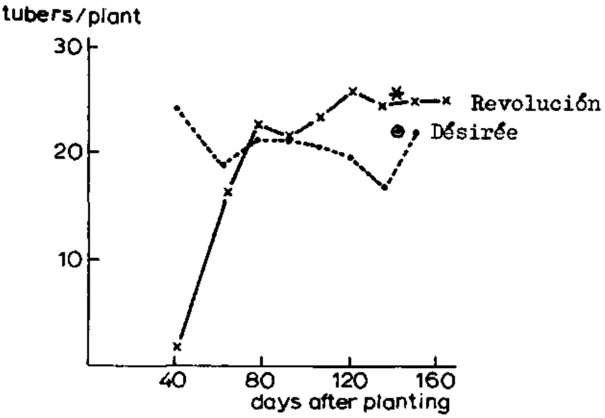


Fig. 4.5 Average number of tubers per plant (including tuber initiations) in the potential growth experiment, at a density of 53 300 plants/ha
⁎ , ⊙ : Double N observation plots.

Between days 42 and 91, Revolución reached an average total growth rate of about 280 and Désirée of about 220 kg/ha.d. From day 68 onwards, both cultivars invested practically all the dry matter produced in tubers only. Tuber initiation was earlier in Désirée, and on day 42 about 1 t/ha tuber dry matter was produced, whereas Revolución had just started initiation and did not have a measurable tuber weight.

Final fresh tuber yield of Revolución was between 80 and 84 t/ha, about 10% more than that obtained from Désirée. This was mainly caused by a lower dry matter percentage of the tubers of the Peruvian cultivar (Fig. 4.3). According to local marketing standards based on size and healthy appearance, Revolución produced about 3.5% non saleable (mainly too small) potatoes; for Désirée this percentage was less than 0.5%.

Maximum bulking rates attained were about 1000 and 1250 kg/ha.d for Désirée and Revolución, respectively over a period of approximately fifty days. In total, the major bulking period was about eighty days for Désirée, starting on day 40 and about ninety for Revolución from day 60 onwards.

Fig. 4.4 shows the number of tubers per plant as a function of time (average of 48 plants). At the first sampling, on day 42, Désirée had all its tubers already initiated, i.e. in later samplings the number no longer increased. Generally, about twenty tubers per plant were counted. On day 42, Revolución had just started tuber initiation, and only by day 80 most of the tubers had been initiated. The tuber number continued to increase until day 120 stabilizing around a value of 25 tubers/plant.

LAI, SLA and light interception by the canopy are plotted in Fig. 4.5. Two months after planting, Désirée reached its maximum LAI of 3.3; subsequently leaf area decreased linearly reaching an LAI of 2.0 on day 119 before dying off rapidly. The leaf area of Revolución developed much faster and was maintained for a much longer period. Maximum LAI reached a value of 8.0 on day 105; subsequently, leaf area declined almost linearly, reaching a value of 0.4 on day 147.

In spite of the much higher leaf area developed by Revolución, its light interception did not show very much difference with Désirée until day 60, when both crops reached maximum light interception of 84% and 79% for Revolución and Désirée, respectively. The foliage of both crops then started to lodge and light interception decreased. The advantage of the larger leaf area of Revolución was more pronounced then and the difference in light interception between the cultivars increased. Light interception in the plots that received additional N was higher, especially during the early growth phase (Fig. 4.5). However, for both cultivars the maximum light interception at high N fertilization was only about 5% higher than that at the standard N rate of the experiment.

The two cultivars also differed significantly in crop height, which reached a maximum of about 75 cm in Revolución and less than half that height in Désirée. Revolución also flowered abundantly about two months after planting, while a little earlier only some sparse flowers were observed in Désirée.

The SLA did not differ much between the cultivars. It fluctuated between 14 and 20 m^2/kg for Désirée and between 15 and 22 m^2/kg for Revolución, the higher values being associated with maximum leaf area.

4.3.2 *N fertilization response and nutrient uptake*

In the course of the growing period, Revolución absorbed 240 kg N, 50 kg P and 520 kg K/ha (Fig. 4.6). Most of the nutrients were taken up during a period of the eighty days, starting 20 days after planting. After that, no

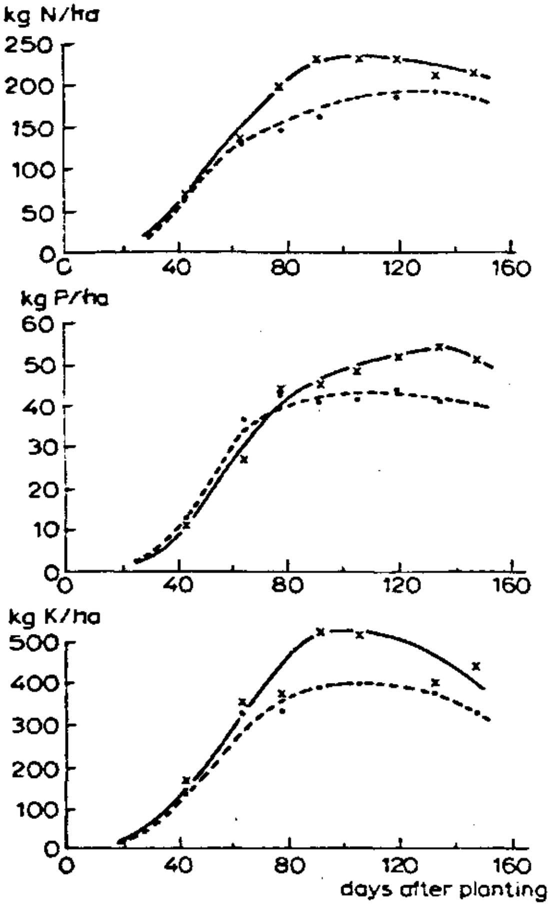


Fig. 4.6 Cumulative uptake of N, P and K by two potato cultivars growing in San Camilo. x——x : Revolución; •------• : Désirée.

further net uptake took place and, in the case of K and N, the crop was even losing these nutrients. The pattern of uptake by Désirée was practically identical but the level was approximately 20% lower. The N, P and K concentrations in the various plants parts of Revolución and Désirée were almost identical throughout the growing period (Fig. 4.7). The concentrations in roots and tubers were the most constant and very similar, with values of 1.0 to 1.3, 0.30 to 0.35 and 3.0 to 2.5% for N, P and K, respectively.

The N concentration in the foliage did not show great fluctuations, on average varying between 2.5 and 2%. Variation was more pronounced in the leaves (between 3.5 and 2.5%) than in the stems (between 1.0 and 0.8%). The concentration decreased with increasing crop age, but it was interesting to note that, about 130 days after planting, it increased again in the leaves. The same phenomenon, but much more pronounced, was observed in the P concentration of the leaves. After a gradual decrease from 0.35% 60 days after planting to 0.25% on day 105, a sudden increase occurred, up to 0.60% on day 147. In contrast, the P concentration in the stems decreased almost linearly from 0.4% at the first sampling to 0.1% at the end of the growing period. The P concentration of the total foliage reflected more strongly that of the leaves than that of the stems. Hence, the pattern was similar to that of the leaves: a decrease in concentration till day 105 from 0.35 to 0.25%, followed by an increase to 0.35% at final harvest. The course of the K concentration in the total foliage, stems and leaves was similar: a gradual decrease from the first sampling till the final harvest from 5 to 1.5, 7 to 3 and 6 to 3% for leaves, stems and total foliage, respectively.

The additional N fertilization applied in several strips in the experiment initially produced visibly more foliage in both cultivars. This difference disappeared by day 136 in Désirée, but remained in Revolución, expressing itself in about 70% extra foliage compared to the standard fertilization. Nevertheless, neither in Désirée, nor in Revolución any increase in tuber weight resulted. On day 136 the high N plots showed N concentrations in above-ground tissue, tubers and roots that were 25 to 50% higher than in the standard treatment (Fig. 4.7).

Fig. 4.8 shows the time course of NO_3-N concentration in the petioles of newly unfolded leaves both under standard as well as the additional N-fertilization. A steep decline was observed, going from 8500 (Revolución, standard N) or 15000 mg/kg NO_3-N (all other treatments) on day 20 to levels of 100-200 mg/kg (standard treatments) or 1000-2000 mg/kg (additional N treatments) on day 70. From then on values started to fluctuate somewhat (Revolución) or increased very slightly (Désirée).

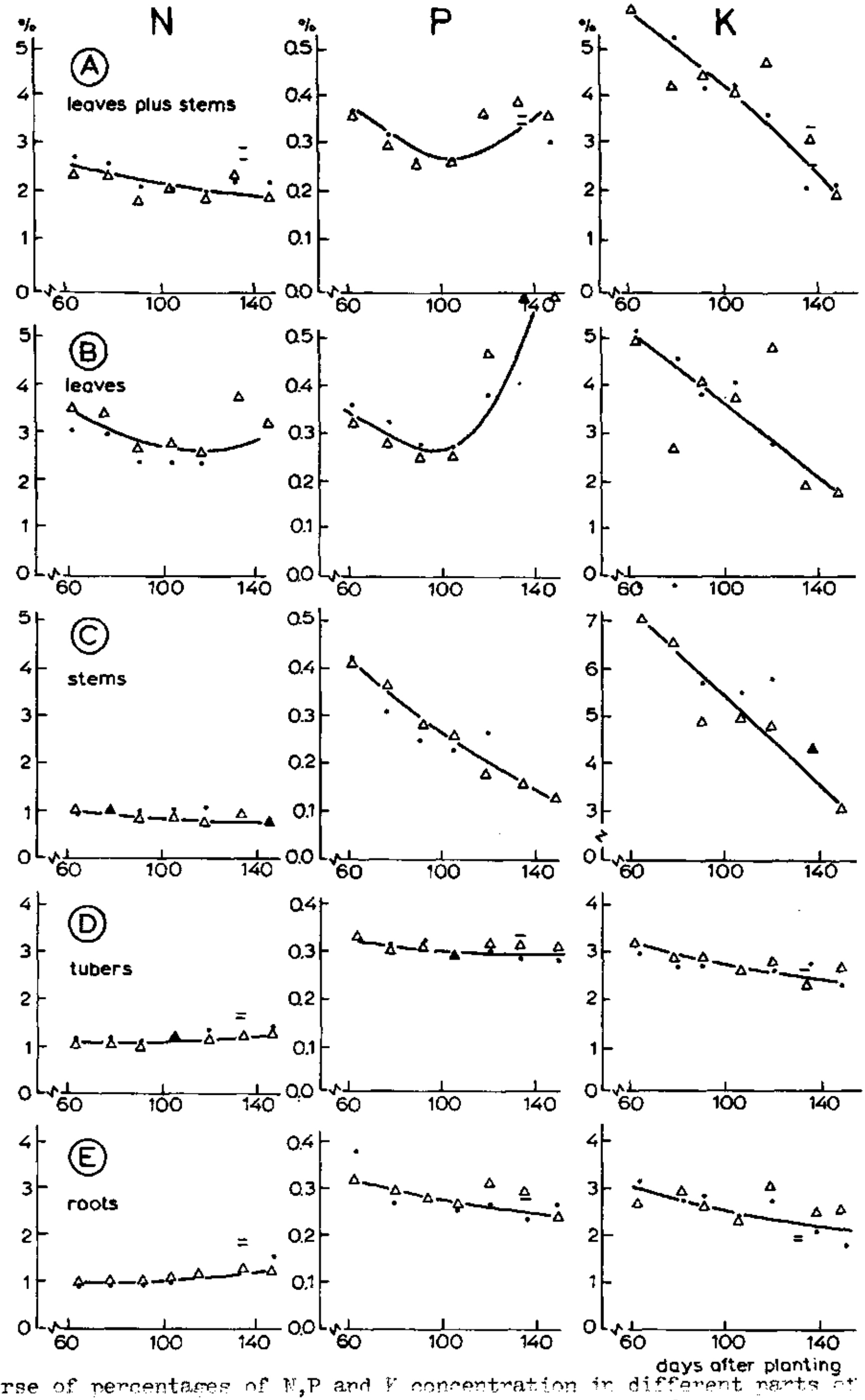


Fig.4.7

Time course of percentages of N,P and K concentration in different parts of potato crops growing in San Camilo. △ : Revolución; • :Désirée; – : concentration measured in double N plots.

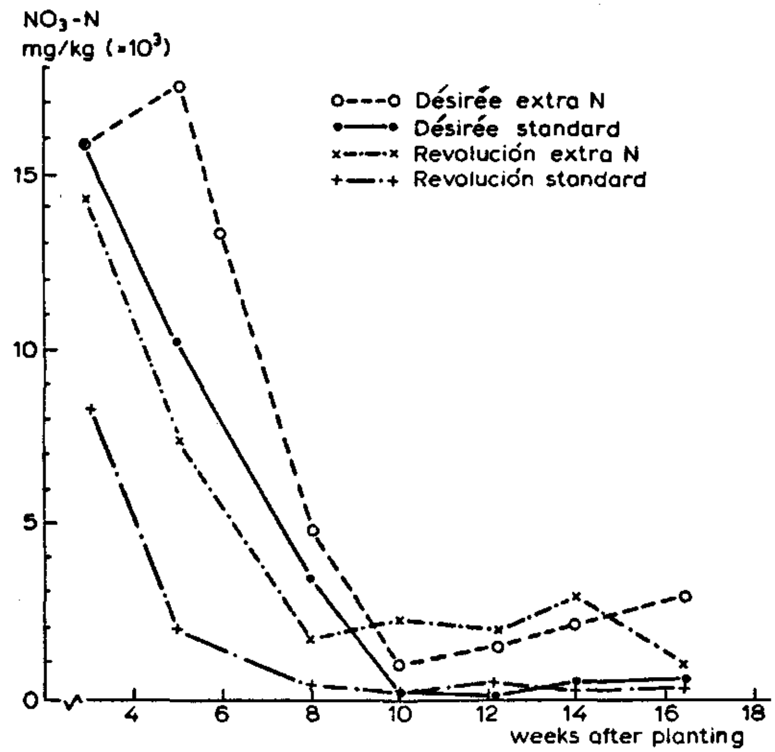


Fig. 4.8 NO_3-N concentration of the petioles in newly unfolded potato leaves in San Camilo.

4.3.3 *Single line experiment*

The rain-gauge measurements demonstrated that the distribution of irrigation water showed a regular pattern over the plots of the single-line experiment, i.e. the amount of water applied gradually decreased with distance from the irrigation line used for the supply of the neighbouring potential growth experiment (Fig. 4.1). Because of this, the amount of water irrigating the single-line experiment was related to the amount of water supplied to the potential growth experiment. Significant ($P < 0.001$) linear correlations (r between 0.84 and 0.93) were obtained between the amount of water supplied in the potential growth experiment and the quantity measured in the single line experiment.

Cumulative dry weight of total crop and of tubers for four pairs of adjacent ridges at increasing distance from the line source, is presented in Fig. 4.9; final dry matter weight, tuber yields (dry weight) and water supply for the four pairs, are summarized in Table 4.1.

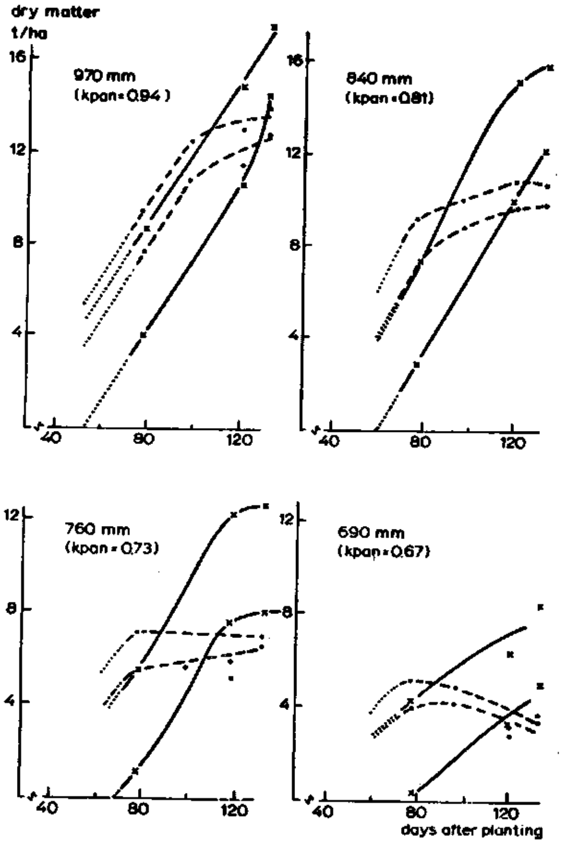


Fig.4.9

Cumulative total dry matter (———) and tuber dry matter (•-----) under different irrigation regimes, for potato crops growing in San Camilo. × : Révolución; • : Désirée.

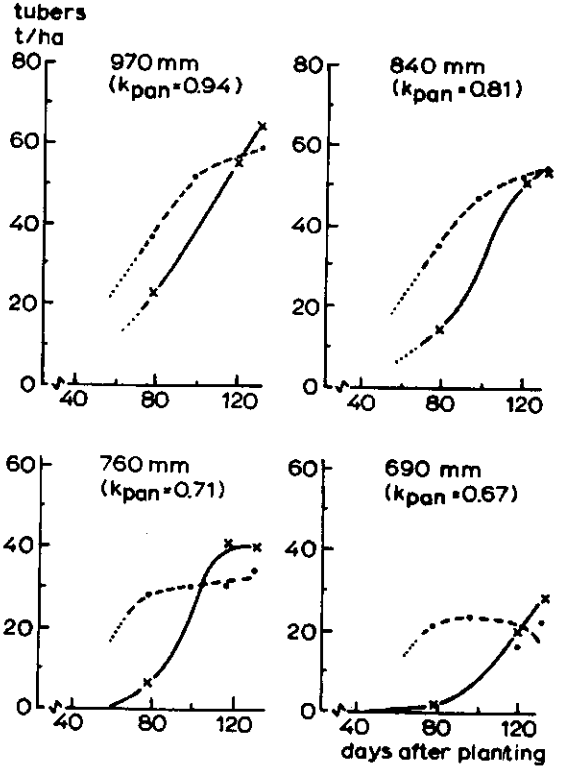


Fig.4.10

Cumulative tuber weight (fresh) under different irrigation regimes, for two potato cultivars growing in San Camilo. ×——× Revolución; •- - - -•: Désirée.

(Inset is total amount of irrigation water applied in both Figures)

Table 4.1 Total and tuber yield (dry matter, t/ha) at final harvest as influenced by the quantity of irrigation water applied for two potato cultivars grown in San Camilo.

Irrigation water applied (mm) corresponding k_{pan}	970 0.94	840 0.81	760 0.73	690 0.67
cv. Revolución				
Total dry weight	17.3	15.9	12.6	8.6
Tubers	14.4	12.2	7.9	5.1
cv. Désirée				
Total dry weight	14.1	10.6	7.0	3.8
Tubers	12.9	9.8	6.6	3.6

The decrease in dry weight of Désirée with decreasing amounts of irrigation water was not only due to the lower water availability, but also to severe leaf burning due to the additional N fertilization, applied to adjust the decreasing N supply as a consequence of lower water supply. This effect was rather strong in the drier treatments, where dry matter accumulation ceased after day 80, coinciding with very pronounced burning symptoms.

Fig. 4.10 shows the growth curve of the tubers (fresh weight) for the different irrigation treatments. The four irrigation treatments, ranked from the wettest to the driest, produced tuber yields of 65, 55, 42 and 29 t/ha, respectively for Revolución and 60, 56, 35 and 22 t/ha, repectively for Désirée. In the two drier treatments, Désirée attained the maximum tuber weight practically by the first harvest on day 78.

In Fig. 4.11 the number of tubers per plant at different sampling dates, as influenced by the amount of irrigation water applied is presented. A limited supply of water resulted in a lower number of tubers in both cultivars, however, with a completely different pattern of tuber development. At the first sampling date (on day 80) Désirée possesed about 20 tubers per plant in all irrigation treatments. At the final sampling, this number had decreased to 19/plant for the wettest and to 13 for the driest treatment. In Revolución a difference existed at the first sampling date and the numbers continued to increase until the last sampling on day 134: for the wettest treatment from 20 to 34 tubers/plant and for the driest from 10 to 23/plant.

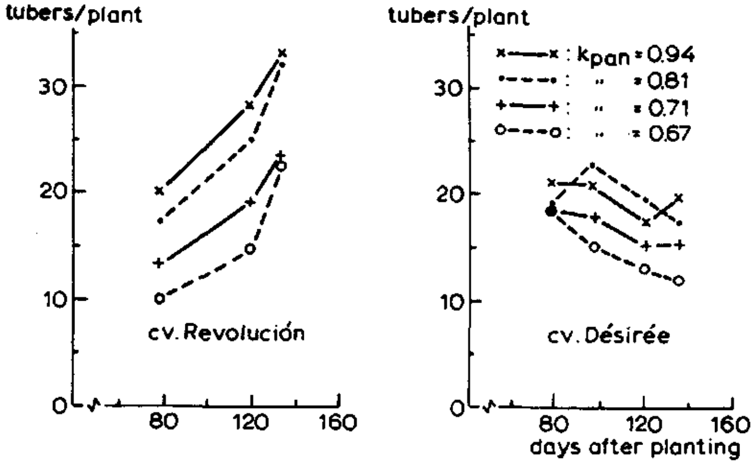


Fig. 4.11 Number of tubers (including tuber initiations) under different irrigation regimes, for two potato cultivars growing in San Camilo.

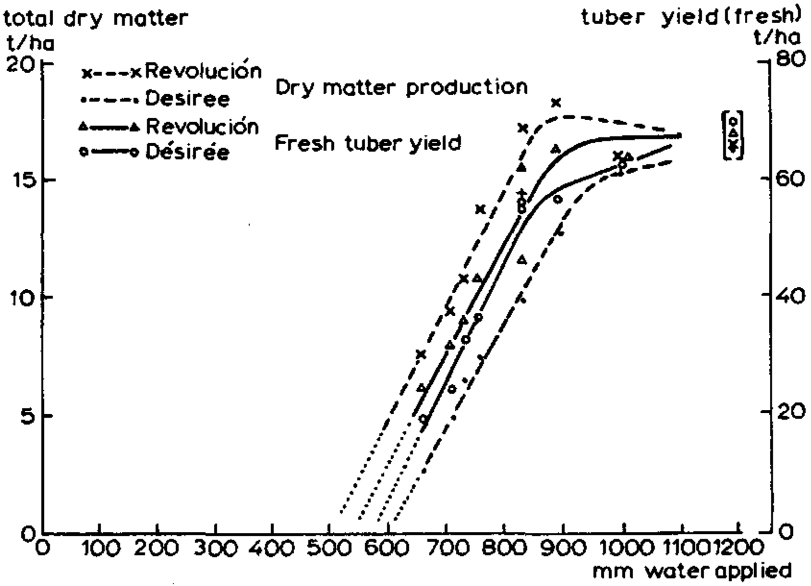


Fig. 4.12 Response of total dry matter production and fresh tuber yield to quantity of irrigation water, for two potato cultivars growing in San Camilo. [ ] : measured in the potential growth experiment.

In Fig. 4.12, total dry weight and fresh tuber yield (per individual ridge) at the last harvest (on day 134) are plotted versus the total amount of irrigation water applied until then. Total dry weight as well as tuber yield showed a very clear linear relationship from about 500 to 900 mm water applied:

- regarding total dry matter production:

  for Revolución: $DW = 0.0478\ I - 24.04$ ($r = 0.96$; $p < 0.001$)
  for Desiree : $DW = 0.0440\ I - 26.29$ ($r = 0.99$; $p < 0.001$), with DW is total dry weight in t/ha and I is irrigation water applied in mm.

- regarding tuber yield:

  for Revolución: $T = 0.1827\ I - 97.56$ ($r = 0.95$; $P < 0.005$)
  for Desiree : $T = 0.1913\ I - 108.95$ ($r = 0.97$; $P < 0.001$), with T is fresh tuber weight in t/ha and I is irrigation water applied in mm.

4.4 DISCUSSION

From the results described in Section 4.3, the following main conclusions may be drawn:

- The local cv. Revolución exhibited a very high growth rate under the high irradiance regime in San Camilo, exceeding the growth rate of the cv. Désirée, from temperate climates. However, tuber yields were about the same, mainly because of a less favourable harvest index for Revolución.
- Both cultivars could maintain their high growth rates for only a rather short period of about two months.
- Despite a rather dense planting pattern, a significant proportion of the incoming irradiance was not intercepted by either of the two cultivars
- To achieve high fertilization efficiency, fertilizer supply should be concentrated in the first two and a half months after emergence, as nutrient absorption was restricted to that period.
- The high yield level and the nutrient concentrations at the final harvest indicated that fertilizer supply had been sufficient in San Camilo. However,the foliage concentrations measured during the growing period were generally lower than found elsewhere, suggesting that the method of application and environmental factors influenced these levels significantly.
- Both potato cultivars showed similar sharp responses to irrigation, but only over a small range of 500-900 mm water applied. The former suggests a very efficient use of water absorbed by the crop, but at the same time indicates the latter that a great proportion of the water applied is not taken up by that crop and is lost to soil surface evaporation and percolation.

These conclusions will be discussed in the following Sections.

4.4.1 *Growth and development*

Under the high irradiance regime in San Camilo and with ample supply of nutrients and water, cv. Revolución exhibited very high growth rates (Fig. 4.2). Although Désirée clearly fell behind in total dry matter production, the final dry tuber yield was practically identical to that of Revolución. The maximum fresh tuber yields of 76 and 84 t/ha for Désirée and Revolución, respectively, are of the same magnitude as top experimental yields in different countries in temperate regions (Van der Zaag & Burton, 1978; Gunn, 1978; Doll et al., 1971) as well as in sub-tropical regions (McGillivary, 1950; Shalhevet et al., 1979; 1983; Shimshi et al., 1983). Van der Zaag (1982) classified the factors influencing final tuber yield as follows:

- factors influencing total irradiance interception, such as length of the growing period, irradiance intensity and soil coverage.
- factors influencing canopy photosynthesis, such as senescense of the foliage, air temperature and water potential of the leaves.
- factors influencing dry matter content and distribution.

4.4.1.1 Intercepted irradiance in relation to its intensity and length of the growing period

Despite the much larger leaf area of Revolución, light interception up to day 63 was about identical for both cultivars (Fig. 4.4). After that period Désirée started lodging and light interception decreased dramatically. Before lodging the growth rate of Désirée was similar to that of Revolución (about 300 kg/ha.d), subsequently, it was reduced by more than half to about 135 kg/ha.d. Revolución started lodging only after day 110 and maintained therefore its capacity for light interception until that dat. As a consequence after day 63, its growth rate decreased less to about 210 kg/ha.d. As from day 63 onwards, all dry matter increase in both cultivars was invested in the tubers, tuber growth rate was about 75 kg/ha.d higher for Revolución. However, Désirée started tuber production earlier, so that both cultivars had about the same dry tuber weight by day 119. After that date total dry weight decreased, because of the loss of decomposed foliage material.

Lodging characteristics, differences in tuber initiation and in growth rates, would characterize Désirée as an early cultivar and Revolución as a late one (Gmelig Meyling & Bodlaender, 1981). However, the length of the effective growth period was equal for both cultivars and the duration of tuber growth was even longer for Désirée because of its earlier tuber initiation.

Leaf area duration (LAD, the integral of LAI over the growth period), introduced by Watson (1952) as a measure of total assimilation throughout the crops life cycle, was modified for potatoes by Radley (1963), by replacing LAI values over 3 by that value. This modification, based on the observation that an LAI of 2.5 to 3 is optimal for potatoes (Ivins & Bremner, 1965), improved correlations with dry matter production (Bremner & Taha, 1966; Bremner & Radley, 1966). Applying this procedure to Revolución and Désirée, resulted in values of 48.6 and 34.3 weeks, respectively, or a difference of about 40%. This was reflected in about 3.5 t/ha or 20% higher total dry weight for Revolución. The relative difference between LAD and dry weight can be explained by the maintenance respiration requirements of the additional roots and foliage, which amounts to about 55 kg/ha.d, totalling about 5 t/ha over the complete growing period.

Compared with the modified LAD values of 50 and 75 weeks for the more productive early and late cultivars in England, (Bremner & Radley, 1966; Bremner & Taha, 1966), the values measured in Peru indicate that duration of productivity of the foliage was less favourable than in temperate regions, where it is often the major factor determining the yield level (Sibma, 1970).

In the Netherlands, the level of irradiance during the growing season showed a weaker correlation with yield than the duration of this season (Sibma, 1970). Sale (1973a) reported an even more limited influence of irradiance in a high solar radiation environment in Australia. He suggested that this was due to a sink limitation during most of the growing period and that the small influence of irradiance was correlated with its positive effect on the sink size in the beginning of the growing period. However, several observations contradict this sink theory, i.e. almost always more tubers are initiated than developed (Bremner & Taha, 1966) and the often positive effect of gibberellic acid treatments on sink size (tuber number) without influencing total tuber weight favourably (often even unfavourably) (Bodlaender, 1982). Scott & Wilcockson (1978), reconsidering Sale's data (1973a, b), found the same linear correlation between intercepted irradiance and total dry weight as in England, when temperature influence on respiration was taken into account.

4.4.1.2 Intercepted irradiance in relation to soil cover

A striking feature is that light interception in San Camilo at its maximum was about 80%, so that a considerable part of the energy was not intercepted by green parts and hence not used for photosynthesis. Most of this light was lost between rows, despite the rather close spacing of 75 cm. As, in many situations, growth rate was found to be an almost linear function of the fraction of light interception (De Wit, 1965; Scott & Wilcockson, 1978; Bean & Allen, 1981), one would expect yield to increase with a narrower distance between the rows of 60 to 65 cm, or a total density of 62000 to 66000 plants/ha. However, in general the response to planting densities was small or absent. Results obtained by Ifenkwe & Allen (1975), Edowes (1975), Svensson & Carlsson (1975), Caesar et al. (1981) and Thow (1981) seem to indicate that very little effect can be expected from higher planting densities if tuber yields are already high (above 45 t/ha fresh). Moreover, at denser spacing tuber grading is almost always less favourable and the market value is therefore less (Caesar et al., 1981). Also Allen (1978) reported that in England at wider row spacing taller plants were produced that did not lodge and were probably more effective in light interception and utilization later in the season than the lodged plants in a narrow-row spacing. A practical problem communicated recently from San Camilo, is that at smaller row spacing not enough soil is available to make good ridges (Medina, personal communication). Data from Scott & Wilcockson (1978) indicate that also in an experiment in England, potato canopies did not intercept more than 87% of the light, even with a high LAI (up to about 5) and densities of 109 000 plant/ha, planted in a square pattern (about 0.30 m x 0.30 m).

The absence of responses to higher planting densities as reported generally from temperate regions at higher latitudes, contrasts strikingly with the, almost linear response obtained at low latitudes (30 °N) in Tunis, under short day conditions (Caesar et al., 1981). This response could be associated with the very low overall production of the cultivars used originating from Northern Europa. At the lower densities a closed canopy would not be reached and light interception would consequently be very low. However, other factors such as mineral nutrition and water supply could also have had a significant influence. This could easily be deduced from the fact that in places in the Middle East, such as Libya (Imam, 1975) and the Negev in Israel (Shalhevet et al., 1979, 1983; Shimshi et al., 1983) two to four times higher yields were obtained with the same or similar cultivars.

The importance of cultivar differences, with respect to responses to planting density can also be deduced from the San Camilo results, where the potential growth experiment, having a 33% greater number of plants within the rows can be compared to the the "sufficient irrigation" treatments of the single line irrigation experiment. The tuber dry weights of Revolución in both experiments were almost the same, whereas Désirée produced 7.8% more tuber dry matter in the denser planting. Differences in favour of the closer spacing were more pronounced for tuber fresh weights, probably because of "over-irrigation" in the potential growth experiment: 7.6% and 12.1% for Revolución and Désirée respectivily. The two cultivars showed a clearly different response with respect to tuber number. Désirée produced in both experiments the same number of tubers per plant (about 20) with comparable irrigation, but the final tuber number in Revolución was inversely proportional to planting density amounting to 33 tubers/plant in the single line experiment compared to 25 tubers/plant in the potential yield experiment. Revolución could, therefore, efficiently compensate for the lower plant density by increasing the number of tubers/plant. Désirée only produced heavier tubers, but this compensation was somewhat less efficient.

4.4.1.3 Maintenance of canopy photosynthesis

A considerable number of data on potato production indicate that the way to achieve high yields is to maintain the foliage productive for an extended period of time. As shown in Section 4.4.1.1, this was a major problem in connection with the utilization of the high amount of irradiance in San Camilo and the same was reported from similar environments in Southern Australia (Sale, 1973a,b) and in Israel (Shalhevet et al., 1983). Dry matter production often ceases, despite the fact that the foliage still looks green and healthy. Van der Zaag (1984) indicated that under high maximum temperatures during the day and/or a high night temperature, the production of the crop decreases considerably. Measurements by Bodlaender (1977) indicate that in the last month of the vegetation period photosynthesis at light saturation was about half the value obtained in the preceding months. Under the climatological conditions in San Camilo (Fig. 2.1), the high night temperatures between mid-December and mid-February (day 65 to day 120) have probably accelerated senescence. Therefore, an improvement in the duration of photosynthetic activity of the foliage may be obtained by planting two months earlier, at the beginning of August.

4.4.1.4 Dry matter distribution and dry matter content

The results in Fig. 4.2 clearly indicate the significant differences between cultivars with respect to dry matter distribution, and its consequences for yield. At the moment of the highest total dry weight, recorded in both cultivars on day 119, only 70% of the dry matter was invested in the tubers in Revolución, whereas in Désirée this fraction was as high as 86%. The latter fraction is similar to the value of 85% used by Sibma (1977) to calculate potential tuber yields for an average year in the Netherlands. However, that value seems rather high for these temperate conditions and generally values between 75% and 80% are obtained. The fraction of 70% for Revolución was also obtained by Ezeta & McCollum (1972) with the Peruvian *andigena* cultivar "Renacimiento". Because of the difference in harvest index, Revolución would have to produce 20% more dry matter, to match the tuber production of Désirée; and this was close to the real measured difference.

An interesting possibility to take advantage of the high total dry matter production of Revolución would be to change the harvest index, reducing foliage dry matter production in favour of tuber dry matter. Breeding programs in wheat and rice, which have used such a strategy, have produced the cultivars that caused the "green revolution" in several third world countries. A change in dry matter distribution may also be produced by spraying with growth retardants such as daminozide (= B-995, B-9 or Alar), chlormequat-chloride (CCC, Cycocel), 2,4 D or a mixture of mepiquat-chloride and ethephon (trade name: Terpal). The first results of treatment with daminozide on highly fertilized plots (200 kg N/ha) in the Netherlands, sprayed when the foliage was "closed in the row", were very promising. Tuber yield increased by about 10% compared with the untreated crop, to 83.2 t/ha (Bodlaender & Algra, 1966). The daminozide treatment caused a marked change in the dry matter distribution: stem weight decreased and tuber weight increased, whereas leaf weight was essentially identical. In later experiments often no effects on tuber yield were obtained, because the foliage started to regrow later in the season, so that there was no longer any advantage. More consistent was the phenomenon of an increase in the number of tubers and a corresponding increase in the fraction size 28 - 45 mm. This is the reason that daminozide is actually used in the Netherlands on a limited scale in seed potato production (Bodlaender, 1982 and personal communication). The results from chlormequat-chloride were generally disappointing. The results from the mixture of mepiquat-chloride and ethephon were promising for the seed-potato production. Recent experiments with 2,4 D (1.5-3.0 kg a.i./ha) showed a marked increase in total tuber yield (up to 20%) and especially in the seed tuber fraction (up to 60%). One disadvantage, at least for seed potato production, is the marked and unfavourable deformation of the foliage treated with this product (Bodlaender, 1983).

According to Van der Zaag (personal communication), potato cultivars produce more foliage in longer day conditions such as in the Netherlands. Cultivars like Désirée have been selected, unintentionally, for a more or less optimal foliage production in these environments and they produce therefore not enough foliage in the short day conditions of Peru, especially if combined with high irradiance. On the other hand, *andigena* cultivars such as Revolución produce under Dutch conditions practically only foliage and no tubers. To our knowledge, no special potato breeding programmes for optimal distribution patterns for short-day conditions are in progress. With a more or less optimal harvest index of 0.8, the production of Revolución could increase by about 15% reaching 90 to 95 t/ha under the San Camilo conditions.

It should be noted that the final high fresh tuber yields in San Camilo were partially associated with a rather low dry matter percentage of 17.3 and 18.5% for Revolución and Désirée, respectively, compared with percentages of about 20 to 22% generally reported. Data from Shalhevet et al. (1983) suggest that such low dry matter contents are partly a result of ample irrigation (above $k_{pan} = 0.85$) and partly a cultivar characteristic.

4.4.2 *Aspects of NPK fertilization and uptake*

4.4.2.1 Nitrogen

At the final harvest Revolución had absorbed about 210 kg N/ha and Désirée 180 kg N/ha, of which, in both cultivars, approximately 145 kg/ha was present in the tubers, a quantity similar to that found in good crops elsewhere (Harris, 1978a).

Compared to the 388 kg N/ha applied during the entire experiment, the fraction of N recovered in the harvested crop was rather low, at 54 and 46% of the fertilizer for Revolución and Désirée, respectively, even if it is assumed that no N is supplied from the soil in the unfertilized situation. This was mainly due to the continution of the weekly applications towards the end of the growing season, done to ensure that growth would not be hampered by any shortage of nutrients, especially N. However, in Fig. 4.6 shows that the maximum accumulation of N by the crop had taken place by about day 100, after which N uptake practically ceased. At that moment 240 and 180 kg N/ha had been taken up by Revolución and Désirée, respectively, values which are lower than the 240 to 270 kg N/ha indicated by Van der Zaag (1980) for a crop of 13 to 14 t/ha tuber dry matter in the Netherlands. The difference is most pronounced for Désirée, mainly because of the small amount of foliage. Until day 100, 293 kg N/ha had been applied through the sprinkler irrigation system. Hence, the amount of N taken up by the crop was 82 and 62% of the applied fertilizer for Revolución and Désirée, respectively. For the Peruvian cultivar in particular, this seems to be a reasonable recovery fraction, compared with values of 50 to 65% found in high-yielding potato crops on soils with a low natural N supply as in San Camilo (Ezeta & McCollum, 1972; Mattingly, 1972). Fig. 4.6 clearly shows that N fertilization in San Camilo should be concentrated in the two and a half months after emergence, when the average rate of uptake was 3 to 4 kg N/ha.d.

Several published results reveal that there were benefits with split application of N on light soils under conditions of rather high rainfall or irrigation, which otherwise would have caused leaching of the N fertilizer if applied as a basic dressing only. In heavier soils or under drier conditions, there was often no advantage (Harris, 1978a; Hunnius & Munzert, 1979; Dilz & Bodlaender, 1982; Bodlaender et al., 1982). The method used seems, therefore, to be appropriate for the sandy soils in San Camilo. An additional advantage of split application for tall cultivars such as Revolución is that stem production is reduced by 10 to 20% compared to a single N application, giving a somewhat stronger foliage (Kortleven, 1959; Dilz & Bodlaender, 1982).

Kortleven (1959) also indicated a delay in foliage senescence, although the effect did not seem to be very pronounced. This is in agreement with the absence of yield response, when splitting the N application occurred in situations where leaching of N was negligable. Contradictory observations of a more rapid senescence of the foliage have also been made (Van Loon, personal communication).

The time course of N concentrations in the various plant parts measured in San Camilo shows a much more gradual decline than the patterns reported by Kortleven (1959) and Harris (1978a). In San Camilo, the concentrations at the first sampling were lower by about 2 to 3% (foliage) and 1% (tubers), but at the final sampling, the concentrations were about the same or even somewhat higher. Presumably, the split application was the main cause of these differences. This means that foliage-N concentration is quite sensitive to the release rate of mineral N in the soil and therefore less valuable for a midway diagnostic measurement of the N status of the crop. For example, until about three and a half months after planting, the average N concentration found in the foliage in San Camilo was below the values of the unfertilized potato crop, described by Kortleven (1959), in an experiment where a strong response to N fertilization was observed. Nevertheless, one could argue that the lower N-concentrations in the early stages indicated that the crop in San Camilo experienced, effectively, a kind of N deficiency that could have been alleviated by additional fertilizer applications and this, in fact, was achieved with the later periodic fertilizations. This explanation also suggest that the potato crop may increase dry matter production from additional N fertilizations so long as it is able to absorb the nutrients. In San Camilo that was the case up to about three months after planting. Bodlaender et al. (1982) in the Netherlands reported positive results from over-fertilization of a late cultivar (Alpha) until the beginning of August, which coincided with the end of the elongation of the foliage. Later fertilizations had no positive effects on tuber yield.

Similar to the total N concentration, differences with published results elsewhere were also observed for the NO_3-N concentrations in the petioles (Fig. 4.8). Again, in San Camilo, a much more gradual decline occurred because of much lower initial values if compared to data from Idaho (Gardner & Jones, 1975), Minnesota (Doll et al., 1971) and the Netherlands (Van Loon, personal communication). However, at lower latitudes, Tyler et al. (1961, in Harris, 1978a) in California and Gupta & Saxena (1978) in Northern India measured NO_3-N concentrations in the petioles, that were more comparable with the results from San Camilo. In the Netherlands split N application also produced lower NO_3-N values at the start of growth (Van Loon, personal communication).

Doll et al. (1971) concluded that NO_3 concentrations in petioles decrease so rapidly with time, that a concentration which would have indicated a deficient level on one sampling date might be considered to be an excessive level at the next sampling. It is almost impossible, therefore, to establish a critical petiole NO_3 level, unless the physiological age of the plant is known precisely. Besides, such a value varies among on cultivars, place of cultivation and growing techniques and would therefore not be very useful.

Van Keulen & Van Heemst (1982) analysed the relation between total N uptake of a potato crop and final tuber dry weight for many fertilization experiments and reasoned that in the low range of nutrient availabilities about 100 kg dry weight of tubers would be produced for every kg of N taken up by the crop. For the data of Feigin (1977) in Israel, Liegel & Walsh (1976) in Wisconsin and Bodlaender & Reestman (unpublished results) in the Netherlands, a range of 87 to 95 kg tuber dry weight per kg N taken up by the whole crop was found. The somewhat lower value is probably due to a lower harvest index, than was assumed by Van Keulen and Van Heemst (1982).

As most of the N ultimately ends up in the tubers, it is not surprising that a similar characteristic relation also exists between N uptake in the tubers and tuber dry weight. From the above mentioned sources an average of 105 kg tuber dry weight per kg N in the tubers was calculated in the low range of nutrient availabilities. The variability in this value was about the same as for the relationship with the N taken up by the whole crop. An advantage of the tuber yield/tuber-N relationship is, that it is easier to obtain and requires less labour and expense than that necessary to acquire the tuber yield/total plant-N uptake. Also, the concentration of N in tubers appears to be a rather stable parameter. In our measurements it remained constant over the whole sampling period (day 60 to 140).

The tuber yield tuber-N relationship provides the possibility of eventually using that as a diagnostic tool that will be of value for successive crops in the same field. At the final harvest, the tubers have an N concentration of at least 0.9 to 1.0%. If such a percentage is obtained with a low yield, then probably not enough N was available to the crop. Whenever a low yield is obtained with a higher N percentage than 0.9 to 1.0%, then N availability would not have been the most important limiting factor. In a situation where a high yield was associated with above minimum

N concentrations, it means that the crop possibly had just enough N and that not very much gain is to be expected from a higher N fertilization. In San Camilo, the standard N-fertilized crop ended with a high tuber yield and a N concentration of 1.2 to 1.3% in the tubers. It was therefore to be expected that the high N fertilization checks did not produce more yield and only resulted in higher tuber-N concentration of 1.7 to 1.9%.

4.4.2.2 Phosphorus

Total P uptake (50 kg/ha) was similar to the quantity indicated by Van der Zaag (1980) for a good crop in the Netherlands. The P concentration in the foliage during crop development changed, as for N, more gradual than indicated by Harris (1978a). Hence for the diagnostic value of the foliage-P concentration the same limitations apply as for the N concentration.

The P concentration in total foliage, tubers and roots at final harvest was more or less identical to that at the first sampling date, in contrast to a clearly decreasing tendency in the data presented by Harris (1978a). It is remarkable that in San Camilo the stem-P concentration decreased continuously, whereas that of the leaves increased very pronounced towards the end. As a result, the overall P concentration in the foliage remained more or less constant (Fig. 4.7). This indicates that in the ageing foliage, P is transported from the stems to the leaves. The different time course of tissue-P concentration in San Camilo from that obtained in England (Harris, 1978a), could not be attributed to the method of application, because in both situations nutrient was all applied just before planting. The different results at the two sites again indicate that it appears to be rather difficult to find some general practical method to use leaf, stem or total foliage P concentration as a guide for fertilization.

Van Keulen & Van Heemst (1982) reasoned that for P in the low range of P availabilities about 600 kg of tuber dry weight would be produced for every kg P taken up by the crop. For the data of P fertilization experiments presented by Carpenter (1963) in Maine, Van der Pauw (1948) in the Netherlands and Dainty et al. (1959) in the United Kingdom, a range of 620 to 695 kg tuber dry weight per kg of absorbed P was found. Also for this element, a consistent relationship between P absorbed by the tubers and tuber dry weight was found, resulting in a range of 735 to 815 kg tubers per kg P absorbed in the tubers. P analyses of tubers in San Camilo indicate that, similarly to N, the variability in tuber-P concentration is as small as that of the P concentration in the total crop. Following the same reasoning as for N, the consequence is that a low yield combined with a P concentration in tubers of 0.125 to 0.135%, indicates that P deficiency is a probable major limiting factor. A P concentration of 0.3% as found in San Camilo, combined with a high yield indicate that P supply certainly was not constraining in this experiment.

4.4.2.3 Potassium

When foliage development was at its maximum, the potato crop had absorbed 520 (Revolución) and 400 kg (Désirée) K/ha. These are large quantities compared to the 150 kg/ha fertilizer-K applied up to that time. This modest fertilization level was given on the basis of our experience with alfalfa, showing that San Camilo soils have a rather large K-supplying capacity. Van der Zaag (1980) reported that a good potato crop at the time of maximum foliage development has absorbed about 350 kg K/ha. At the same time, the K concentration in the foliage should not be lower than 4%, whereas at harvest the K concentration in the tubers should be 1.5 to 2.0%.

These values are lower than those obtained in San Camilo (Fig. 4.7) so apparently there was no K deficiency.

Although uptake of K by the tubers is very high, results from the survey by Van Keulen and Van Heemst (1980) suggest that, in general, K shortage is not a widespread phenomenon. In the case of limited availability, about 80 kg of tuber dry weight can be produced for every kg K taken up by the crop. This value is nearly the same, when related to the K present in tubers only, because under limited K availability the foliage at harvest contains only a very low K concentration of 0.3% (Van Keulen & Van Heemst, 1982). The results of some experiments, however, indicate much more variability than for N and P, with values of 68 kg (Knowles & Watkin, 1940) to 106 kg tuber dry weight (Johnston et al., 1970) for every kg K present in the tubers at harvest, corresponding with K concentrations of 1.47 to 0.94%. The data presented by Widdowson & Penny (1973) and by Johnston et al. (1970) indicate a more curvilinear relationship between total uptake and tuber yield, than for N and P. However, high tuber yields were only obtained when the final tuber-K concentration was higher than 1.5%, which agrees with the previously mentioned range of 1.5 to 2.0% reported by Van der Zaag (1980).

In the San Camilo experiment the K concentration in the tubers at final harvest was 2.5%, indicating that there was no shortage of this element.

4.4.3 *Crop-water relations*

Van der Zaag & Burton (1978) stated that in the highly developed potato growing area of the Netherlands, the average farm yields are still less than half the potential potato yield calculated for this environment, and they suggested that the main cause for this large difference is shortage of water. The crop seems to be particularly susceptible in the tuber bulking period (Van Loon, 1981).

Under the arid conditions of San Camilo, the single line method proved to be very efficient for rapidly acquiring adequate information about this factor. In particular, when combined with some periodic harvests, this technique provides information on the effect of water on crop growth over the whole range of moisture supplies, from abundant to zero (although because of lack of seed tubers the lowest ranges were not fully explored in our experiment).

Combination of the data presented in Figs. 4.9 and 4.11 suggests that Revolución started tuber initiation only after a threshold value of 4.0 t/ha foliage dry matter was produced. Water stress under sub-optimum water supply decreased the rate of dry matter production, all the material being first invested totally in the foliage. In the dryer treatments it took more time to reach the threshold value and consequently tuber production was initiated later. After that moment the formation of new tubers proceeded at the same rate in all treatments, but tuber growth rate was reduced with increasing water stress.

Désirée, apparently initiated at an early stage about 20 tubers per plant regardless of water, of which several aborted, depending on the degree of water stress. Moreover, tuber growth started much earlier than in Revolución, especially in the drier treatments.

Under conditions where drought can be expected towards the end of a growing season, an early cultivar like Désirée is therefore a safer choice. At the end of the growing period, the rate of tuber growth of Revolución was clearly higher than that of Désirée, especially in the drier treatments. However, because of the burning symptoms caused by the extra N fertilization, which was more severe in the drier treatments, any conclusion about the yield of the two cultivars must be conditional.

Additional N fertilizer was applied at a rate inversely proportional to the amount of water received in the drier treatments of the single line experiment, to compensate for the smaller amount of dissolved fertilizer applied with the lower application of irrigation water. That turned out to be in error. When the amount of water applied is reduced with a certain fraction, the amount of dissolved fertilizer decreases proportionally. However, the quantity of water available to the crop will always decrease more than proportionally, because the loss of water due to soil surface evaporation will (at least) remain equal in the drier treatment. Consequently, the growth of the crop, and the associated demand for nutrients, will also decrease more than proportionally. Thus, on a relative basis, always more fertilizer will be available for the crop in the dry treatments than for the fully irrigated crops. That reasoning assumes that not much of the supplied N is lost because of volatilization, which is very likely because the fertilizer was injected in the irrigation system during the first two-thirds of the irrigation period. Such a practice uses the final third of the water to "clean" the foliage and to transport the fertilizer deeper into the soil profile.

The relation between water supply and total dry weight as well as that between water supply and fresh tuber weight, which was almost identical for both cultivars, appeared to be linear in the range from limited to sufficient water supply (Fig. 4.12). This confirms the theory of De Wit (1958) that total dry matter production is proportional to total transpiration, independent of actual water availability. The yields obtained with 900 to 1000 mm water were similar to those of the potential growth experiment with 1200 mm irrigation water.

An estimate of the transpiration coefficient (TRC) can be obtained from the slope of the lines in Fig. 4.12, resulting in 209 and 229 kg water/kg dry matter produced for Revolución and Désirée, respectively. To produce 1 kg of tubers (fresh weight) Revolución transpired 55 kg water and Désirée 52. These data suggest that the potato crop uses its absorbed water more efficiently, than many other C_3 crops with TRC values in the range of 400 to 800 kg water/kg dry matter. This is contradictory to the image of potatoes as a water demanding crop. An explanation may be deduced from the extrapolated intercepts with the horizontal axis, representing the amounts of irrigation water lost by soil evaporation and percolation beyond the range of the roots. These losses were very high in San Camilo: 570 to 600 mm for Désirée and 500 to 530 mm for Revolución. Thus more than half of the applied water was not used by the plants but lost by soil surface evaporation and drainage below the root zone.

The first results in a pot experiment in San Camilo showed an average TRC of 240 kg water/kg dry matter (Van der Meer et al., 1983). Goudriaan (unpublished results) calculated TRC-values from photosynthesis measurements in the Netherlands of 115 to 240 kg water/kg CH_2O. The lower values in this range were obtained in young foliage under water stress; these TRC values were about 25% lower than those found without water stress. The higher values were obtained in older canopies, showing no differences between wet and dry treatments. From the TRC values presented by Rijtema & Endrödi (1970) 90% were within the range of 170 to 270 kg water/kg dry matter, whereas Harris (1978b) stated that the potential response to irrigation of potatoes in England was in the range of 2 to 2.5 t (tuber fresh weight) per ha, for every cm of irrigation water. This equals about 40 to 50 kg water/kg tuber (fresh weight) produced, which is comparable with the San Camilo results. Analyzing data from Israel (Shalhevet et al., 1983) a value of 84 to 88 kg water transpired for the production of 1 kg fresh tubers was calculated. This is equivalent to a TRC of about 350 kg water/kg dry matter.

All these data indicate a high transpiration efficiency by the potato crop, which may be the result of the sensitive stomatal behaviour. According to Aboukhaled et al. (1975), stomata in potatoes start to close at a leaf water potential of -0.35 MPa and Campbell et al. (1976) indicated similar values from measurements in a growth chamber. This is much more sensitive than for some other C_3 crops such as cotton, soybean, temperate perennial grasses and wheat, that only start to close their stomata between -1.0 and -1.3 MPa (Boyer, 1970; Rijtema, 1965; Aboukhaled et al., 1975). Stomatal sensitivity to light is also very pronounced in the potato plant, in contrast to many C_3 plants that have nearly fully open stomata with much less light than is required for saturation for photosynthesis (Ku et al., 1977; Dwelle et al., 1983).

To take advantage of the high transpiration efficiency of the potato crop, it is necessary to minimize the enormous non-productive loss of water. Trickle irrigation could be a promising technique. Surface and sub-surface (at a depth of 10 cm) trickle irrigation at low irrigation frequency (application when soil moisture potential was 0.06 MPa) produced the same tuber yields of similar grades as sprinkler and furrow irrigation, but at 30% lower water use (Sammis, 1980). Shalhevet et al. (1979, 1983) reported from experiments on a loessial desert soil 8% higher yields from trickle irrigation than from sprinkler irrigation, using the same amount of water. However, no differences in yield of marketable potatoes were obtained. The extrapolated water loss from evaporation and deep percolation on that soil was only 200 and 100 mm for sprinkler and trickle irrigation plots, respectively. This seems to indicate that in the sandy soil of San Camilo a considerable quantity of the water loss was from deep percolation.

Whichever irrigation method is applied, the answer to better irrigation efficiency seems to be a favourable balance between irrigation interval and a tolerable stress level. Longer intervals reduce soil evaporation, but in the potato crop, growth is also easily affected (Harris, 1978b). In lighter soils striking the right balance is particularly difficult to obtain. The results reported by Sammis (1980) show that in loamy soils, even under trickle irrigation, losses could be reduced by about 15%, by increasing the interval between applications.

There are no facilities for trickle irrigation in most countries with irrigated agriculture. In such situations, early cultivars such as Désirée in San Camilo, having a high harvest index and a relatively low foliage production, seem to present the best prospects (Table 4.2). Table 4.2 also shows that an irrigation level, that produces near maximum yields (in San Camilo with $k_{pan} = 0.81$) gave the best yield-water supply ratios (Ryw in kg (tubers)/m^3 applied irrigation water). Especially in areas where irrigation cannot be controlled and the availability of irrigation water depends on weather conditions, the best strategy is to plant an early cultivar at an acreage no larger than can be irrigated at a level for near maximum yield in the period of expected water supply. Also, fertilization and plant density should be adapted to that yield level. If the water supply runs out earlier than expected, a reasonable yield can still be obtained. For example, in the case of San Camilo, when water supply would have ceased by day 75, Désirée would still have produced 35 t/ha fresh tubers with an irrigation regime according to $k_{pan} = 0.81$. The corresponding Ryw still would have been 7.4 kg tubers/m^3 irrigation water, which is close to the maximum Ryw of 7.7 kg/m^3 obtained in this experiment. If the late cultivar Revolución would have been planted, only half as many potatoes would have been produced at the moment of water restriction, resulting in a low Ryw of 3.7 kg/m^3.

When (irrigation) water supply is irregular, planting early cultivars under conditions of optimum mineral nutrition and phytosanitary control is a generally favourable strategy for most crops in different farming systems.

Table 4.2 Fresh tuber yield (t/ha) and yield-water supply ratio (Ryw in kg/m^3) of Revolución (R) and Désirée (D), at final harvest and at the periodical sampling of maximum Ryw. Between parenthesis: days to max. Ryw.

	k_{pan} = 0.94		k_{pan} = 0.81		k_{pan} = 0.73		k_{pan} = 0.67	
	yield	Ryw	yield	Ryw	yield	Ryw	yield	Ryw
Total period (134)	R 64.6	6.7	54.6	6.5	40.1	5.3	28.7	4.2
	D 59.5	6.1	55.4	6.6	34.6	4.6	21.7	3.1
Period to max. Ryw	R 64.6 (134)	6.7	50.8 (121)	6.7	41.5 (121)	6.1	28.7 (134)	4.2
	D 51.8 (97)	7.4	47.0 (97)	7.7	27.8 (78)	6.3	20.9 (78)	5.2

5 *GROWTH DYNAMICS OF RHODES GRASS*

Rhodes grass is a tropical perennial C_4 grass native to East and South Africa and with rather recent history of use as a pasture species (Whyte et al., 1959). In several countries, e.g. Australia, Cuba, Japan and Israel, favourable experience have been gained, reason enough to start exploratory research in Southern Peru. An additional reason was the possibility of validation of existing simulation models, as reported by Dayan & Dovrat (1977) and Dayan et al. (1981a,b) and to test their predictive performance for an environment in which there was no previous experience at all with this grass. Although valuable data were obtained during the experimental period of two years, they must be considered as preliminary.

5.1 METHODS

Rhodes grass, cv. Katambora (Barnard, 1972), was sown on 16th april 1980 in a sandy field, that had previously been used for maize (experiment M 1, see 6.2.1). Because of the low temperatures in the winter season, initial growth was slow and the first cutting could only be made on 25th August 1981. That date was taken as the beginning of the experiment.

The field was divided into five replicates of 12 m x 60 m, each. Each replicate was further sub-divided into three main plots, receiving one of the following fertilization treatments:

(A) 520 kg N/ha.yr as ammonium nitrate, applied in fortnightly dressings;
(B) 1560 kg N/ha.yr as ammonium nitrate, applied in weekly dressings;
(C) as (B) but complemented with 300 kg P/ha.yr as triple superphosphate applied in fortnightly dressings.

Each fertilizer treatment was further sub-divided into four sub-plots, that were used consecutively to determine growth curves during different periods of the year. Each growth curve was based on six successive cuttings in one sub-plot of a strip of about 6.5 m^2, chosen at random. These cuttings were carried out at fortnightly intervals, following the initial general harvest of the total field, with the exception of the first two periods, when the cutting interval was only one week. The three sub-plots not used for the determination of the growth curves were subjected to a maintenance cutting regime with a four week interval and a low N fertilization of 520 kg/ha.yr (identical to treatment A).

After the sixth cutting in each period, the whole field was harvested again (general harvest) to start the growth curve of the next period in the second sub-plot of each treatment. The new sub-plots for the treatments B and C, had by then already received the high N fertilization level for three weeks.

After the fourth period, the first sub-plot was again used for the fifth period, the second for the sixth, and so on. This repetition scheme assumes that the after-effects of cutting a sub-plot periodically for the determination of a growth curve, are negligible after three general harvests. For each new period, the harvested strips within each sub-plot were randomized again. Harvesting was done with an Agria power mower, leaving a stubble of about 5 cm. Directly after cutting, all harvested material was removed from the field.

In total, growth curves for seven periods were determined. For the seventh period the area of two adjacent sub-plots was added to the experimental plot, to be able to cut more than six strips and to obtain a growth curve for a period longer than twelve weeks.

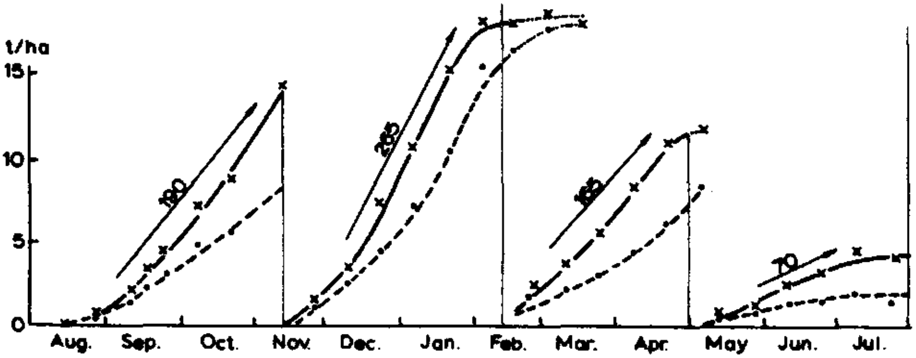


Fig. 5.1 Growth curves for Rhodes grass in San Camilo, under high (x —— x; 1560 kg N/ha.yr) and low (• - - - - •; 520 kg N/ha.yr) N fertilization. Arrows indicate linear growth rate .

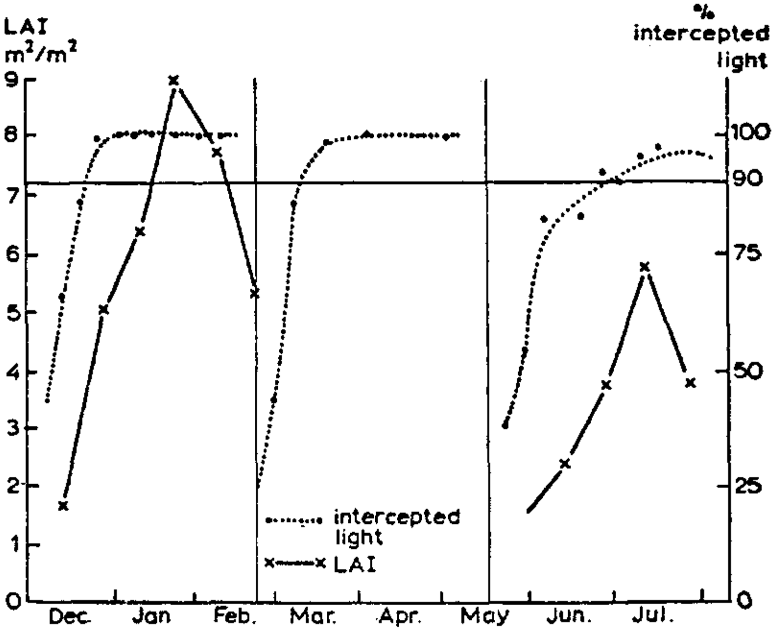


Fig. 5.2 Course of leaf area index (x —— x) and % intercepted light (• - - - - •) during some growing periods, of Rhodes grass growing in San Camilo at high N levels.

Dry matter yield was obtained after drying samples at 70 °C as described in Section 2.4; these samples were also analysed for N, P and K concentration. LAI and SLA were determined with the periodic harvests during three growth curve determinations by sampling 0.5 m^2, from which the leaf area of a sub-sample was measured with an electronic area meter. The actual leaf area of the sample was obtained via dry weight conversion. In the period of March to May 1981 the meter did not react to very thin leaves and reliable results were not obtained.

Light interception by the sward was measured simultaneously with leaf area determinations using a bar of 1 m fitted with photo-electric cells, generally between 10.00 and 11.00 a.m.

During the growth curve determination from February to May 1981 the flowering stems were counted periodically (every 7-14 days).

5.2 RESULTS

5.2.1 *Potential growth of aerial biomass*

The growth pattern, as obtained in San Camilo, is presented in Fig. 5.1. The data are averages of two years, with exception of the winter period, that resulted from one single determination (May to July, 1981). For potential growth the high N-fertilizer treatments (B and C) are relevant. At this high N level the crop showed a reasonably high growth rate during a period of approximately nine months. From August to November (spring) the linear dry matter growth rate was 190 kg/ha.d and production reached a level of 14 t/ha, whereas still no levelling off occurred. In the subsequent period up to mid February (summer), the growth rate attained 265 kg/ha.d and dry matter accumulation ceased when 18 t/ha dry matter had been produced. Between mid February and the beginning of May (autumn) the linear growth rate and final production were 165 kg/ha.d and 12 t/ha, respectively. Hence, a total of 44 t/ha of dry matter was harvested from the experimental plots during these nine months. Linear growth rate during the winter months (May to July) was lower (70 kg/ha.d) and the dry matter production did not reach 5 t/ha, despite the high N dressing.

In summer and winter, reliable data on leaf area development (Fig. 5.2) were reached. In summer, high LAI values of about nine were obtained, in winter a maximum LAI of almost six was measured. After reaching these values, leaf area declined at approximately the same time that the growth rate declined. This decline, however, did not influence light interception by the canopy.

SLA in summer fluctuated between approximately 20 and 25 m^2/kg, somewhat higher than in winter when values were usually between 15 and 20 m^2/kg. The number of flowering stems was determined during only one of the periods (February to May 1981). It increased linearly with time, the rate being higher at high N than at low N fertilization (Fig. 5.3). In both treatments flowering started around three and a half weeks after cutting. When the number of flowering stems was plotted versus total dry matter, difference between the two N levels disappeared (Fig. 5.4).

As Rhodes grass was sown in the same field as maize that had shown a clear negative effect from the absence of sub-soiling in one of the blocks, a similar comparison was made for Rhodes grass. However, the Rhodes grass in the non sub-soiled block did not produce any significant difference, so it is obviously not very sensitive to mechanical soil resistance.

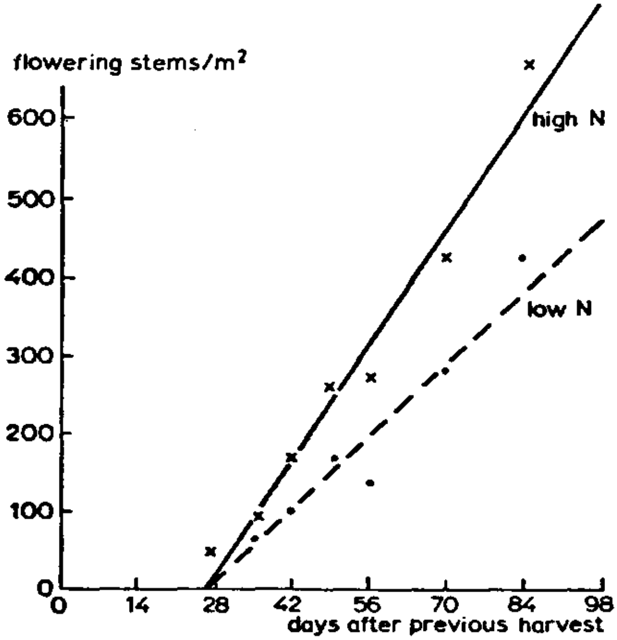


Fig. 5.3 Number of flowering stems/m^2 (FSA) in Rhodes grass grown in San Camilo at two different N levels. Linear regression equations:
High N : FSA = 10.6 * days - 277.0 (r = 0.99).
Low N : FSA = 6.6 * days - 167.2 (r = 0.97).

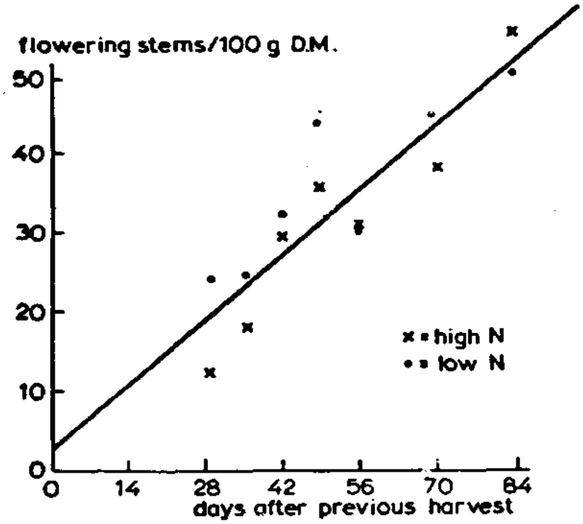


Fig. 5.4 Number of flowering stems/100 g dry matter (FSW) in Rhodes grass grown in San Camilo at two levels of N. Linear regression equation: FSW = 0.58 * days - 4.4 (r = 0.90) .

5.2.2 *Fertilization aspects and nutrient concentration*

A striking phenomenon in the growth behaviour of Rhodes grass in San Camilo was that the response to high N fertilization was relatively modest when crop growth rate and hence the demand for nutrients was highest and vice-versa (Fig. 5.1). The high N treatment gave a 15% increase in production over the low treatment in the period of the highest production (November to February), whereas a 100% increase was obtained in winter (May to July). In spring (August to November) and autumn (February to May) the high N fertilization resulted in intermediate responses of 74% and 54%, respectively. Averaged over the nine months of good growth the high fertilization level resulted in a 39% higher dry matter production, from 31.6 to 43.9 t/ha in total.

Phosphorus fertilization did not increase dry matter production. The average NPK concentration of the different periodical harvests are presented in Fig. 5.5. The high N treatment not only increased the N concentration by on average 40% (from 1.6 to 2.3%), but also the P and K concentration by approximately 20% (P: from 0.18 to 0.22%; K: from 1.9 to 2.3%), compared to the low N treatment. Hence, combined with the increase in dry matter production, the high N plots extracted about 65% more P and K from the soil. The P concentration in the plots that received supplementary P fertilization (in addition to the high N treatment) was about double that of grass fertilized with high N only.

Fig. 5.6 presents the average NPK concentrations for the six different growth periods in the course of the experiment. Again, the same differences in NPK concentrations of high and low N fertilized treatments show up. In the N + P fertilized treatments there was a gradual increase in the average P concentration so that in the last period the P concentration was about 20% higher than at the start of the experiment. In all other treatments, the fluctuations were insignificant or absent. In growth period IV (winter) the K concentration was lower than in all the others.

Based on the average concentration at the final harvests during the whole experiment, the P/N ratio of the low N treatment was 0.11, that of the high N 0.09 and that of the high N + P 0.23. Over the whole experimental period, 79% of the applied nitrogen from the low N and 56% from the high N treatment was recovered in harvested dry matter.

5.3 DISCUSSION

From the experimental results the following conclusions may be drawn:

- The growth of Rhodes grass was very good in summer, reasonably good in autumn and spring and rather bad in winter. The growth behaviour seems to be related to the prevailing night temperatures. Under favourable conditions dry matter accumulation continued for a prolonged period and ceased when the green leaf area declined.
- To achieve high yields of good quality, N fertilization plays a key role. The relative influence of fertilization was greater when growth was hampered by lower temperatures. P and K uptake increased together with herbage production, but more than proportionally.
- Although Rhodes grass demonstrated several attractive qualities, such as high yield, excellent persistence and weed-suppressing characteristics, the possibility of obtaining a high fertilization efficiency and the absence of susceptibility to mechanical soil resistance, several questions still have to be answered before recommendation is justified. These include aspects of feed quality, practical conservation methods, optimal nitrogen

and water supply, optimal cutting frequency, etc.
These conclusions will be discussed in the following Sections.

5.3.1 *Growth of aerial biomass*

Rhodes grass fertilized with N demonstrated good growth compared to a similar experiment in Israel, where this grass is very popular. In Israel, a total of 38.3 t/ha dry matter was harvested in four growth cycles during seven months of good growth (Dayan & Dovrat, 1977). Thus, although a lower cumulative production was obtained, the average daily growth rate was somewhat higher in Israel than in San Camilo. This was mainly the result of generally higher linear growth rates and a faster regrowth after cutting. In Israel, in three out of four growth cycles a linear growth rate of more than 250 kg/ha.d was obtained, whereas in Peru this level could be reached in only one. It seems probable, as demonstrated by West (1973) in other C_4 grasses, that low temperatures, especially during the night significantly hamper the expression of the full production potential. This will be discussed in more detail in Section 6.4.1.

An interesting phenomenon is the decline in growth rates that occurred in Israel at a level of 6 to 12 t/ha, much earlier than the levels of 12 to 18 t/ha reached in Peru. Dayan et al. (1981b) suggested that the growth rate in the field was inversely proportional to the relative number of flowering stems. This could not be tested for the San Camilo conditions, as only absolute counts of flowering stems were made. However, the absolute numbers were clearly lower than those presented by Dayan & Dovrat (1977). Moreover, in Israel the number of flowering stems, either expressed per m^2 or per unit of dry matter, usually reached a maximum level early in the growth period, whereas in Peru these values increased linearly till the end of the growth period (Fig. 5.3 & 5.4). Although some of the dissimilarities may be explained by cultivar differences, the number of flowering stems does not appear to be a useful indicator for the growth decline in Peru.

From Fig. 5.4 it can be deduced that in San Camilo differences between high and low N fertilizer treatments disappeared when flowering was expressed per unit dry matter. Apparently flowering was largely determined both by age and by the absolute quantity of biomass in the field. Another phenomenon related to the decline in growth rate is the simultaneous decrease in leaf area in the field, as observed in San Camilo. The results of Dayan & Dovrat (1977) indicate a similar relation between growth rate and decrease in leaf area. They also found that prevention of lodging did not influence the leaf area reduction. In San Camilo, lodging occurred only at the end of the last growth period, when measurement was continued for eighteen weeks after cutting. By that time growth had already stopped.

It would appear that after a certain time, Rhodes grass no longer forms new leaves and the ageing and senescent older leaves are no longer replaced. Consequently the green leaf area declines and the photosynthetic capacity of the older remaining leaves simultaneously decreases. This ultimately results in the cessation of dry matter production.

The yields obtained during the periods of good growth, were higher than can be obtained in practice, even under optimal supply of nutrients and water, because before starting the growth curve measurements, the sward was cut at short intervals of four weeks in Peru and two weeks in Israel. This practice promotes a relatively green stubble with many viable buds, which assures a quick regrowth (Dovrat et al., 1980; Dayan et al., 1981a). This is then followed by a long period of undisturbed growth until the maximum production level is attained. In this way, the resulting growth pattern is more favourable than can be obtained in practice under either a frequent

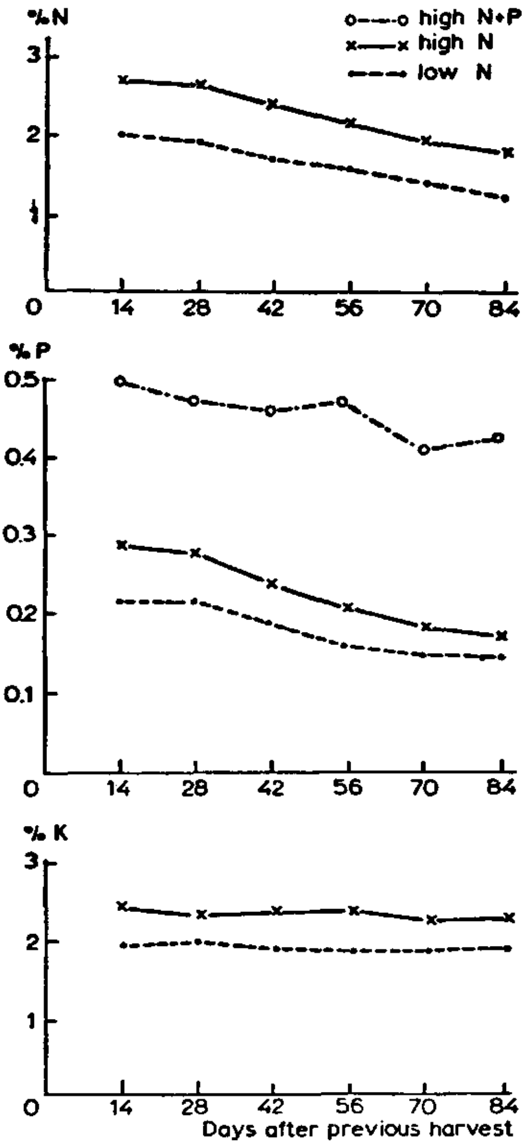


Fig. 5.5 Annual average tissue-NPK concentration of Rhodes grass in San Camilo in relation to the time after cutting.

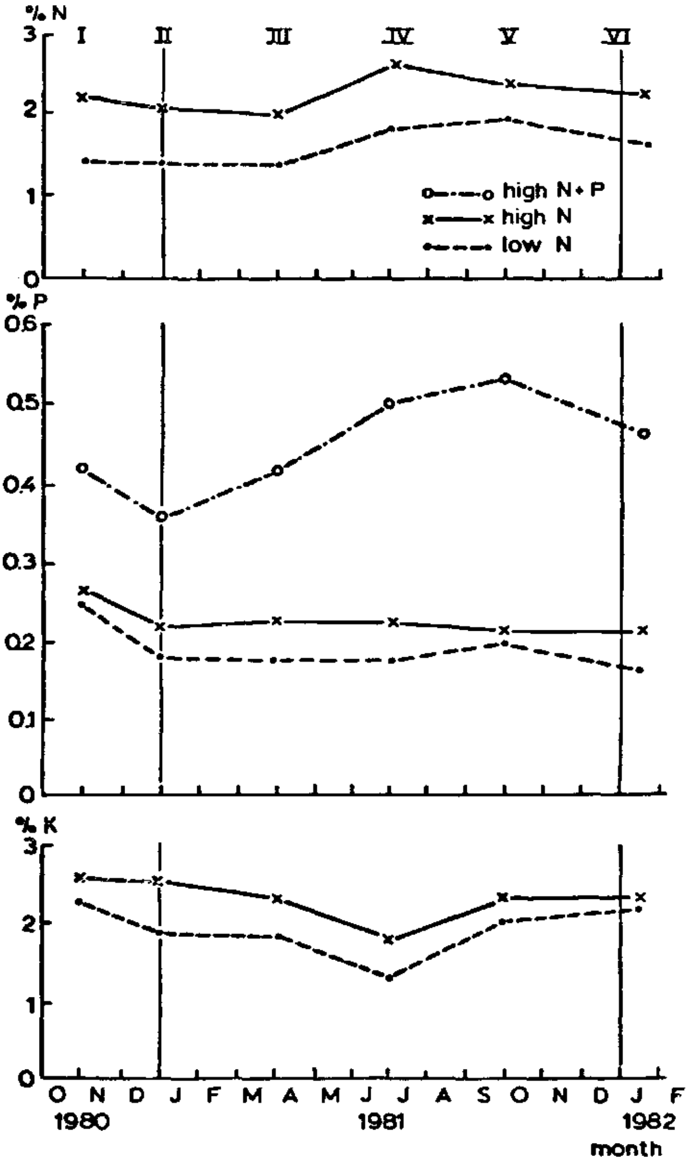


Fig. 5.6 Average tissue-NPK concentration per growth period (I - VI) during the course of the experiment in Rhodes grass grown in San Camilo (average of the six periodic harvests of a growth curve determination).

cutting schedule with a rapid start, but a short period of undisturbed linear growth, or with longer cutting intervals with longer continuous growth but also a long initial period of slow growth.

Under a fixed cutting schedule in Israel, yields of 30 and 20 to 25 t/ha.yr were obtained under experimental and commercial conditions, respectively (Kipnis & Dovrat, 1967; Dovrat & Arnon, 1971; Dovrat & Kipnis, 1981). These yields are about 80 and 60% of those obtained in growth curve experiments there. If similar ratios would apply to San Camilo, experimental and commercial yields of 35 and 25 t/ha.yr, respectively, can be estimated.

The absence of response to sub-soiling in Rhodes grass, contrary to the results for maize, is in agreement with data published elsewhere, reporting fairly large differences in sensitivity to mechanical soil resistance between plant species (Russell & Goss, 1974; Taylor & Ratliff, 1969).

5.3.2 *Fertilization aspects and nutrient concentration*

The proportionally higher response to N fertilization in the colder winter months when N demand is lowest, has also been observed in tropical grasslands in Africa (Van Keulen, personal communication). It could be that this unexpected response is related to an increased resistance to the injury of chloroplasts caused by low night temperatures, as reported for other tropical C_4 grasses (West; 1973; Section 6.4.1). One possibility is that this is the result of a more flexible structure of the chloroplasts, due to the high N availability, so that more starch can accumulate before damage occurs. Another possibility is that of a faster recovery when a large amount of N is available, mainly because of accelerated synthesis of new chloroplasts after low temperature damage (West, 1973).

An increased P and K concentration as a conseqence of high N fertilization is not commonly found. A dilution effect is frequently observed due to the higher growth rate, as found for P in our maize experiment and as reported by Salette (1970) for K. The increased P concentration due to the high N supply may be related to the increased protein concentration in the biomass. Penning de Vries & Van Keulen (1982) indicated the physiological and biochemical basis of the interrelationship of N and P, both being components of nucleic acids and their complementary presence in enzymatic processes in the active plant cell. They report that for most species the ratio of the weight of P to N in the tissue was never below 0.04 and never exceeded 0.15 g/g. In an optimally balanced situation the ratio was about 0.10. Hence, when the N concentration increases due to N fertilization, the P/N ratio tends to fall below the optimum and that induces additional P uptake by the crop to restore the optimum again, if P is available.

The over-fertilization with P, in combination with the high N fertilization, apparently created an unbalanced situation, as the P/N ratio increased up to 0.23. It seems that under surplus availability of P and N the crop was not able to correct this ratio by restricting either the P uptake or a further increase in the uptake of N. However, the dry matter production was not reduced by this unbalanced P/N ratio. In San Camilo high P/N ratios were also found in potentially growing potatoes and maize (September sowing), being 0.18 and 0.20, respectively. These results indicate that high P/N ratios under excess availability of both elements are probably not harmful and that the maximum P/N ratio of 0.15 found in the Sahel for non-leguminous crops (Penning de Vries & Van Keulen, 1982) is not generally applicable.

The K concentration in the above-ground dry matter also increased in the high N treatment. This may be explained by its function as a positive charge for counterbalancing organic and inorganic anions (Van Keulen & Van Heemst, 1982). In the San Camilo soils, N is mainly present in the form of NO_3^- (Versteeg et al., 1982). Hence, the strongly increased NO_3^- absorption at high N fertilization would be accompanied by a smaller, but significant increase in uptake of K^+ ions to maintain electro-neutrality in the plant tissue.

Because in these preliminary experiments no treatment without fertilizer applications was included, it is not possible to calculate the recovery of the N fertilizer and only the ratio between applied fertilizer-N and harvested herbage-N could be calculated. This shows that 79% of the low N and 56% of the high N application was recovered in the harvested dry matter. However, if winter fertilization and production is not taken into account, these percentages increase to 100% and 65% for the low and high N application, respectively. These values are comparable with the data on N fertilization and recovery by Bahia grass (*Paspalum notatum*) and Pangola grass (*Digitaria decumbens*) reported by Blue (1970), and higher than the figures for Rhodes grass given by Henzell (1971).

Under the continuous very high N fertilization regime, including the winter period, considerable quantities of N were not recovered in the herbage. In the sandy-stony soils of the region, probably most of that N percolated below the rooting zone. Similar leaching phenomena were also reported by Woldendorp et al. (1966) during periods of low pasture growth rates and by Prins et al. (1981) for excessive N fertilizations under temperate humid conditions, especially on sandy soils. However, Woldendorp et al. (1966) also estimated that during active growth periods, 15 to 20% of the NO_3^- present in the rhizosphere denitrified, even in well-aerated sandy soils.

Results of Blue (1970) in Florida and Prins (1983) in the Netherlands indicate that on permanent grassland, up to a certain N fertilization level, a situation can be created, in which the applied N is almost completely recovered in the herbage. In that situation, a very high fertilization efficiency is obtained, with minimal risk for herbage-NO_3 accumulation or environmental NO_3 pollution. Based on the estimate of a maximum Rhodes grass yield of 35 t/ha, with an N concentration of 2% at a nine weeks cutting interval in San Camilo, N fertilization should not exceed 700-750 kg/ha and should only be applied during the nine months of favourable growth conditions (August-April).

5.3.3 *Possibilities for Rhodes grass under San Camilo conditions*

The results obtained in San Camilo indicate that with a high N fertilization during the nine months with favourable conditions, very high yields can be obtained. The high N fertilization treatment (about 1000 kg N/ha, taking only into account the favourable period) increased dry matter production by nearly 40% and doubled the crude protein yield, compared with the low N level (350 kg N/ha during the same period). As suggested in the previous paragraph similar high dry matter yields may be obtained with lower N applications of about 700 to 800 kg N/ha.

The first indications about the quality of the Rhodes grass produced in San Camilo are encouraging. Van der Putten (unpublished results) found in vitro digestibility (Tilley & Terry, 1963) of 65 and 70% for Rhodes grass herbage of six and four weeks, respectively. The minimum crude protein concentration of tropical grasses at which voluntary intake by cattle is restricted, lies between 6.0 and 8.5% (Milford & Minsen, 1966), clearly below the levels obtained in Rhodes grass in San Camilo. However, additional herbage in the region is mainly needed during winter, when the productivity of Rhodes grass is also very low. Consequently, a qualitatively good, and for the local farmers acceptable conservation method (hay or silage) would be necessary. This, together with the rather high N fertilizer demand may limit rapid acceptance in the region.

Nevertheless, Rhodes grass shows some characteristics which could make it an attractive additional pasture species in the future. Firstly, the sward is very dense and its persistence excellent, without significant maintenance measures. The weed-controlling characteristics of the sward may be utilized in rotations with older alfalfa fields, while at the same time it can use the residual N left by the alfalfa. The second attractive characteristic is the high water-use efficiency of this tropical C_4 species, twice that of C_3 species such as alfalfa and rye-grass, due to the low transpiration coefficient (Valdivia & Zipori, 1982). Therefore, in periods when irrigation water is scarce and temperatures are favourable, as is often the case at the end of spring, more herbage could be produced with Rhodes grass than with any of the C_3 species, presently grown.

For the winter period, Rhodes grass hay or silage would have to compete mainly with maize silage (lower N demand but with annually recurring establishment costs) and in the future maybe also with fodder beet. The latter has shown a good potential in San Camilo, in winter as well as in summer, with similar N fertilizations as for maize while it can be harvested sequentially without the need for conservation. In addition, the energetic value is very high. On the other hand, the annually recurring establishment is very labour-intensive and the fodder may only be given in small daily portions (about 20 kg fresh fodder beets/d, substituting a maximum of 30% of the herbage ration) (Anon. 1980b).

In San Camilo so far, no experiments have been carried out with grass-legume mixtures. Compared to monocultures of Rhodes grass, mixtures with alfalfa have given significant yield increases under dryland conditions in South-East Queensland, when no N was applied (Christian & Shaw, 1952). In that study, it was emphasized that intermittent grazing was necessary to maintain the alfalfa component. Under irrigated conditions, yields of two other non N-fertilized tropical grasses were considerably improved when sown in companion with alfalfa ('t Mannetje, in Leach, 1978). However, the yield of the alfalfa component was only significantly improved by the grass contribution later in the summer, when temperatures were rather high for alfalfa. For the San Camilo conditions, the success of a mixture of Rhodes grass and alfalfa seems questionable, because the components are not complementary in seasonal growth, but both are growing best in summer and less in winter. Therefore, mixtures of alfalfa with temperate grass species that produce good in winter, seem more promising.

Many questions with respect to the possible use of Rhodes grass in practice still need to be answered, the most significant ones being concerned with cutting frequency, optimum N fertilization and water supply, forage conservation techniques, and behaviour of the sward under limited water supply. The possibility thus of this grass becoming an important herbage in the region exists, but only if the answers to the above questions turn out to be attractive.

5.4 MODELLING ACTIVITIES WITH RHODES GRASS

5.4.1 *Introduction*

The results of modelling activities with respect to Rhodes grass under the Mediterranean conditions in Israel have been published by Dayan & Dovrat (1977) and Dayan et al. (1981a, b). For potential dry matter

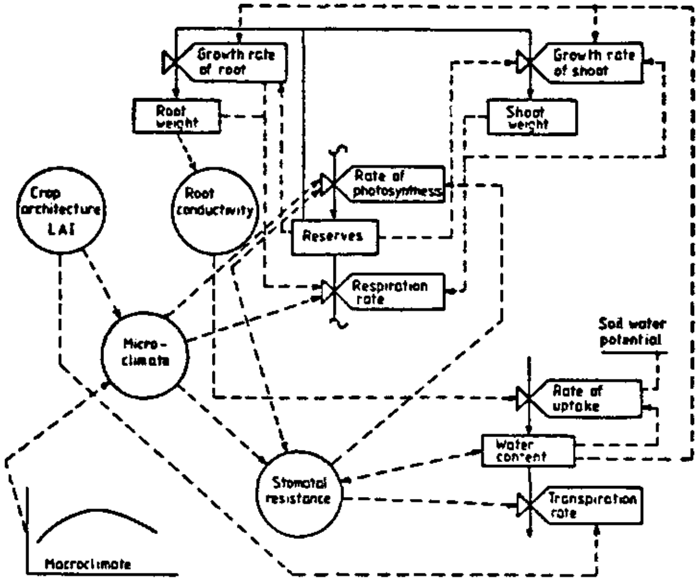


Fig. 5.7 **Simplified relational diagram of the simulation model BACROS.** Rectangles represent state variables; valves represent rates of change of the state variables; circles represent **intermediate or auxiliary variables or systems (from de Wit et al., 1978).**

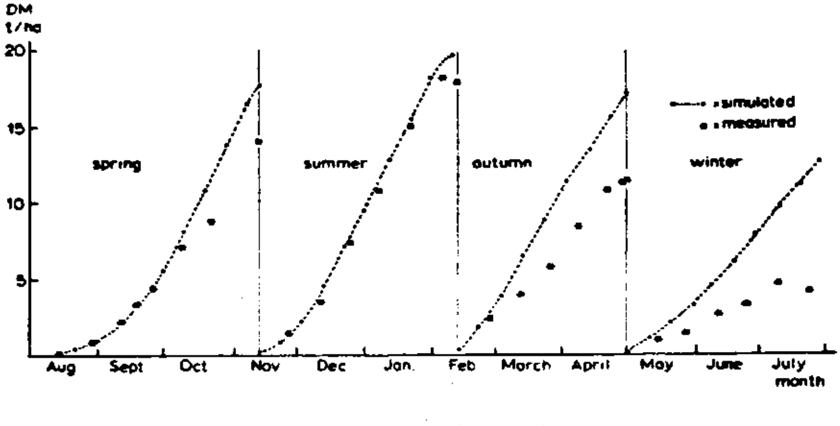


Fig. 5.8 Measured (*) and simulated (-------) growth of Rhodes grass in San Camilo, using the BACROS model.

production, use was made of the simulation model BACROS. Their results exhibit reasonably accurate predictions of above-ground dry matter production and water use, on the basis of crop-specific parameters, partly determined under controlled conditions, partly derived from field observations. Deviations from measured field data were largest during the initial growth stage, i.e. directly after cutting, and towards the end of the growth cycle. The deviations after regrowth were related to tiller dynamics and could be accounted for by using a descriptive model, simulating the tiller dynamics and growth of Rhodes grass after cutting (TILDYN; Dayan et al., 1981b).

These results created positive expectations with respect to extrapolation to comparable environments elsewhere. This was one of the reasons to carry out experiments with periodic harvests of Rhodes grass in the San Camilo environment. In this Section a comparison of the field data with simulation results obtained with BACROS is presented.

5.4.2 *Short description of the concepts of BACROS (Basic Crop Simulator)*

A summarized description of the version, published by De Wit et al. (1978), is given first. In the model BACROS the vegetative growth of a crop well supplied with water and nutrients is considered. In Fig. 5.7, a simplified relational diagram is given following the Forrester notation (Forrester, 1961); the rectangles represent the four state variables distinguished for the growing crop, i.e. the amounts of shoots, roots, reserves and the water content. The first three state variables define dry matter production, whereas the water content is important for the calculation of transpiration and water uptake of the crop. The valves represent the rates of change. These are the main processes responsible for changes in the state variables, such as the rates of photosynthesis, respiration and transpiration.They define ultimately how fast a crop grows. Calculation of these rates of change is fairly complicated as they are influenced by several components of the system and by environmental conditions outside the system. These components, the auxiliary variables, are represented by circles in the relational diagram. Phenomena outside the system, that influence the rates of change but are not affected by the processes within the system, are called forcing variables. In BACROS these are the weather conditions and the moisture status of the soil. Sometimes, other variables are introduced via independent functions that are not influenced by the behaviour of the system. In such cases these additional variables are used as forcing functions. The most important reason for such simplifications is that the principles underlying the functional relations are not sufficiently well known. One example in BACROS is the LAI, which is often introduced as a measured function.

The most important calculations can be summarized as follows: from the weather data obtained from standard meteorological stations, relevant micro-weather data are calculated, necessary for the computation of the rates of photosynthesis and transpiration of various leaf layers in the canopy. An important characteristic governing these rates is the stomatal resistance (Rs), varying according to stomatal opening (wide: low Rs) and closure (narrow: high Rs). In maize, stomatal opening is generally regulated by both the CO_2 concentration within the stomatal cavity, which is influenced by the photosynthetic activity, and the turgidity of the leaf, which is determined by its water content. As stomatal resistance plays a major role in both exchange processes, transpiration and photosynthesis are strongly interrelated.

Total respiration is calculated as the sum of maintenance respiration and growth respiration. The first is proportional to the dry weight and is calculated on the basis of the chemical composition of the crop. It is directly influenced by temperature with a factor 2.0 per 10 °C (Q_{10} of 2). On the other hand the growth respiration is only a function of the chemical composition of the growing material.

Partitioning of assimilates between roots and shoots is governed by a functional balance in the crop, influenced by its moisture status. This description favours allocation to the roots at the expense of the shoot when the plant suffers from water stress. The water status of the crop is determined by the balance between transpiration and water uptake. In the model, an instantaneous equilibrium between the two is assumed at each time interval. Water uptake by the roots is calculated from the root resistance, which is a function of the amount of roots, their age distribution and the soil temperature. If at any moment the transpirational demand, governed in first instance by evaporative demand and stomatal resistance, is higher than root water uptake, the water status of the plant (in terms of potential) is adjusted, to which the model reacts by an increase in R_s (closure of stomata). The higher R_s is maintained until transpiration and water uptake are in equilibrium, which results, as in reality, in a decrease of the photosynthesis.

5.4.3 *Some technical aspects of the BACROS computer program*

The total calculations of a normal run of one season of maize take about four minutes of computer time, when calculated in time steps of one hour.

Table 5.1 List of variables to be specified for the model BACROS. The variables in category 1 must always be provided. Those in category 2 must be added if specific experiments are simulated. The variables in category 3 are needed as supplementary data for accurate simulations (after Penning de Vries, 1982b).

Category	Plant	Meteorology	Various
1	C_3 or C_4 photosynthesis pathway; stomatal CO_2 regulation absent or not; width of leaves	daily values of global radiation, minimum and maximum temperatures, humidity and windspeed	Latitude, period of vegetative growth
2	LAI development and time course of dry matter production	-	-
3	effect of temperature on photosynthesis; relation between stomatal resistence and relative water content; plant height, data about the chemical composition	more accurate measurements of category 1 weather data; values of the constants used in the equation for long wave radiation	-

In Table 5.1 a list is given of the variables, that must be specified for the use of the BACROS model. For the San Camilo situation all the necessary variables were available, except for some of those in category 3. Because of the available experience with maize and Rhodes grass that was not considered a serious drawback for simulation of these crops.

5.4.4 *Simulation of potential growth of Rhodes grass*

5.4.4.1 Model adaptations

The major differences between the simulation for the Israeli and the San Camilo conditions was, that in the latter cases, leaf area was introduced in the model as a forcing function, rather than being calculated from simulated dry matter. This was also done in the validation studies with maize (De Wit et al., 1978; Section 6.5 below). The main reason is that the understanding of crop morphology in different environments is still rudimentary.

A second modification was the adaptation of the root resistance parameter (WCRR) to 2500 instead of 1200 (kg/ha)/(g (H_2O).bar.s.m^2) used in Israel. The reason was that in preliminary runs unrealistically high shoot/root ratios of about ten were simulated. Partly because of this, the simulated above-ground dry matter production and the linear growth rate were about 50% higher than those measured in the field. Moreover, in the Israeli study WCRR had been estimated by trial and error, on the basis of field data.

5.4.4.2 Results and discussion

A reasonable agreement between simulated and measured data was obtained for the summer period (November till February), when the highest temperatures occur, but during the colder period (May to July) simulated growth rates were more than twice the measured ones. In spring (August to November) and autumn (February to April) deviations were about 25 and 50% respectively (Fig. 5.8).

Evidently, the Rhodes grass simulations show major deviations when a well-developed canopy suffers from low night temperatures. In the summer period, minimum night temperatures are well above 10 °C and the agreement between experiment and simulation, using the parameter data from Israel, is encouraging. The deviations in the simulations for the periods with cold nights could well be the result of damage to the photosynthetic capacity of leaves of tropical grasses, as reported by Hilliard & West (1970) and West (1973). Consequently, such influence of low temperatures on photosynthetic performance must be incorporated in a simulation model, if realistic simulations for temperature-sensitive crops in many parts of the world are desired.

The Rhodes grass simulation in spring showed a better fit with the measured values than those for the autumn period. Two explanations for this phenomenon could be presented: firstly, low temperatures are less damaging in the early stages of growth, as many of the leaves still appear under more favourable conditions, and existing ones may show adaptation to the unfavourable conditions (De Wit et al., 1978); secondly, in the early stages of growth the production is largely determined by the intercepted energy which is a function of the leaf area. The latter was introduced as a forcing function in the model, and consequently part of the reduction in growth is being taken care of.

The simulation trial showed that the model BACROS, as applied to Rhodes grass in Israel, is still not reliable for growth predictions of the crop in other environments, not even when LAI is introduced as a forcing function. This is partly due to weak parameters, such as the root resistance (WCRR), about which no firmly established knowledge is available at present. However, careful examination of the simulation results on the basis of field evidence, may correct this type of shortcomings to some extent, for example when unrealistic results are obtained such as too high shoot/root ratios. On the other hand, the predictions were unrealistic because the model does not take into account some basic proporties, such as the susceptibility of Rhodes grass to low night temperatures, which is never a problem during the growing season in Israel. As a result, the prospects for Rhodes grass in winter in San Camilo seemed very attractive when judging the simulation results, whereas the actual production was clearly disappointing. Hence, it may be concluded that simulation models like BACROS only have a limited reliability for prediction of the potential growth of specific crops in different environments of the world with the aim of introducing new species and/or cultivars. Properly executed experiments will always be a pre-requisite before drawing any conclusions. Simulation models may help to interpret experimental results and highlight aspects that otherwise would have been overlooked.

6 *GROWTH DYNAMICS AND AGRONOMY OF MAIZE*

6.1 INTRODUCTION

Maize is the most important C_4 crop in the La Joya area and is used as a rotation crop after alfalfa. This was one of the reasons for studying it in some detail. In addition, it was used extensively for the development of the comprehensive simulation model BACROS (De Wit et al., 1978) and the data sets from Peru might therefore also be useful for further testing and improvement.

Three experiments were carried out. The first one to obtain a picture of the potential growth pattern of the crop, with emphasis on N and K fertilization. The second one to obtain data about the water balance of the crop in San Camilo. Because initial growth had been rather slow in the first experiment, it was decided to postpone sowing of the second one until November to observe a possible influence of the higher temperatures in that period and to include a high plant density treatment. The first sowing in this second experiment failed because of a severe insect attack. The field was, therefore, ploughed and resown in January 1981. This provided information about the growth behaviour of maize when exposed to the cold temperatures of April and May, during the later stages of development. In this report, only the growth of maize under the control irrigation treatment will be presented. The results of the other treatments in relation to the water balance of the crop are discussed elsewhere (Valdivia et al., 1982).

A third maize experiment was sown in November 1981 to obtain more detailed information on growth during the first 100 days. For that purpose two fields were sown at the same time, one under the pampa conditions of San Camilo at 1300 m a.s.l. and another in the nearby Tambo valley at 30 m a.s.l. Because of the difference in altitude there is a significant temperature difference. Compared with San Camilo, in Tambo the average minimum was 6 °C higher at 18 °C and the average maximum temperature was 8.5 °C higher at 35 °C during the experimental period. Consequently, the two experiments provided better insight in the influence of temperature, especially during initial development. A complication arose from the difference in soil type. Optimal nutrients and water were supplied at both sites to minimize a specific soil effect and in San Camilo check plots were also installed with soil originating from the Tambo valley. Different cultivars and sowing depths were also investigated.

Apart from these three main experiments, some additional field and pot trials were carried out, to obtain preliminary data on specific growth factors or to obtain more precise data about phenomena observed in the field.

6.2 METHODS

In the following sub-sections the methodology of the different maize experiments is described. N, P and K were applied as urea, triple superphosphate and potassium sulphate and rates are expressed in kg pure element per hectare.

6.2.1 *Experiment M 1. N x K fertilization experiment*

This experiment was established on September 19th 1979 in a sandy field after four years of alfalfa. The field was sown with the Peruvian hybrid PM 210 at a plant density of 0.80 x 0.20 m (62500 plants/ha). N and K were each applied at 0, 250 and 500 kg/ha in a 3 x 3 completely randomized factorial block design with four replicates. Plot size was 4 m x 12 m. The field was ploughed after sub-soiling and at the same time P was incorporated at a rate of 92 kg/ha. Before sowing, 1/3 of the N and 2/3 of the K were applied. A second application of the remaining 1/3 of the K, another 1/3 of the N and 33 kg of P was given just before earthing-up on day 50 after sowing, when the maize was about 40 cm high. The remaining N was applied on day 110. Another earthing-up was carried out on day 100. By mistake, block I was situated in a part of the field that had not been sub-soiled and had previously a different rotation.

At final harvest, after 159 days, a net area of 12.5 m^2 was cut. To determine a growth curve, four intermediate harvests of 0.4 m x 4.0 m strips perpendicular to the plant rows (10 plants) were also taken at 42, 75, 106 and 134 days after sowing. The location of the strips within each plot was chosen at random.

At each sampling, the fresh weight was determined, several plants were chopped by a power chopper and a sub-sample of ca. 1 kg taken for drying at 70 °C, to determine the dry matter content. Subsequently, the sub-sample was ground to determine the N, P and K concentration of the whole plant, according to the methods indicated in Section 2.4.

For determination of LAI, one representative plant of each sample was selected and its green leaf blades measured individually according to the method described in Section 2.4.

During the first 10 days, a daily sprinkling irrigation of 10 mm was given to ensure proper germination and emergence. From that moment onwards the field was irrigated according to pan evaporation, using a k_{pan} = 1.0. At first, water was applied every two days, but this frequency was gradually decreased to weekly applications from 35 days after sowing. Over the whole growth period 1333 mm of water was given.

6.2.2 *Experiment M 2. Irrigation experiment with two planting densities*

The experimental methods for this experiment were identical to those described for experiment M 1, except that the field had been under alfalfa one year less. The experiment was sown on January 12th 1981.

As a consequence of the results of experiment M 1, K was not supplied. Phosphorus was incorporated with the disking at a rate of 79 kg/ha and 400 kg N/ha was applied using a fertilizer pump that injected the fertilizer into the irrigation water during sprinkling. In total, seven dressings were carried out at fortnightly intervals, starting 21 days after sowing. The first three N applications were 40 kg/ha each, followed by four applications of 70 kg/ha.

Because no seed was available of PM 210, used in experiment M 1, a similar hybrid, PM 205, was used.

The design was a split-plot with five complete blocks; main plots were five irrigation treatments, sub-divided into two equal sub-plots for high (200 000 plants/ha, spacing 0.50 m x 0.10 m) and low (50 000 plants/ha, spacing 1.00 m x 0.20 m) densities. Sub-plot size was 6.0 m x 12.0 m, of which 5 strips of 2.5 m^2 each were reserved for periodic harvests 44, 65, 86, 107 and 142 days after sowing. The location of each periodic harvest within a given sub-plot was chosen at random. Sampling was carried out as described for experiment M-1. During the first 20 days, the whole experiment received a daily irrigation of 10 mm for establishment. After that, the experiment was sprinkler-irrigated weekly. Only the results of the treatment irrigated according to a constant k_{pan} = 0.8, are given (see Section 6.1). A total of 743 mm water was given.

6.2.3 *Experiment M 3. Effect of temperature*

This experiment was sown on November 18th 1981 in San Camilo and the following day in the warmer Tambo valley. All other activities and measurements in Tambo were carried out one day later than in San Camilo, with the exception of the final harvest that took place 18 days earlier. On both sites, a spacing of 1.00 m x 0.125 m or a density of 80 000 plants/ha was used. Soil preparation was as described for the previous experiments. In San Camilo, the experiment was sown in the field of the irrigation experiment (M 2) that had been fallow for six months. In Tambo, the field had been under maize until just prior to the start of this experiment.

At both sites, 160 kg P/ha was incorporated with the disking. In San Camilo, 360 kg N and 635 kg K/ha were supplied via the trickle irrigation system at intervals of 6 days, starting on day 15 from sowing. Per application, 5.6 kg/ha N and K were supplied until day 57 and subsequently 21 kg N/ha and 43 kg K/ha until day 135. In Tambo, 150 kg K/ha was broadcast just before sowing and 250 kg N/ha was applied in three equal portions: before sowing, on days 47 and 82.

On both sites, a 2 x 3 factorial design in completely randomised blocks was used, four blocks in San Camilo and five in Tambo. Treatments were the three cultivars PM 205 (Peruvian), NY 806 (Israeli) and Anko (Dutch), each sown at two depths of 2 and 5 cm, respectively. Plot size was 5.0 m x 5.0 m, in which five strips of 2.0 m^2 (0.67 m x 3.0 m) each were used for periodic harvests 33, 47, 63, 82 and 103 days after sowing. The location for each periodic harvest within a given plot was chosen randomly. After these harvests no more space was left within the net area for exact measurement of the final yield. Therefore, these were estimated in Tambo on day 131 from the neighbouring cultivar trial (see 6.2.4) and in San Camilo on day 149 from the left-over plants.

At each sampling, measurements were carried out as described for the previous experiments.

To test the possible influences of differences in soil type between the two sites, a truckload of Tambo clay loam was incorporated in the maize rows in four additional check plots in San Camilo in furrows with a cross section of 0.25 m x 0.25 m.

The field in San Camilo was drip-irrigated every three days on the basis of a $k_{pan} = 0.8$, after an establishment phase of 15 days with a daily irrigation of 10 mm via sprinkling. A total of 910 mm water was applied. In Tambo, the water was supplied to the field via gravity in furrows along the maize rows, for one hour at intervals of ten days. These practices ensured that, sufficient water was applied to both sites and no aeration problems occurred.

6.2.4 *Additional trials*

Additional trials were carried out with two objectives. The first was to study specific factors that could be investigated later, if they showed a significant effect. These were:

- cultivar trials, adjacent to experiments M 1 and M 2, with Peruvian, Israeli and Dutch hybrids. Sowing was on the same day or one day later than the neighbouring main experiment.
- a trial with four different soil treatments parallel with experiment M 2 : (1) incorporation of 50 ton/ha of manure, (2) incorporation of 15 ton/ha fresh alfalfa forage, (3) methyl bromide soil disinfection and (4) check without treatment.

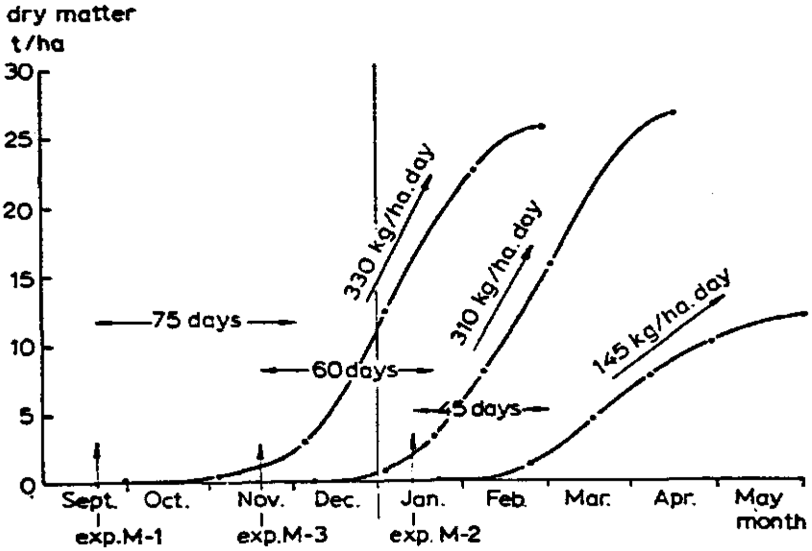


Fig. 6.1 Time course of dry matter accumulation for three maize experiments in San Camilo for different sowing dates (exp.M-1:18/9/79; exp.M-2: 12/01/81; exp. M-3: 18/11/81). Horizontal arrows indicate period after sowing necessary to reach linear growth stage.

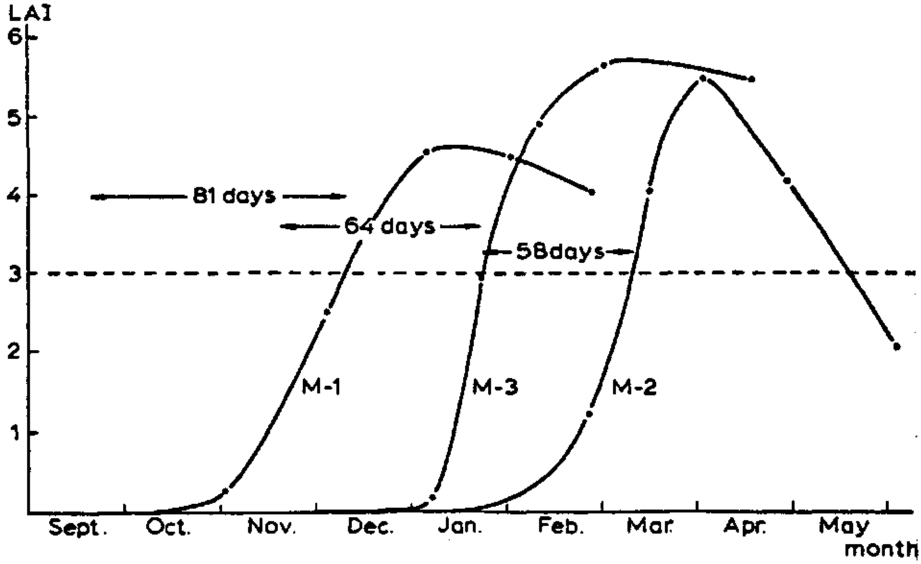


Fig. 6.2 Time course of LAI of maize in San Camilo from different sowing dates (see Fig. 6.1). Horizontal arrows indicate period from sowing to LAI of three.

- some plots in the border area of experiment M 1, with and without extra P (250 kg P/ha).

None of these trials produced results that required further investigations.

The second objective was a more detailed investigation of certain phenomena observed in the field. For maize there was one example: because of irregular growth at the beginning of experiment M 1, the soil from spots with poorly growing maize was sampled to test for deficiencies in elements other than NPK. After mixing the soil, 44 pots were filled, sown with maize (thinning to one plant per pot) and irrigated with different nutrient solutions, each having all but one nutrient elements. In this way 11 treatments were obtained: -Ca, -Mg, -S, -Fe, -Mn, -Zn, -Cu, -B, -Mo and two check treatments, one with all the elements and the other with none. This trial produced no indication of a particular deficiency. Later on, it turned out that this irregular pattern always disappeared at a later growth stage and that careful sowing at equal depth resulted in a more regular first development.

6.3 RESULTS

6.3.1 *Aerial growth*

6.3.1.1 Growth curves in San Camilo

Overall production of above-ground biomass of maize, well supplied with water and nutrients on sub-soiled fields, as measured in San Camilo in the three experiments between 1979 and 1982, is presented in Fig. 6.1. The maize, sown in spring (M 1) and early summer (M 3) showed high maximum growth rates of over 300 kg/ha.d for a period of about two months and reached a total amount of above-ground dry matter of 26 t/ha. The maize sown in mid-summer (M 2) had a lower growth rate of 145 kg/ha.d and a total dry matter production of 10.7 t/ha.

The period from sowing until the start of linear growth (hence germination and the exponential growth stage) covered about 75, 60 and 45 days for the experiments sown in September, November and January, respectively.

In Fig. 6.2, the time course of LAI is presented, with an indication of the period from sowing until the attainment of a LAI of three. Further, a rapid decline in LAI in experiment M 2 can be observed during the last two months, corresponding with the period of low linear growth rates in Fig. 6.1.

6.3.1.2 The influence of plant density

In Fig. 6.3 growth curves are compared for a high plant density (200 000 plants/ha) and a low plant density (50 000 plants/ha) of maize, sown in January (mid-summer), for both a tall, mid-late hybrid (PM 205, fig. 6.3a) and a short, early hybrid (PM 701, Fig. 6.3b). The densely sown field showed a higher initial growth rate than that with the low density, especially for the hybrid PM 701. During the grain-filling stage most of the difference disappeared, largely because of lodging. Eventually, the final dry matter production of the robust hybrid PM 205, sown at low density, was almost the same as that of the densely sown short hybrid PM 701 and was higher than either PM 701, sown at low density, or PM 205 at high density.

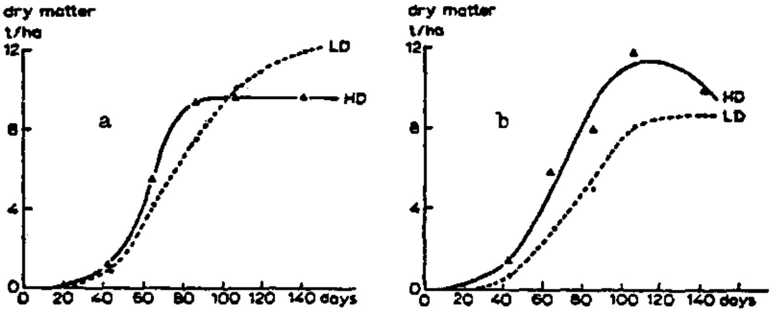


Fig. 6.3 Growth curves of maize cv.PM 205 (a) and cv.PM 701 (b) sown at high (HD: 200 000 pl/ha) and low (LD: 50 000 pl/ha) plant density.

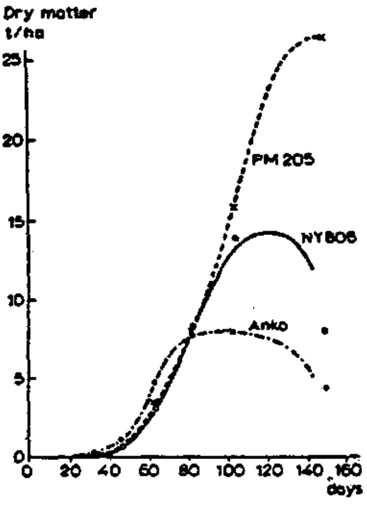


Fig. 6.4

Growth curves of maize cv.PM 205, cv.Anko and cv.NY 806 in San Camilo

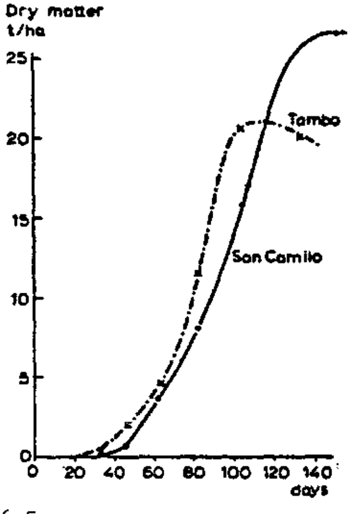


Fig. 6.5

Growth curves of maize cv.PM 205 in Tambo (alt.30 m) and in San Camilo (alt. 1400 m).

6.3.1.3 Cultivar differences

In Fig. 6.4, the growth in San Camilo of PM 205 is compared with the early Israeli hybrid NY 806 and the cold-tolerant Dutch hybrid Anko. Early growth of Anko was somewhat faster than that of the other hybrids till about two months after sowing. Anko then started flowering and development was completed at about day 100, with a very low production level of about 8 t/ha, compared to a production of 26 t/ha for the Peruvian hybrid. The Israeli hybrid showed almost the same initial growth rate as the Peruvian hybrid, but flowered and finished its development earlier and at a much lower production level of 14 t/ha.

6.3.1.4 The influence of altitude

Maize had a somewhat higher growth rate in the warmer Tambo valley than in San Camilo, but that was associated with earlier maturity resulting in a lower total production of 20 t/ha (Fig. 6.5). The faster initial growth in Tambo was particularly evident from the increase in the length of the plants, measured from soil to the final point of the lifted upper leaf. The relation between plant height and dry weight during the exponential growth stage was distinctly different for Tambo and San Camilo (Fig. 6.6). However, at both sites relation was similar for all three cultivars, despite their very different growth behaviour in general.

The higher initial growth rate of maize in Tambo was confounded with an effect of the different soil types that appeared to be of significance (Section 6.3.1.6).

6.3.1.5 The influence of sub-soiling

The absence of sub-soiling in block I in the fertilization experiment (M 1), resulted in a distinctly lower linear growth rate in the N-fertilized treatments of that block (330 vs. 175 kg/ha.d) and the exponential growth stage was also unfavourably affected. That resulted in a 40% reduction in the final dry matter production from 26.6 to 17.4 t/ha (Fig. 6.7). Concurrently rooting depth was reduced from 70 to about 35 cm. The effect of sub-soiling, however, was confounded with the effect of a different previous crop, i.e. barley instead of alfalfa. That resulted in an even more pronounced lower growth rate and final dry matter yield in the N_0 treatment of block I compared to the other blocks, i.e. 245 vs. 110 kg/ha.d and 22.2 vs. 8.7 t/ha, respectively.

6.3.1.6 The effect of soil type

The check-plots in experiment M 3 in San Camilo, with clay loam soil from Tambo in furrows in the plant rows showed a dramatically higher maximum growth rate during the linear growth stage than the other plots (300 kg/ha.d vs. 500 kg/ha.d). Growth during the exponential stage was also distinctly better (Fig. 6.8). This resulted in a total of 36.2 instead of 26.3 t/ha. Table 6.1 shows that there were no significant differences in the concentrations of macro- and micro-nutrients in the plants. The concentrations in plants grown in the furrows with Tambo soil were generally slightly lower than those in plants grown in the local soil.

Plant water potential, measured with a Scholander pressure bomb just before irrigation, was -1.69 ± 0.17 MPa (average and standard deviation) for plants growing in Tambo soil and -1.91 ± 0.30 MPa for maize in the normal pampa soil. The difference was weakly significant ($P < 0.10$). After irrigation, no differences could be detected in plant water potential.

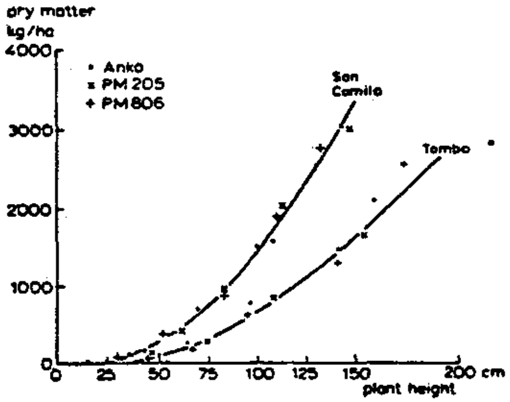


Fig. 6.6
Relation between dry matter yield and plant height of different maize cultivars in San Camilo and in Tambo, during the first two months after sowing.

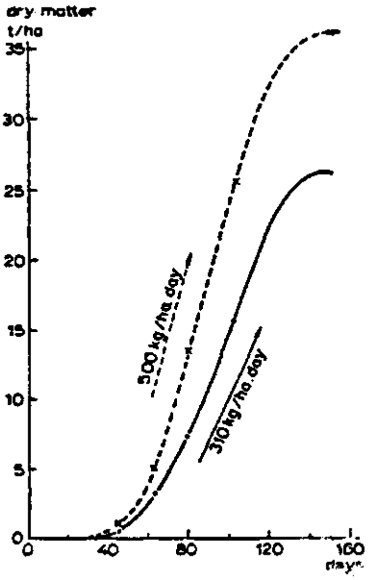


Fig. 6.8

Growth curves of trickle irrigated maize cv.PM 205 in two different soils in San Camilo. •——•: normal pampa soil: x- - -x: incorporation of Tambo clay loam in the plant rows.

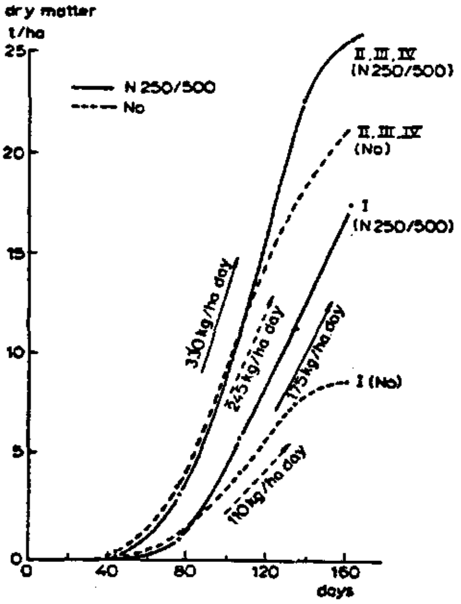


Fig. 6.7

Growth curves of maize cv.PM 210 at different levels of N in blocks with different rotations and soil preparation in San Camilo.
Blocks II,III,IV: subsoiled after alfalfa:
Block I : non-subsoiled after barley.

Examination of several profiles showed that in the furrows filled with Tambo clay loam more fine white roots were present. In the pampa soil, the root system was less dense, the fine roots appeared more yellowish and looked more lignified.

Table 6.1 Macro- and micro-nutrient concentration in maize cv. PM 205, grown in the pampa soil of San Camilo (S.C.) and in furrows filled with Tambo clay loam (T) at the San Camilo experiment station, on different sampling dates.

Sampling date:	21/12		6/1		20/1		11/2		4/3	
Nutrient	S.C.	T	S.C.	T	S.C.	T	S.C.	T	S.C.	T
N g/kg	36.1	38.1	28.9	27.9	18.7	16.1	13.2	12.8	12.4	12.6
P g/kg	5.4	5.0	4.4	3.7	3.5	2.8	2.3	2.0	2.2	1.9
K g/kg	43.4	47.8	45.8	49.6	38.2	34.3	28.0	28.9	16.6	18.7
Mg g/kg	3.9	3.0	3.4	2.8	2.9	2.3	2.2	2.2	2.5	1.9
Ca g/kg	6.3	5.5	4.7	4.6	3.8	3.7	3.3	3.1	3.3	2.9
S g/kg	3.4	3.6	2.8	2.5	2.0	2.0	1.7	1.8	1.8	1.6
Fe mg/kg	6.2	5.0	3.4	2.5	3.6	2.3	3.5	1.9	1.9	2.2
Mn mg/kg	100.6	83.7	78.2	63.2	49.5	43.4	42.8	37.4	30.8	32.6
Zn mg/kg	27.0	41.9	24.6	27.1	20.5	21.3	13.0	17.2	14.2	16.5
Cu mg/kg	13.2	11.8	11.0	8.6	6.7	6.0	5.8	5.2	5.4	5.2
Co mg/kg	0.1	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.1	0.0
Mo mg/kg	1.7	1.9	1.6	1.7	1.6	1.4	1.1	1.1	1.3	1.0

6.3.2 *NPK uptake and yield responses*

6.3.2.1 Nitrogen

The pattern of N uptake and dry matter accumulation in maize from different experiments in San Camilo and in Tambo is presented in Figs. 6.9 and 6.10. In almost all situations, ample N fertilizer (between 250 and 500 kg N/ha) was applied, with the exception of the N_0 plots in experiment M 1 (Fig. 6.9b,e), where no N had been given. To facilitate comparison, dry matter accumulation and N uptake are presented in the same graph at a relative scale of 100 kg dry matter to 1 kg N taken up. This presentation shows that in most situations the two lines run parallel during the linear growth stage. Hence, in these experiments N was taken up at a rate of about 1% of the dry matter growth rate during most of the growing period. However, the N uptake line preceeds the dry matter accumulation line in time, reflecting the higher N concentration in the young tissue. In these situations no significant yield differences between fertilizer application rates of 250 and 500 kg N/ha were observed. In two cases where maize growth was limited by factors other than N, the N uptake during the linear growth stage exceeded the value of 1% of the dry matter accumulation rate (Fig. 6.9a, growth curve from January-sown maize and Fig. 6.10f when irrigation was limiting). However, without N fertilizer, the N uptake rate was lower than 1% of the dry matter accumulation rate during the second half of the linear growth period resulting in significant yield reductions (Fig. 6.9b,e). Compared to N-fertilized maize that decrease was about 17% when grown after alfalfa (Figs. 6.9b,c), but three times higher after barley (Figs. 6.9d and e).

Another feature shown in several situations was that the crop was losing N at the end of the growing period, presumably because of leaf loss (Fig. 6.9a the January sowing and in Fig. 6.10 all situations except d).

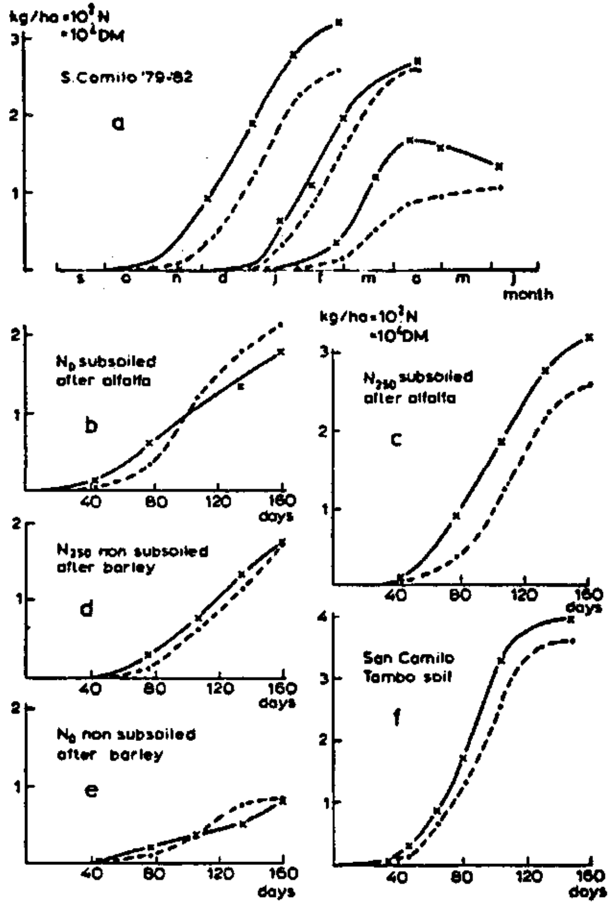


Fig. 6.9

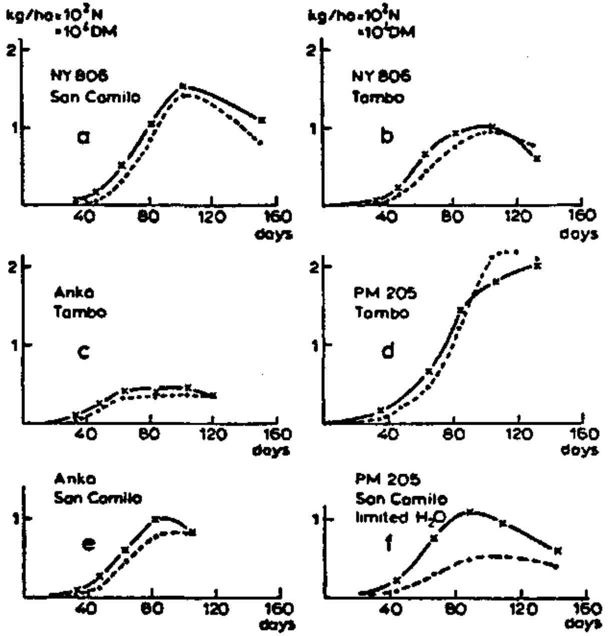


Fig. 6.10

N uptake (x———x) and dry matter production (•-----•) of maize cv.PM 205/210 (Fig. 6.9) and other varieties (Fig. 6.10) in San Camilo and in Tambo.

6.3.2.2 Phosphorus

In Figs. 6.11 and 6.12 the uptake pattern of P in maize in our experiments is compared with dry matter accumulation on a scale of 500 kg dry matter: 1 kg P taken up. In the situations presented in Figs. 6.12a and b, no P fertilizer was applied; the other data refer to maize that had been fertilized with 80-250 kg P/ha. In most situations, the uptake line runs parallel to the line of dry matter accumulation during the linear growth stage, hence P was taken up at about 0.2% of the dry matter accumulation rate. In the P_0 situations (Figs. 6.12a and b) and with PM 205 in Tambo (Fig. 6.11b) P uptake proceeded at a lower rate of 0.16% of the dry matter accumulation rate, but the corresponding productions were not lower than in the plots that had received 250 kg P/ha in the same field (Figs. 6.12c and d). In some cases, the crop loses P at the end of the growing period, presumably because of leaf loss.

6.3.2.3 Potassium

The K uptake pattern, for the different experiments in San Camilo and Tambo, is compared with dry matter accumulation at a scale of 50 kg dry matter: 1 kg K taken up in Figs. 6.13 and 6.14. In most of the experiments both lines run about parallel during the first half of the growing period, so that during that stage uptake was about 2% of the dry matter accumulation rate. In the experiments sown in January (Figs. 6.13a and 6.14f) the K uptake rate was about 3% of the corresponding dry matter accumulation rate. During the second half of the growing period the uptake rate always decreased very rapidly to zero and was followed in most experiments by loss of K from the above-ground material. This phenomenon was also observed in experiments where almost no loss of leaves occurred (Figs. 6.13a - first two curves -, b, c, e and Fig. 6.14a and b). The K concentration of the tissue at the final harvest was never below 1%. In the K_0 treatments of the fertilization experiment, no differences were found in either K uptake, or dry matter production, compared with the treatments that received 250 or 500 kg K/ha.

6.4 DISCUSSION

From the results presented in Section 6.3, the following conclusions may be drawn:

- In San Camilo, high maize yields were obtained from sowings in September and November, although the September sowing exhibited a very slow initial growth. In contrast, the January-sown maize showed fast growth in the beginning but was unfavourably affected in April and May during the second half of the linear growth stage. That resulted in a low final yield.
- In the warmer Tambo valley the initial and linear growth rates were higher than in San Camilo. However, phenological development was also accelerated, which ultimately resulted in less dry matter than in San Camilo.
- Soil structure and soil type strongly affected maize growth, in spite of an optimum supply of water and nutrients and the absence of pests, diseases and weeds.
- The use of cold-tolerant hybrids from northern Europe and high planting densities shortened the initial growth stage somewhat, but that often resulted in a significantly lower final production.

- Under all conditions, N fertilization was necessary for maximum maize production, but following an alfalfa crop the response was significantly lower than following barley.
- The natural supply of both P and K was sufficient in San Camilo.

These conclusions are discussed in the following Sections.

6.4.1 *Growth behaviour in different periods in San Camilo*

The relatively poor growth and the associated low yield of the January-sown maize, is a common feature in the San Camilo region for maize that is still in the field during the colder months of the year (April to September). Low temperatures are generally considered the main cause.

In a review article on the effects of low temperatures on maize growth, Miedema (1982) distinguished the following types of temperature influence:

1. freezing injury;
2. chilling injury (damage from low non-freezing temperatures between 0 and 12 °C);
3. growth at sub-optimal temperatures above the injury threshold of 12 °C.

In Table 6.2 the minimum, mean and maximum temperatures during the three maize experiments are given, averaged over the whole growth cycle, the first five weeks after emergence and the period of linear growth. For each of these periods the number of rather cold nights (below 10 °C) are also presented. Freezing temperatures were not recorded in San Camilo and the average temperature during daytime did not vary much. Therefore chilling injury due to low night temperatures seems most probable.

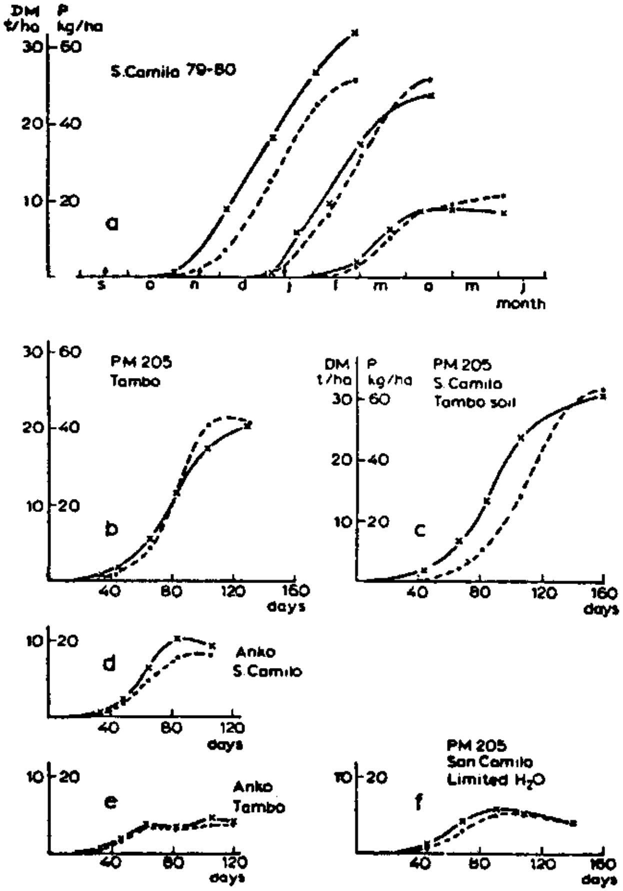
Table 6.2 Average minimum, maximum and mean temperatures from different growth periods of 3 maize experiments in San Camilo

Sowing date	50 days after sowing			60 days linear growth stage			total growth period			number of nights < 10 °C	
	min.	mean	max.	min.	mean	max.	min.	mean	max.	during 50 days after sowing	during linear growth
September 10	8.5	17.4	26.3	12.5	19.9	27.3	10.7	18.9	27.0	33	3
November 19	11.2	19.5	27.8	13.1	20.4	27.8	11.2	20.7	27.6	11	0
January 12	13.8	21.0	28.2	10.2	18.7	27.2	11.7	19.6	27.4	0	28

Two of the observed phenomena seem to be related to the number of cold nights. Firstly, the slow initial growth of the maize sown in September coincides with a high number of cold nights during the first 50 days after sowing. On the other hand, the low linear growth rate for the maize sown in January coincides with a high number of cold nights during that period.

The lower temperatures in San Camilo in the spring (September) did not produce the chlorotic seedlings characteristic for cold spring months in temperate regions. Miedema (1982) reports evidence that the latter was caused by low temperatures (10 °C) during daytime. Such temperatures during the night, produced green seedlings with a normal chlorophyll content.

Similar damage as observed in San Camilo has also been reported for other "thermophilic" crops. Tailor and Rowley (1971) reported that in young plants raised in a glasshouse, the photosynthetic rate in leaves of the C_4 species maize, sorghum and Pennisetum dropped instantaneously when temperature was lowered from 25 °C to 10 °C and upon restoration of the temperature to 25 °C,



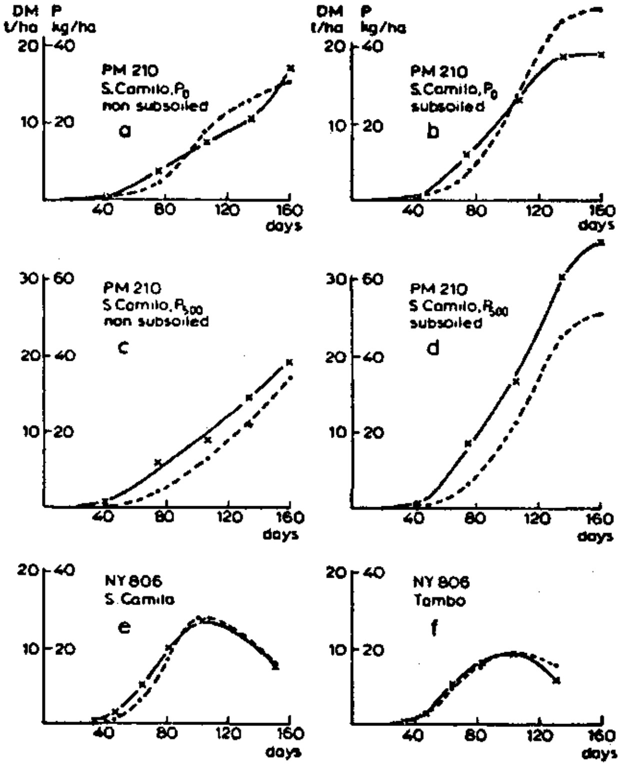


Fig. 6.12

Fig. 6.11

P uptake (x——x) and dry matter production (•-----•) of maize in San Camilo and in Tambo.

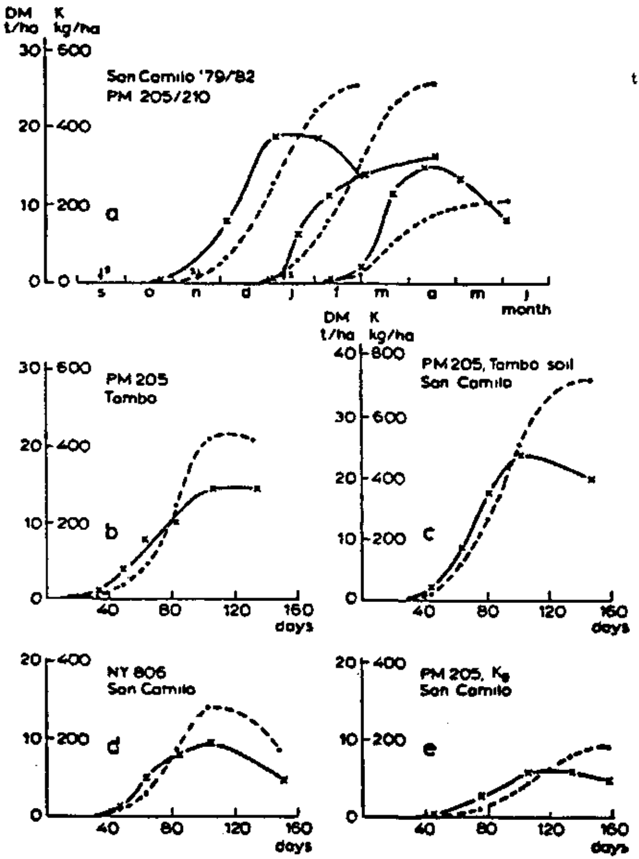


Fig. 6.13

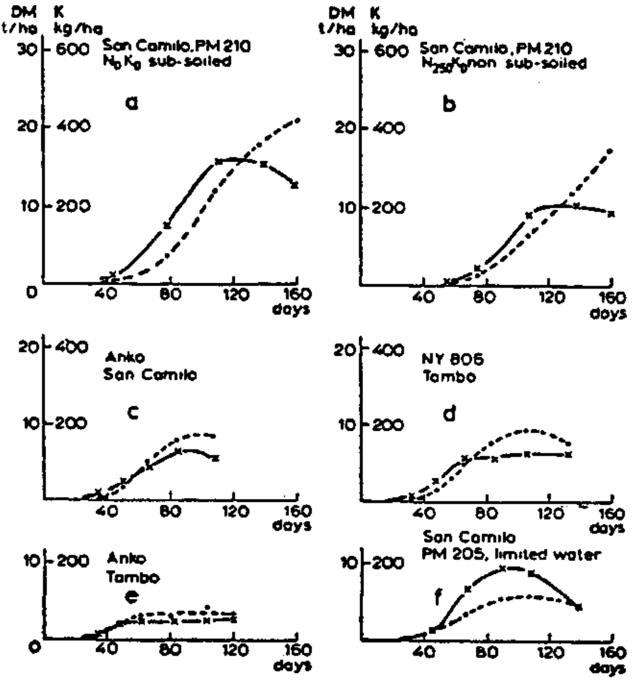


Fig 6.14

K uptake (x———x) and dry matter production (•- - - -•) of maize in San Camilo and in Tambo.

the photosynthetic rate recovered only to a very limited extent. A similar damage developing more slowly was also observed in soybean, a legume (C_3) adapted to warm climates. The degree of damage increased with both light intensity and the length of the period leaves were at 10 °C, but varied among species, maize and sorghum being most sensitive. Also Scott (1970) reported a rapid drop in photosynthesis and a slower but continuing decrease to virtually zero levels for maize, when the temperature was lowered from 20 °C to 2 °C. When the plants were returned to 20 °C they showed a brief return to measurable levels of CO_2 uptake before falling again to below measurable levels.

Taylor & Graigh (1971) found that low temperature damage of sorghum was reflected by ultra-structural changes and swelling of the mesophyll chloroplasts. When only the night temperature dropped to 10 °C, the most striking phenomenon was that at of a pronounced increase of starch grains in the chloroplasts. That phenomenon was also reported by Hilliard and West (1970) and West (1973), working with the tropical (C_4) grasses *Digitaria decumbens, Pennisetum typhoides* and *Eragrostis curvula.*

West (1973) reported that low night temperatures caused more permanent damage than low day temperatures. After a pre-treatment of two weeks at 10 °C at night the photosynthesis had been decreased to half the initial rate, after that the night temperatures were restored to the original level (25 °C). Accumulation of starch in the mesophyll chloroplasts caused the injury, resulting in a 50% reduction in the Hill reaction. In contrast, the reverse treatment (day 10 °C, night 30 °C) depressed dry matter production only during the treatment period, but photosynthesis was completely restored afterwards. These results suggest, that after a clear day a certain minimum night temperature is required to prevent accumulation of starch.

In cold-tolerant selections of some C-4 grasses starch accumulation in the chloroplasts did not occur during colder nights (West, 1973). That observation is in agreement with the phenomenon of consistently higher (about 25%) respiration rate in a relatively cold-tolerant grain sorghum, compared to a sensitive type, reported by Eastin et al. (1976).

The processes described so far could be at the basis of the suggested correlation between the number of cold nights and both the low linear growth rate in the January-sown experiment or the slow initial growth in the September-sown experiment. In contrast to the former, the maize in the latter experiment recovered and achieved a high production, presumably because many leaves appeared after the period of cold nights and showed normal photosynthetic behaviour. In that respect, Tailor & Graigh (1971) observed practically no changes in the chloroplasts of the mesophyll at the lower side of the leaves, if that was not fully exposed to the light. However, when that side was also completely illuminated by turning it upside down, the damage was similar to that of the upper side.

The cold nights during the January-sown experiment, occurred when all productive leaves were exposed to high irradiance during daytime and no more new leaves were formed. In addition, the meteorological conditions did not improve afterwards. Therefore, the photosynthetic mechanism could not recover and its capacity was permanently lower.

The different reaction of maize submitted to low night temperatures from the very beginning, compared with that of a crop subjected to cold only at the end of the season, may also be explained by tolerance developed through some hardening mechanism. Indications for such an adaptation can be deduced from the photosynthetic behaviour of maize plants, subject to different temperatures during measurements. When these plants had grown in a relatively warm environment, photosynthesis was clearly more affected during a period of low temperatures, compared to plants of the same cultivar previously grown in the field in rather cold weather (De Wit et al., 1978).

A positive correlation between yields of maize and sorghum and average air temperature during the first five weeks after emergence was observed in the high plains of Kenya (1600-2000 m a.s.l.) (Law & Cooper, 1976; Cooper & Law, 1977; Van Arkel, 1980a,b). However, in that region the minimum temperature was above the chilling temperature range and the effect is therefore probably due to growth in "sub-optimal temperatures" as distinguished by Miedema (1982). Moreover, that temperature effect was generally confounded with soil moisture stress (Cooper & Law, 1977; Van Arkel, 1980b).

6.4.2 *Maize growth in the Tambo valley*

Maize sown in the warmer Tambo valley showed both increased initial growth and linear growth compared to that in the colder San Camilo conditions (Fig. 6.5). That is probably largely due to the influence of the clay loam soil, as similar growth rates were observed in check plots on that soil in San Camilo (6.4.3). More relevant is the fact, that accelerated phenological development and senescence due to the higher temperatures in Tambo, resulted in a 30% shorter growing period and therefore a 20% lower yield compared to San Camilo. This is in agreement with data provided by Van Heemst (1984b) indicating that phenological development is mainly governed by temperature. For a given crop and cultivar, the effective temperature sum, the product between days and temperature above a certain threshold value is constant for each development stage. For maize, a threshold value of 10 °C is usually taken, which would result in a 40% faster development in Tambo, given the difference in average temperature at both places. As indicated above, the real difference between the development at both sites was less pronounced, suggesting that for the Peruvian hybrid, the threshold temperature may be about 5 °C lower.

6.4.3 *The influence of soil structure and soil type*

It is often assumed that potential biomass production is obtained if in a given environment enough water and nutrients are supplied, weeds are effectively eliminated, the plants are kept healthy by sufficient pest and disease control and care is taken that the aeration of the soil is adequate. Under such conditions, irradiance and temperature are the main variables that limit the growth of a crop (Miedema, 1982; Penning de Vries, 1982b).

At the start of the FAPROCAF project, clear indications were already obtained that soil physical conditions might also present constraints to growth of some crops. The development of alfalfa roots in San Camilo was restricted to only the upper layer of 0 to 35 or 45 cm. Examination of profiles showed a layered rooting pattern, but there were no indications of the presence of hardpans, problems of low water permeability or insufficient aeration. However, sub-soiling to a depth of 0.90 to 1.00 m, removed the layered soil structure and caused a rather homogeneous rooting pattern over that depth and resulted in a 20% increase in fresh biomass production and an approximate 10% increase in dry matter production (Pinto, personal communication). Another indication that mechanical resistance in these pampa soils can be very high was the fact that a Catterpillar D-8 was unable to draw one ripper tooth in a single turn to the desired depth of 0.90 to 1.00 m in some soils in the Majes pampa (Zipori, personal communication).

With respect to crop performance were the results obtained with maize in the fertilization experiment (M 1) particularly striking. In that experiment the linear growth rate in the non-subsoiled block I was reduced by a factor two and final dry matter production by nearly 40% (Fig. 6.7). Although the effect of sub-soiling was confounded with the effect of a previous crop of barley instead of alfalfa, the latter should be of minor importance in the N-fertilized treatments, where up to 500 kg N/ha was applied and no trace of disease or pest was found.

As could be expected, the interaction of the preceding alfalfa crop with sub- soiling was clearly significant in the N_0 treatments. The combined absence of sub-soiling and rotation with alfalfa resulted in even more pronounced decreases in growth rate (from 245 to 110 kg/ha.d) and final production (from 22.2 to 8.7 t/ha), than in the N_0 treatments of the sub-soiled blocks.

The observation with respect to rooting depth suggests that at least part of the sub-soiling effect is the consequence of reduced percolation below the root zone, which results in more efficient utilization of the irrigation water by the crop.

The spectacular increases in growth rate and final production, obtained by growing the Peruvian hybrid in San Camilo in furrows with clay loam soil from the Tambo site (Fig. 6.8) were remarkable. That experiment was set up to separate a possible effect of soil type from effects of climatological differences between Tambo and San Camilo. The results certainly show, against all expectations, that the Tambo clay loam influenced the growth of maize positively. Plant nutrient concentrations (Table 6.1) and plant water potentials (only just before a new irrigation) hardly differed on the two soil types, so that these variables do not provide good explanations for the 35 to 40% difference in final production. However, the denser rooting and larger number of fine white roots in the Tambo clay loam soil suggest that the relatively high mechanical resistance of the pampa soil prevents the development of an optimally functioning root system, so that the water uptake capacity is restricted. Although sub-soiling undoubtedly decreases the compaction of the pampa soils, it could not bring about the optimal conditions of the Tambo clay loam.

Schuurman (1965) reported that compaction of sandy soils markedly reduced the formation and growth of oat roots. Mechanical resistance was assumed to be the only reason for that restricted growth. Artificial compaction of the sandy soils increased bulk density from 1.24 to 1.52 g/cm^3 and reduced pore volume, especially in the range of pore sizes comparable to or wider than root diameters (0.1-1 mm). Wiersum (1957) showed that plants were unable to decrease their root diameter to penetrate smaller pores. Therefore, rooting can only proceed by enlarging the pores by pushing aside the surounding soil and overcome often considerable mechanical resistance.

The plants of Schuurman (1965) growing in the compacted soil, showed reduced water uptake and shoot growth to less than 20% of the plants in the "loose soil" control treatment. As in San Camilo, there were no indications of lack of oxygen or nutrients as liberal amounts of fertilizer had been applied.

The assumption of restricted root growth in the San Camilo soil because of mechanical resistance is also in agreement with the results, published by Boone & Veen (1982) on maize grown in pots, filled with marine sandy loam that was compacted to different bulk densities. They observed restricted root extension growth, smaller specific root length, larger root diameters and less laterals per cm length of main root at the higher mechanical resistances. Under their experimental conditions with a low supply of phosphate, the uptake of that nutrient and, concomitantly, shoot growth, were reduced in proportion to the mechanical resistance. The same effect was observed for K when P supply was adequate. When light intensity was low, mechanical resistance decreased the root growth somewhat, but not the growth of above-ground parts.

In San Camilo, where irradiance is high, nutrient supply abundant and evaporative demand high, water uptake instead of nutrient uptake can be expected to become constraining first. Veen (personal communication) suggested that mechanical resistance affects root absorption capacity by a simultaneous effect of a restricted absorption area due to thicker and shorter roots, and a relatively smaller part of active root tissue. The latter is caused by the fact that, while the formation of new root tissue is restricted, suberization of the endodermis continues at the normal rate. Barley (1962) and Taylor & Ratliff (1969) reported that at higher soil resistance the weight of the roots was reduced, but less pronounced than root length. Differences in response among crops exist, but maize appeared to be one of the most sensitive (Scott-Russell & Goss, 1974).

In contrast to the effect of sub-soiling the sandy pampa soils, as observed in the fertilization experiment and with alfalfa, it is unlikely that the effect of the Tambo clay loam, applied in 25 cm deep furrows in San Camilo, can be attributed to an increase in available water through the reduction of percolation. Rooting depth was identical in both soils and, more important, irrigation frequency was more than double that in the fertilization experiment. It seems more likely therefore that, although water was available, the plants could not take it up because of the restrictive effect of soil resistance on root morphology and, consequently, on its water uptake capacity.

Hence, it may be concluded that soil physical conditions, like mechanical resistance, may significantly reduce maize growth, especially if other conditions such as the level of irradiance, nutrient and water supply are favourable. In San Camilo, under such circumstances, improvement of these physical conditions, either by sub-soiling or by incorporating clay loam in plant lines, increased the linear growth rate by a factor of three and doubled the final maize production. More research on practically and economically feasible practices to apply these experimental results is necessary.

6.4.4 *The effect of cultivar characteristics and plant density*

Cold-tolerant hybrids from northwestern Europe and some hybrids from Israel, were tested after the observation of the slow initial growth in the first maize experiment (M 1) in combination with high plant densities. Under the San Camilo conditions, such a slow initial growth is disadvantageous as it results in more water loss by direct soil evaporation and by percolation. The treatments proved that initial growth could sometimes be accelerated, but only to a limited extent, by both a high planting density (Fig. 6.3) and early-developing or cold-tolerant hybrids (Figs. 6.3b and 6.4), but almost always at the cost of the final yield.

The introduced hybrids from northern Europe and Israel were selected under the longer day conditions prevailing in the growing seasons in the region of origin and apparently were not suited to the shorter day conditions in Peru. Although genotypic variation in photoperiodic sensitivity is enormous, even accepted day-neutral hybrids were greatly affected by photoperiod changes, resulting in fewer leaves and a faster reproductive development under short-day conditions (Struik, 1982). Even so, the more rapid initial growth of the Dutch hybrid Anko suggests that cold temperature tolerance could probably be improved by breeding and selection.

Investigations concerning the initial exponential growth period, revealed a reasonably accurate relation between dry matter growth and plant height during this stage, independent of the phenotypically very different hybrids (Fig. 6.6). This indicates that during the initial growth stage (until no more leaves are being formed, so just before silking), it would seem likely to be able to determine crop dry matter production with reasonable accuracy by measuring the length of several individual plants. This offers the simple possibility of collecting information about initial growth of maize in experiments, without destroying the plants as is the case with periodic harvests. To determine the relationship in a certain experiment, only a small extra area of one particular cultivar or treatment has to be sown for length measurements and simultaneous periodic harvests.

6.4.5 *Aspects of N supply and uptake*

In most of the experiments in Peru, N was taken up at a rate of about 1% of the dry matter accumulation rate during most of the growing period. However, if growth was hampered by factors other than N availability, such as the low night temperatures of April and May (Fig. 6.9a, January sowing) or limited moisture availability (Fig. 6.10f) the relative rate of N uptake during the linear growth stage was clearly higher, reaching up to about 2.2% of the dry matter accumulation rate. The rapid senescence in both these experiments and in those with the early developing cultivars Anko (Figs. 6.10c and e) and NY 806 (Figs. 6.10a and b), caused a loss of N due to loss of leaves in the final growth stage of the crop.

Without N fertilization, the relative uptake of N was lower than 1% of the dry matter accumulation rate during the second half of the growing period (Fig. 6.9b and e). The importance of sub-soiling is again illustrated in Figs. 6.9b and d, as the yield of N-fertilized maize in a non-subsoiled field was lower than non-fertilized maize under sub-soiled conditions. The relatively high yield in the latter treatments was apparently caused by residual effects of the preceding alfalfa. Nevertheless, by fertilizing, the relative N uptake was restored to 1% of the dry matter accumulation rate, which resulted in about a 17% increase in production (compare Figs. 6.9b and c). Fertilization of maize, grown after barley, also restored the relative N uptake to the 1% level, but that resulted in an approximately three times larger relative increase in dry matter (compare Figs. 6.9e and d).

Also in other places similar relative N uptake rates of about 1% of the dry matter accumulation rate were observed in experiments with adequately N-fertilized maize (Jordan et al., 1950; Hanway, 1962b; Bigeriego et al., 1979). However, Yanuka et al. (1982) reported a higher relative N uptake of about 2% of the dry matter accumulation rate. However, at the end of the growing period, the relative rate declined to about 1.4%. Under limited N supply, the relative N uptake rate declined to less than 1% of the dry matter accumulation rate during the linear growth stage, resulting in N concentrations below 1% at final harvest (Jordan et al., 1950; Hanway, 1962a, b; Bigeriego et al., 1979). As soon as the total N concentration in the dry matter fell below 1%, the growth rate was gradually reduced. If this occurred at a relatively late stage of growth, the reduction in final production was rather small (Bigeriego et al., 1979).

The relation between tissue-N concentration and growth rate may be explained on the basis of a direct linear relation between the N concentration in leaves and their apparent photosynthetic rate up to a level of 5% N under laboratory conditions, in plant species such as wheat (Marshall, 1978), tall fescue (*Festuca arundinacea*), *Panicum maximum*, *Panicum milioides* (Bolton & Brown, 1980) and maize (Wong et al., 1979). The increase in photosynthetic rate per unit increase of leaf-N concentration was about twice as high in C_4 than in C_3 crops (Bolton & Brown, 1980; Schmitt & Edwards, 1981). In field situations, however, even under high fertilization, leaf-N levels not higher than 3 to 3.5% were found (Bolton & Brown, 1980; Hanway, 1962c).

In developing countries, fertilizers are generally expensive and difficult to obtain. Moreover, the situation is worsened by the low income of the farmers and poor credit facilities. Under such conditions, it is of paramount importance to understand the fertilizer response and, in the case of N, to judge whether it is possible to make use of cheap biologically fixed N. In the following discussion attempts are made to develop applicable criteria.

Hanway's data (1962c) suggest that the differences in leaf-N concentration between adequately fertilized and deficient maize are biggest at silking time, especially for the leaves just above the upper ear. In maize under adequate N supply these leaves had N concentrations of 2.8 to 3.0%, compared with values of 1.1 to 1.5% in N-deficient plants. The total N concentration in the leaf generally reflected the N status better than the NO_3-N concentration in the leaves, except at the beginning of the growing period, about one month before silking. At that stage, there were clear differences in leaf NO_3-N concentrations in deficient and well-supplied plants. However, these concentrations decreased so rapidly with time, that it is almost impossible to conclude from a certain NO_3-N concentration whether the crop suffers from N shortage. Moreover, they may fluctuate strongly over short time intervals.

The above data indicate that a diagnosis during the growing period, that is still in time for fertilizer corrections, will be impossible for most practical situations. Another possibility is an analysis after the final harvest, in order to take proper measures for the next season. Our data and those of Jordan et al. (1950), Hanway (1962a) and Bigeriego et al. (1979) suggest that a critical concentration alone is inadequate, as it does not indicate how long the plants have been growing in a deficient situation.

Van Keulen & Van Heemst (1982) proposed to consider the absolute amount of N taken up by the crop at final harvest to judge its nutritional status. For small grains, they stated that at a grain/straw ratio of one, for every kg of N taken up, about 70 kg of grain (at 15% moisture content) will be produced under limited N availability. This value is based on minimum N concentrations of 1.0% and 0.4% in grain and straw, respectively; hence with a grain/straw ratio of one, this results in a minimum N concentration of 0.7% in the total dry matter.

Several published results certainly indicate that the strongest response to fertilization was obtained when in the non-fertilized situation a characteristic minimum N concentration of 0.7% was found (Touchton et al., 1979; Rhoads & Stanley, 1981; Balasubramanian & Singh, 1982), although it was usually about 0.85% (Olson et al., 1964; Jung et al., 1972; Rabuffetti & Kamprath, 1977; Grove et al., 1980; Olson, 1980). This slightly higher value could only partly be explained by a higher grain/stover ratio. In the range of 0.85 to 1.0% the response to N fertilization was usually variable and above 1% it was generally small or absent. The production level at which no further increase due to N application was obtained varied from slightly more than 10 to over 20 t/ha total dry matter or from about 5 to 12 t/ha grain, suggesting that within these ranges other factors such as irradiance, water supply, temperature etc. became limiting.

For a predictive analysis about the magnitude of a possible fertilization response, the yield level should always be taken into account. Only if a low N concentration coincides with a low yield, may a strong fertilizer response be expected. With a low N concentration and a reasonably high yield (Bigeriego et al., 1979), or the reverse (Fig. 6.11), the possibility of a significant N response is small, at least if the other growth conditions remain the same.

In developing countries, it is often very difficult to obtain a complete plant sample after the crop has been harvested. However, cobs or grains can sometimes still be obtained. Fortunately, in most experimental data the N concentration of the grains correlated fairly well with that of the total dry matter. A low yield together with a grain-N concentration of 1.0 to 1.1% usually gave a strong N fertilizer response. If the concentration was between 1.1 and 1.3%, the response was variable, whereas at higher concentrations it was generally small (Olson et al., 1964; Jung et al., 1972; Rabufetti & Kamprath, 1977; Touchton et al., 1979; Olson, 1980 and Balasubramanian & Singh, 1982). However, data reported by Suwanarit (1975) were not in agreement with the above grain-N concentration relations, but they did fit those of the N concentration of the total dry matter.

6.4.5.1 Estimation of residual N contribution from the preceding alfalfa crop in San Camilo

The fact that one of the blocks in experiment M 1 was not sub-soiled, and had barley instead of alfalfa as a preceding crop, enables us to make an estimate of the N supply by the preceding alfalfa crop. The calculation is summarized in Table 6.3.

For the calculation four treatments were taken into account:

a. sub-soiled after alfalfa with adequate N,
b. non-subsoiled after barley with adequate N,
c. sub-soiled after alfalfa without N,
d. non-subsoiled after barley without N.

In addition, two assumptions were made. First, it was assumed that the

Table 6.3 Calculation of the effects of sub-soiling and of alfalfa stubble in maize dry matter production in San Camilo

a. Estimation of the effect of sub-soiling:		
- Measured production sub-soiled blocks with N fertilization	25640 kg/ha	(100%)
- Measured production non-subsoiled blocks with N fertilization	17400 kg/ha	(68%)
- Effect of sub-soiling	8240 kg/ha	(32%)
b. Estimation of net effect of the preceding alfalfa crop:		
- Measured production N_0 plots in sub-soiled blocks (after alfalfa)	21160 kg/ha	(100%)
- Effect of sub-soiling (32%, see a)	6770 kg/ha	(32%)
- Calculated production of non-fertilized maize in non-subsoiled fields, sown after alfalfa	14390 kg/ha	(100%)
- Measured production of N_0 plots in non-subsoiled fields, after barley	8710 kg/ha	(61%)
- Calculated contribution of the preceding alfalfa crop in non-subsoiled fields	5680 kg/ha	(39%)
- The same, in sub-soiled fields (39% of 21160 kg)	8250 kg/ha	

contribution of residual N from the alfalfa crop to total production was negligible in the well-fertilized (250-500 kg N/ha) plots. So from these treatments (a and b) the net effect from sub-soiling could be estimated. The second assumption was that the relative effects of both sub-soiling and the alfalfa stubble on total production remained constant, or in other words: all plots in the subsoiled field had a certain percentage of extra production compared to the non-subsoiled plots and all N_0 plots, sown after alfalfa, had another certain percentage production increase compared to N_0 plots after barley.

The calculated contribution from alfalfa to production in non-subsoiled plots was 5680 kg/ha; the same relative contribution in sub-soiled fields yielded 8250 kg/ha maize dry matter. Hence, at an N concentration of 1% (found in the N_0 plots) this gives for maize under non-subsoiled and sub-soiled conditions, contributions of 60 and 80 kg N/ha, respectively, originating from a preceding alfalfa crop. These contributions are within the range of values calculated by Baldock et al. (1981) in Wisconsin and Sibma (personal communication) in the Netherlands.

6.4.6 *Aspects of P and K supply and uptake*

In experiment M 1 there was a complete absence of response to K fertilization. Several observation plots without P fertilizer showed no evidence of reductions in production compared to P-fertilized fields. Hence, the natural P and K supply of San Camilo soils was sufficient for high maize production.

Because most plant samples, as a routine, were analysed for P and K, uptake curves for these elements could be determined, which will be discussed in more detail.

In most of our experiments, P was taken up at a relative rate of about 0.2% of the dry matter accumulation rate during most of the growth period (Figs. 6.11a, c, d, e, f; Fig. 6.12c, d, e, f). Exceptions were the P-fertilized experiment (160 kg P/ha) in Tambo (Fig. 6.11b) and a border strip in the NxK fertilization experiment, where P had not been applied (Fig. 6.12a, b). In both situations, the relative rate of P uptake was lower at a value of 0.16% of the dry matter accumulation rate. In San Camilo that did, however, not affect the production of the maize, compared with the rest of the field that was fertilized with P.

Also elsewhere similar P uptake patterns were obtained in maize fields well supplied with phosphorus (Jordan et al., 1950; Hanway, 1962b). However, these authors also describe some situations where lower relative P uptake rates (0.12-0.14% of the dry matter accumulation rate) were observed, although only Hanway (1962a, b) mentioned clear symptoms of P deficiency, and a 20% yield reduction compared with well-fertilized maize fields.

Van Keulen & Van Heemst (1982) stated that small grain crops with a grain/straw ratio of one, produce about 600 kg grain (at 15% moisture content) per kg P taken up in situations of limited P availability. At a grain/straw ratio of one, that is equivalent to about 1200 kg total dry matter per kg P or a minimum concentration of 0.083% of the total dry matter. In maize, only a few cases of clear P response were found, generally coinciding with minimum concentrations of between 0.11 and 0.12% (Krantz et al., 1949; Traoré, 1974; Moschler & Martens, 1975; Suwanarit, 1975; Kang & Yunusa, 1977). Above 0.20%, usually no P fertilization response was obtained and between 0.15 and 0.20%, the response was variable. Consequently, the concentration of 0.16% found in San Camilo is within the "variable response" range. Hence, as for alfalfa, there seems no firm guarantee that in the near future, P fertilization for maize will remain unnecessary for high yields. On the other hand, the rotation system with grazed alfalfa and the fact that irrigation water is also continuously supplying P at an annual rate of about 5-10 kg/ha, may prevent an early response to P fertilization.

Data from Traoré (1974) and Kang & Yunusa (1977) suggest that the P concentration in the grains can also be indicative if it coincides with a low yield. Fertilizer-P response was generally obtained if in the non-fertilized situation the P concentration in the grains was between 0.19 and 0.24%; above 0.32% no responses occurred, whereas between 0.24 and 0.32%, variable results were obtained. Consequently, as with N, the P concentration in grains may be useful in assessing the P situation in harvested maize fields.

With respect to K, the relative uptake rate of 2% (or more) of the dry matter accumulation rate during the first half of the growing period in San Camilo seems high compared to the 1% generally reported elsewhere (Jordan et al., 1950; Hanway, 1962a, b; Loué, 1963). Hanway (1962a, b) observed a relative K uptake rate of less than 1% in a clearly deficient soil, which resulted in about 30% less dry matter production, compared to well-fertilized maize. The fact that also without K fertilization, a relative uptake rate of 2% was obtained in San Camilo (Fig. 6.13e; Fig. 6.14a, b) indicates that the natural K supply was more than sufficient.

In the majority of our experiments, as well as elsewhere, the crop lost K at the end of the growing period (Jordan et al., 1950; Hanway, 1962a, b; Loué, 1963). Aldrich & Leng (1974) assumed that this K was dissolved in precipitation water and subsequently leached from the plants, especially from the older leaves. However, in San Camilo the K loss was also observed in drip-irrigated maize, where the leaves remained dry. Therefore, Epstein's explanation (1972), that this K is translocated to the root system, seems more probable.

Maize yields, limited by K have been reported in only a few situations. Hanway et al. (1962) reported the results of 51 field studies with maize, in which a significant K fertilization response was observed in only 11 cases. The report includes data about K uptake by the plants as well as exchangeable K in the soil. On the whole, these data were quite variable and difficult to interpret, and in several cases similar results from tissue analyses gave clearly different responses in the field and vice versa.

Van Keulen & Van Heemst (1982) stated that the variability in the K concentration of the crop is partly the result of a greater impact of the grain/straw ratio, because at harvest a relatively large part of the K is present in the straw. In addition, apart from its physiological function K has a second function as a positive charge accompanying organic anions. However, it can be replaced by other positive ions, thus causing additional variability in the plant- K concentration.

Hanway et al. (1962) indicated that the K concentration of leaves at silking gave the best correlation with grain yield. At that stage, a leaf-K concentration of less than 1.3% usually resulted in K fertilization responses, although there were several exceptions. Second best in this respect was a critical "whole plant" K concentration of 1.0% at silking.

The results of Loué (1963) suggest that the K concentration of the stover at the final harvest may give useful indications for fertilization responses. Strong responses were obtained with a stover-K concentration in the non-fertilized situation of 0.27-0.35%; with a K concentration between 0.35 and 0.80% the response was small and above 0.80% absent. The grain-K concentration seems not indicative, as that was about 0.30% in all cases.

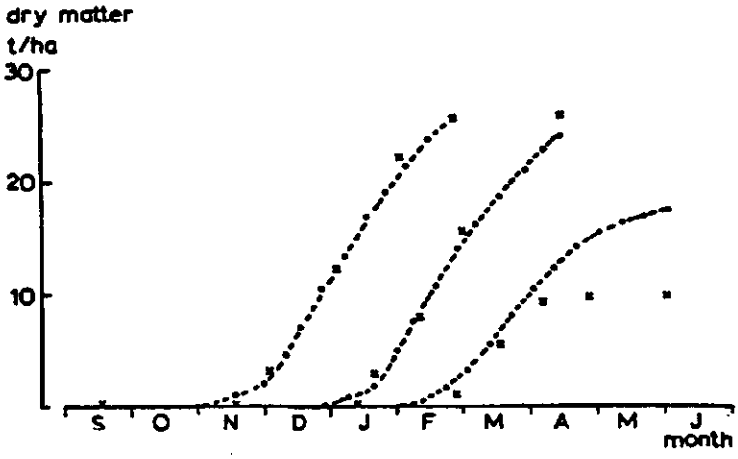


Fig. 6.15

Measured (×) and simulated (•-----•) growth of maize in San Camilo, using the BACROS model with standard initialization.

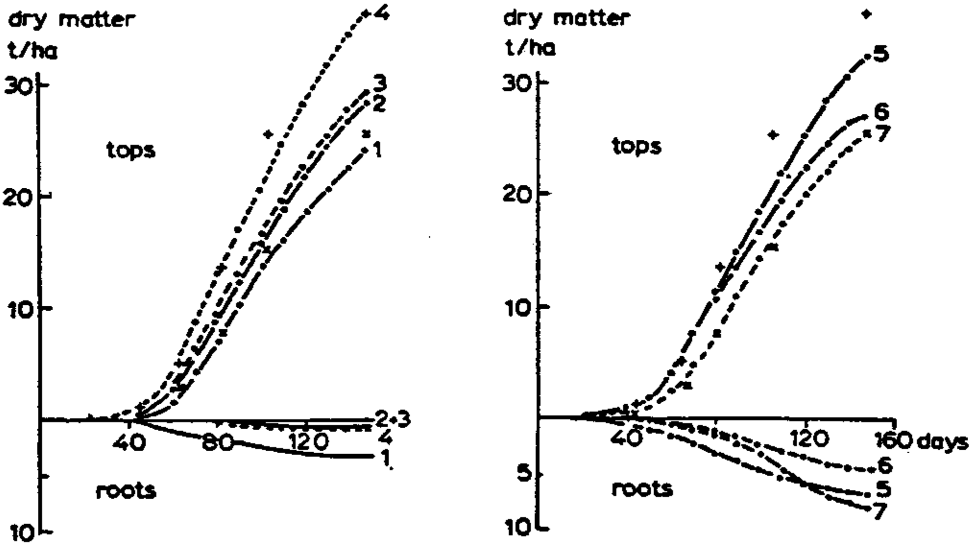


Fig. 6.16

Try-outs of several adaptations of BACROS to simulate maize growth on Tambo clay loam in S.Camilo. 1: standard initialization; 2: no CO_2 regulation and WCRR = 10 kg/ha per g H_2O/bar.s.m^2; 3: as 2 with adapted F_g = 100 kg CO_2/ha.hr; 4: as 3 with extra stomatal regulation feature. +,x: measured values on clay loam (+) and pampa soil (x) respectively.

Fig. 6.17

Simulation of maize growth by the adapted BACROS model. 5: adaptation as curve 4 Fig.6.16 but with standard WCRR of 2500 kg/ha per g(H_2O)/bar.s.m^2. 6: as curve 1 Fig.6.16 but with S-2 F_g curve description: 7: as curve 5 but WCRR = 15000 (kg/ha)/ g(H_2O).bar.s.m^2. +,x: measured values on clay loam (+) and pampa soil (x) respectively.

Summarizing, it appears that K deficiency did not occur in San Camilo and does not seem to be very common elsewhere. Also for more K-demanding crops like alfalfa and potato, it was shown that the K supply of San Camilo soils was generally sufficient. Moreover, the K supply with the irrigation water and the rather efficient recycling through grazing in the farming system, ensure an adequate supply for many years. However, one must remain alert, because yield reductions caused by K deficiency are more difficult to detect than those caused by N or P deficiency.

Another aspect is that both P and K supplies in other pampa soils, such as the Majes region, are less favourable (Zipori et al., 1982). Moreover, future settlements have been planned with much less emphasis on dairy farming and hence a less efficient recycling of nutrients.

6.5 MODELLING ASPECTS OF MAIZE

6.5.1 *Introduction*

More than 15 years ago, Brouwer & De Wit (1968) presented the simulation model ELCROS for simulation of potential growth, under conditions of optimal nutrient and water supply. Although the structure of the model enabled simulation of most plant species, it was presented with parameters applicable to maize. Since then the model has been further developed into the more comprehensive model BACROS. In the course of that process, once again maize data sets were often used for further development and tests of model performance. As a consequence, in the first complete presentation of the model BACROS (De Wit et al., 1978), results of field experiments with maize in the Netherlands, Iowa and California were used for validation. Generally, there was reasonable agreement between simulated and measured results and the authors therefore concluded that at present the model could be used with confidence to simulate potential dry matter accumulation rates of maize in feasible growth situations. Because a reasonable amount of experimental data on maize was collected in San Camilo, BACROS was used for simulation within the framework of the FAPROCAF project. A short description of the model was given in Sections 5.4.2 and 5.4.3.

The maize modelling activities had two major objectives: On the one hand to validate the present version of the model against the measured growth under optimum conditions during the three experimental periods, with the aim of judging its major qualities as well as its weaknesses. On the other hand, attention was paid to the observed differences in growth between Tambo clay loam and San Camilo sandy sub-soiled and non-subsoiled fields, in an attempt to use the model for a first evaluation of the hypotheses discussed in Section 6.4.3.

The central question with respect to the latter objective was whether the model was able to simulate the very high growth rates measured on the clay loam and if so, whether it was flexible enough to test hypotheses for the reduced growth in the other soil conditions.

6.5.2 *Simulation of maize growth for three seasons on sandy San Camilo soils*

For the simulation of maize growth in San Camilo, the standard model for maize, as reported for the validation runs by De Wit et al. (1978), was applied. Meteorological data, measured LAI and N concentrations were used as forcing functions. Results are presented in Fig. 6.15. Simulated and measured results are in good agreement for the maize sown in September and in November, but dry matter production is overestimated for the crop sown in January, especially towards the end of the growing period. That is not so surprising, as the model does not take into account more permanent damage to the photosynthetic system of C_4 species due to prolonged low temperatures, as reported by Hilliard & West (1970) and West (1973). Even when photosynthesis as well as growth, i.e. the conversion of primary photosynthetic products into structural plant material, was assumed to be strongly dependent on the average temperature, viz. decreasing from maximum at 25-35 °C to zero at 15 °C, but without permanent damage, the simulated growth of the maize sown in January decreased only insignificantly.

Despite the absence of the damaging influence of low night temperatures in the model, it predicted correctly the slow initial growth of the September-sown maize, which was also thought to be related to low temperatures. This seems to be the result of the measured LAI, incorporated in the model as a forcing function. During the initial growth stages, when most of the assimilates are used for leaf formation, the influence of the low night temperatures on photosynthesis caused a strong delay in the development of the leaf area, and therefore the low temperature influence was indirectly incorporated into the model. In contrast, the maize sown in summer suffered from low night temperatures after the canopy was fully developed and hence the reduction in photosynthesis was no longer related to the leaf area. Therefore, during that growing stage, the LAI forcing function did not account for low temperature influence and growth was strongly over estimated.

The important influence of the LAI forcing function also appeared, when it was replaced by a calculation of the leaf area endogenously, from the dry matter production and an average SLA value. As a result, the initial growth prediction (until 76 days after sowing) of the maize sown in September was five to eight times the measured growth and five to fifteen times the prediction on the basis of a LAI forcing function. On the other hand, the predicted growth rate in the linear phase was only slightly (about 7%) higher than the measured one. Yet, in that situation because of the favourable early development, the predicted total dry matter production was 37 t/ha instead of 26 t/ha as measured.

Thus, BACROS with standard initialization predicts the growth of properly fertilized maize on the sandy soils of San Camilo reasonably accurately, if two conditions can be fulfilled. First, leaf area data must be available for use in a forcing function and secondly the night temperatures must not drop below 10 °C for a prolonged period of time when the maize has stopped to form leaves (from tasseling stage onwards). For environments similar to San Camilo, with alternating high or moderate day temperatures and low night temperatures, as is the case at high altitudes in many places of the world, the actual model predictions for thermophile crops like maize will often be too high. For such situations an adaptation of the model is necessary.

The necessity to incorporate leaf area development as a forcing function, which is mainly dictated by the fact that morphogenesis is poorly understood, is a major weakness of the model. Such a forcing function may camouflage important areas where knowledge is still insufficient, as with the colder night temperatures during the San Camilo spring. Moreover, in many cases no measured data about leaf area are available and then sometimes rather unreliable predictions can be expected.

6.5.3 *Modelling the very high growth rates on Tambo clay loam*

In Fig. 6.16, curve 1 shows the simulation of maize sown in September growing under optimum conditions in San Camilo, resulting in a reasonable agreement with measured values on pampa soil. However, maize grown in check plots with Tambo clay loam in the same experiment, reached a much higher production. This would indicate that BACROS in fact underestimated potential growth in the San Camilo situation. It seemed important, therefore, to examine how the model could be modified to predict higher growth rates. Evidently, such manipulations should be based on realistic possibilities. Hence, an holistic approach is required, where those parts of the model based on approximate relations that have not rigorously been verified experimentally, are reconsidered.

Increased growth rates in the model can be achieved by higher rates of assimilation or by a reduction in respiratory losses. Assuming lower respiratory losses than presently predicted by the model does not seem justified, as comparisons of measured and simulated respiration rates in crop enclosures indicate that the values of carbon losses during growth and maintenance tend to be underestimated by BACROS (Penning de Vries, personal communication).

A possibility of increasing the growth rate by increasing gross assimilation is, to replace the CO_2-induced stomatal regulation by a description, where the stomata are fully open during the daytime and completely closed at night. With such an adaptation Penning de Vries (1982) reported 20 to 25% higher predictions of growth rates under Sahelian conditions.

Another possibility for predicting higher growth rates, is to decrease the chance of temporary water stress by assuming a lower root resistance. Growth under optimum supply of moisture, as defined in the model, is expressed as a constant soil moisture potential of 0.01 MPa in the root zone (i.e. field capacity). However, temporary water shortage may still occur in the vegetation, if the evaporative demand of the atmosphere is so high, that with the given root system, representing a considerable resistance to water flow, not enough moisture can be transported to maintain the turgidity of the leaves. In the model, the root resistance is calculated from the root weight and its age distribution by employing a so-called weight-to-conductivity ratio (WCRR). This ratio, expressed in the somewhat cumbersome unit of kg roots/ha per g water/bar.s.m^2, was estimated on the basis of reasonable field data from the Netherlands (De Wit et al., 1978), but no independent measurements are available. Moreover, Barrs (1973) reported for a number of crops that root resistance was not constant but inversely related to the required rate of flow to maintain full turgidity. It must be noted, however, that those data refer to plants under controlled conditions, where the highest rate of water flow recorded was substantially lower than that required under field conditions, so that it is doubtful whether this phenomenon is of practical importance in the field. Nevertheless, it seems justified to test the behaviour of the system, introducing a lower value for WCRR, thus effectively decreasing root resistance.

Introducing in combination these two changes, i.e. lowering WCRR from 2500 to 10 and changing the mode of stomatal regulation, resulted in about a 17% higher prediction of the above-ground dry matter production (Fig. 6.16, curve 2). This was largely the result of a substantial change in dry matter partitioning between roots and shoots, due to the operation of the functional balance. The lower root resistance leads to continually higher water contents in the crop and hence to lower root growth rates. Nevertheless, the simulated forage production was still considerably lower than the yield measured on the Tambo clay loam.

The next change introduced in the model, was derived from casual reports of very high rates of photosynthesis of individual leaves at light saturation (F_g values) in tropical maize cultivars (Heichel & Musgrave, 1969; Moss & Musgrave, 1971). Average maximum photosynthetic rates of up to 85 kg CO$_2$/ha.h were measured, whereas some measurements even reached 100 kg CO$_2$/ha.h (Van Keulen, personal communication). However, introducing such a high saturation value in addition to the previous adaptations barely changed the results (Fig. 6.16, curve 3).

The reason for this limited effect appeared to be that the saturation level was hardly ever reached, partly because light saturation occurred only at an irradiance level of over 800 J/m^2.s for the standard asymptotic exponential description of the photosynthesis light response curve of the leaf (Fig. 6.18). Whenever a crop shows a very high photosynthetic capacity, it may also have a more angular shape of the light response curve. Goudriaan (1979) described a series of mathematically related saturation type curves. Based on his nomenclature, the asymptotic exponential, S$_{-1}$, was replaced by the more angular, Blackman type S$_{-2}$ curve (Fig. 6.18). Using this description, the saturation level of 100 kg CO$_2$/ha.h is reached at an irradiance level of 400 J/m^2.s. However, including this adaptation did not increase the simulated dry matter production significantly.

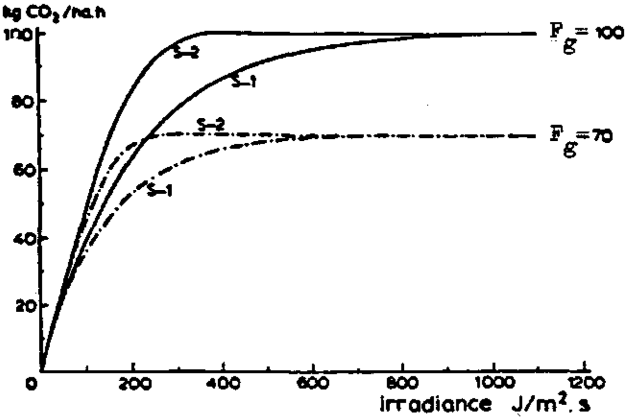


Fig. 6.18 S$_{-1}$ (asymptotic exponential) and S$_{-2}$ light/net photosynthesis curves with light saturation values of 70 and 100 kg CO$_2$ /ha.h (derived from Goudriaan, 1979).

Further examination of the behaviour of the model showed that assimilation under such conditions was limited by the very low CO$_2$ concentrations occurring in the stomatal cavity as a result of the high photosynthetic capacity and the relativity low stomatal conductivity of 0.008 m/s. At high irradiance levels, the CO$_2$ concentration inside the stomatal cavity was much too low to obtain any advantage of the high light saturation characteristic. Therefore, stomatal regulation was redefined subsequently, in such a way that the internal CO$_2$-concentration was set again at a fixed value of 120 vppm, with the provision however, that the stomata not only close if the internal CO$_2$ concentration tends to rise above 120 vppm, but also open wider (higher stomatal conductivity value) if the concentration falls below that value.

This rather speculative adaptation of the stomatal regulation mechanism, produced a reasonably close agreement with the above-ground dry matter production measured on the Tambo clay loam in San Camilo (Fig. 6.16, curve 4). The high specific root conductivity still resulted, however, in a questionably low amount of roots and therefore an extremely high shoot/root ratio of about 35. Re-setting the root resistance to its standard value produced a normal shoot/root ratio of about 6, but the simulated values then remained about 10% below the measurements (Fig. 6.17, curve 5). Re-setting the normal S_{-1} description of the photosynthesis- light response curve with F_g = 100 kg CO_2/ha.h, produced a growth curve very similar to curve 5 (not shown). Re-setting only the saturation level to its standard value of 70 kg CO_2/ha.h, gave only a slight improvement compared to the standard prediction (compare Fig. 6.17, curve 6 with Fig. 6.16, curve 1).

The experiments with the model described so far, indicate that under certain conditions the production capacity of maize greatly exceeds that considered "normal". It is very difficult to adapt the model in such a way that equally high growth rates are predicted and the procedure presented comes dangerously close to "the most cumbersome and subjective technique of curve fitting" (De Wit, 1970). The adaptations in the model should, however, be considered as hypotheses, the quantitative consequences of which could be evaluated by means of the model. The model results suggest that substantial changes in the physiology of the plant must take place, to realize above-ground growth rates of over 350 kg/ha.d, as also reported by Yanuka et al. (1982). More detailed physiological research is necessary to determine the operating mechanism, and the conditions necessary to create such a situation, which is even more important from a practical point of view.

One disadvantage of the changes introduced in the model, especially the one regarding the stomatal regulation mechanism from a technical point of view, is the two to three fold increase in the necessary computer time (up to about five minutes), making it too expensive for anything but a research tool.

6.5.4 *Modelling growth reduction, caused by mechanical soil resistance*

In 6.4.3, it was assumed that growth reduction of maize on the sandy soil of the San Camilo pampa was mainly due to mechanical soil resistance. Under non-sub-soiled conditions, this resistance is presumably still higher than after sub-soiling, leading to more stunted maize growth. Because the adapted growth model was able to predict growth rates similar to the ones obtained on the Tambo clay loam, subsequent attempts were made to account for the influence of mechanical soil resistance in the model to see whether it would react in a similar way.

A high mechanical resistance in the soil will presumably lead to a root system with less than optimum efficiency. In the model, this can be expressed by changing WCRR. In first instance it was increased from 2500 to 15000. Because of the functional balance principle, this adaptation alone would stimulate growth of the roots at the expense of above-ground dry matter. The latter reduction seems realistic, however, the ensuing increase of root biomass certainly is neither according to observations in San Camilo nor to reported measurements elsewhere (Barley, 1962; Taylor & Ratliff, 1969; Boone & Veen, 1982). In fact, the reverse mechanism is more probable: because of high soil resistance, the growth of roots is obstructed, leading to a different root geometry with an increased root resistance. Moreover, suberization may be promoted, thus adding to the decline in root activity. To account for this effect, a maximum root growth rate was defined that hampered the working of the functional balance.

As a result of the very high resistance to water flow in the root system, stomatal conductivity in the model was strongly reduced because of the unfavourable internal water status of the plant, and consequently CO_2 assimilation and growth decreased substantially. The resulting simulated growth curve shows a significant growth reduction (Fig. 6.17, curve 7). Because of the structure of the model, these changes resulted in a five to six fold increase in the original computing time. Apparently, the model was at the limit of its possibilities, because trying to simulate even higher root resistances (as for non-subsoiled fields) failed. With the available computing facilities, this modelling problem could not be solved within time and budget limits (recently, computing facilities have very much improved, making the solution of these kinds of modelling problems less troublesome).

6.5.5 *Concluding remarks*

As was the case for Rhodes grass (Section 5.4), the BACROS predictions for maize growth were not reliable for situations where favourable growing conditions during the day (high irradiance and favourable temperatures) alternate with nights of rather low temperatures (below 10 °C). The main reason for this shortcoming is that the processes playing a major role under such conditions, are not incorporated in the model, as no research has been done under comparable conditions. In other words, some essential piece of the "knowledge puzzle" is missing, but if quantitative information is available, the model can easily be adapted.

On the other hand, without modifications BACROS was also unable to predict either the high growth rates obtained on the Tambo clay loam in San Camilo, or those reported by Yanuka et al. (1982). One possible reason could be the fact that many of the quantitative relations incorporated in the model are based on growth room experiments under controlled conditions, that are clearly different from the field situation. On several occasions, the results of comparable measurements under both conditions showed large differences (Van Keulen, personal communication) and the results obtained in growth rooms may therefore not be directly transferable to field situations. Another reason is doubtless the fact that BACROS respresents an actualized consistent view of a biological system that is still not completely understood. The knowledge of the system shows several gaps for which assumptions have been introduced. The model is thus a synthesis of actual relevant scientific knowledge and continually changes with the progress in this knowledge, as new relevant information becomes available.

Similarly, when hypotheses are introduced, the model in fact shows the quantitative consequences of these hypotheses, within the framework of the scientific views it represents. Results obtained in this way may then be used for further research and the model should therefore mainly be judged as a tool to improve the quality and efficiency of this research. Such use of a model can only be expected to yield maximum profit if a good interaction exists between experimentation for both validation and further development of the model, and the use of simulation results in the planning and execution of successive experiments. Such a profit should be evaluated in terms of a more efficient agricultural research program and as a consequence this can only be done after several cycles of interactive experimentation and modelling activities. Also, the results obtained on the basis of the San Camilo experiments should have been followed by further experimentation and modelling activities. Within the short period of the FAPROCAF project this could not be effected, which explains why still no explicit benefits for the region have been derived from the simulations.

7 *GENERAL DISCUSSION*

7.1 MAJOR FACTORS INFLUENCING IRRIGATED CROP GROWTH IN THE PAMPAS AROUND AREQUIPA IN SOUTHERN PERU

This Section presents a review of the most important factors affecting the yields of the crops studied in San Camilo. For optimum use of irrigation water, i.e. achieving maximum yield per unit water supplied, several factors appeared to be important, some influencing all crops studied and others affecting one or some of the crops more specifically. The following aspects are discussed:

- the water supply;
- the supply of nitrogen;
- the mechanical soil resistance to root development;
- the timing of the growing season;
- the cutting or grazing management;
- the cultivar characteristics.

7.1.1 *The water supply*

As is discussed in detail elsewhere (Valdivia et al., 1982; Zipori & Valdivi, 1982), the amount of irrigation water supplied is the most important yield-determining factor for all crops studied. The most efficient use of irrigation water is obtained when the supply is equal to the crop water requirements for maximum yield. In Section 1.4 it was shown that this is mainly due to the fact that under such an application regime the relative losses of water to soil evaporation and drainage below the rooted soil layer are minimized. Results of Shalhevet et al. (1979) confirm this conclusion.

Doorenbos & Kassam (1979) suggested that for several crops such as sorghum, sunflower, cotton and groundnut etc., the economic yield per unit water increases under water stress as a result of a reduction in dry matter production of mainly the crop residues, leading to increasing harvest indices. Such gain depends on the timing of water stress and occurs only when it is absent during sensitive stages like flowering and reproductive growth. However, results of Shalhevet et al. (1979) indicate that such improvements in water utilization-efficiency are often small or absent. Moreover, when it does occur, its advantage is usually outweighed by the increase in production costs due to the decrease in production per hectare. Thus, when a limited quantity of irrigation water is available, the best choice, also for most drought-tolerant crops, is to limit the cultivated area in order to maximize the production per unit area and so obtain good returns, both with regard to the irrigation water as with regard to other costs.

A strong limitation for improvement of water utilization-efficiency in the Arequipa region originates both from the rather irregular water supply and the practically uncontrolled allocation of irrigation water to the farmers. Although after the rains in the catchment area, the water availability for the remainder of the year should be known from the water level in the lakes, the actual supply to the farmers is very irregular and does not follow a recognizable pattern. This irregularity seems mainly to be associated with the water use by the hydro-electric power plant, supplying part of the electricity for the city of Arequipa. Although the formal control of the water supply is in the hands of the Ministry of Agriculture, effectively very little control is exercised, hence weeks of ample water availability alternate with periods of strict water limitation.

As a reaction to this irregularity, the farmers tend to plant larger than optimum areas, to profit from weeks of ample availability of water, thus taking for granted the lower water utilization-efficiency in periods of limited supply. This behaviour seems rational, as can also be deduced from Fig. 7.1, which presents the relative water utilization-efficiency (defined as the actual water utilization-efficiency divided by the maximum water utilization-efficiency, both in kg yield per m^3 water supplied), as a function of the ratio of quantity of water actually applied (A) and that necessary for optimum utilization-efficiency (Aopt). In the Figure curve 1 represents a rather dense crop stand, comparable with alfalfa, showing a soil evaporation loss of about 0.15 * Aopt (Zipori & Valdivia, 1982). For such a crop, water applications within the range of 0.65 to 1.1 * Aopt, result in more than 90% of the maximum water utilization-efficiency. For the local cultivar Tambo, for which, on average, Aopt was obtained by irrigation according to k_{pan} = 0.85 (Zipori & Valdivia, op.cit.), the irrigation range for obtaining water utilization-efficiencies in excess of 90% of this optimum value is thus between a k_{pan} of 0.55 and 0.94. These values agree well with experimental observations. Hence, for a variable irrigation supply, the average value, a k_{pan} of about 0.75, seems to be the best starting point. Consequently, for crops such as alfalfa, farmers will be able to maintain the water utilization-efficiency at a reasonable level, if the area under cultivation exceeds the one that can be irrigated for maximum yields by not more than 10%, even with actual available water within the range of 25% below to 25% above the expected average.

Curve 2 in Fig. 7.1 represents an example applicable to row crops such as sprinkler-irrigated potatoes and maize, which generally show much higher soil-evaporation losses (in the example a loss of 0.4 * Aopt is assumed). Here, the range with acceptable water utilization-efficiencies is much smaller and the average value coincides approximately with Aopt. Therefore, the farmer should plant only relatively small areas with such crops, in order to assure proper irrigation with sufficient water to reach the maximum yield level. The remaining area should preferably be sown to less sensitive crops, with water utilization-efficiencies comparable to those in curve 1.

An alternative in the case of row crops is the use of more sophisticated irrigation techniques such as trickle-irrigation, considerably reducing soil surface evaporation and resulting in figures comparable to those of Curve 1. However, for the high costs of the investment to be profitable, the farmer is required to obtain maximum returns and thus to irrigate with sufficient water for maximum yields. But, because of the higher irrigation efficiency caused by the reduction in water losses, the required water supply is considerably less. For example, in San Camilo trickle-irrigated maize and tomatoes required 30 to 50% less irrigation water for maximum yield than with sprinkler-irrigation (Valdivia et al., 1982; Pinto et al., unpublished results).

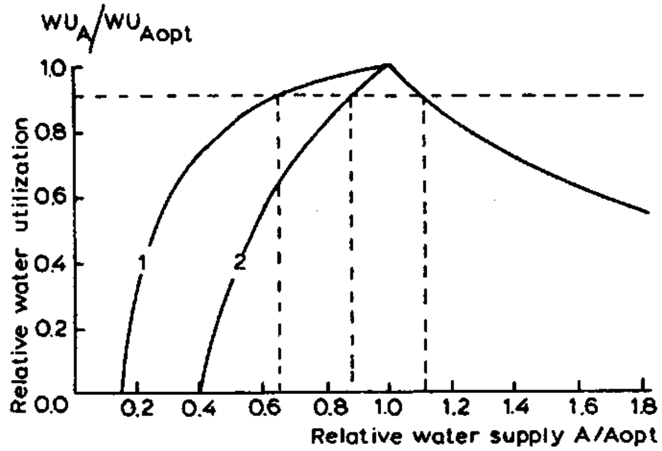


Fig. 7.1

Relative water utilization (WU_A/WU_{Aopt}) as a function of the relative water supply (A/Aopt) for two different types of crops.
Curve 1: densely sown, soil evaporation loss = 0.15 * Aopt.
Curve 2: sown in rather wide rows, soil evaporation loss = 0.4 * Aopt.
Further explanation in text.

Measures towards a more efficient water use at the farm level, such as timing of irrigation hours (preferably not during day time), maintenance of the irrigation facilities, investments in more efficient systems and supply of the water according to the demands of the crop, are difficult to realize within the actual organisation of the water distribution. The main reason is that the amount of irrigation water actually used is not checked and consequently, an efficient use is not rewarded nor is abuse penalized. In fact, irrigation scheduling is practiced allowing different groups of farmers to irrigate a fixed number of hours on allotted days. However, because there is no check on the amount of water used, many farmers in the sprinkler-irrigated areas have widened the outlets of their sprinklers to increase the water supply, often resulting in pressure problems and bad water distribution. This system does not allow the individual farmer to choose the best strategy for an efficient use of the often scarce amount of available water. Also in other countries, the allotment of water in rotation, rather then selling it at specified prices to buyers, leads to a great deal of waste (Garruthers & Clark, 1981).

It may thus be concluded that the irrigation water-use efficiency in the Arequipa region can still be improved considerably. Firstly, on a macro-scale by scheduling of the available water per month per irrigation district as soon as the availability of the water in the lakes of the catchment area is known; this would allow a more regular and foreseeable distribution of the irrigation water to the farmers, and consequently a more efficient planning of a cropping calendar. Secondly, on a micro-scale, by recording the actual use of irrigation water by the individual farmer, and billing him accordingly; this is probably an indispensable condition for attaining a conscious use of the irrigation water and a succesful introduction of measures to improve irrigation efficiency. Without such an incentive it is unlikely that the farmers will change habits, which often lead to a considerable loss of the limited amount of available water in this desert environment.

7.1.2 *The N supply*

To achieve potential yields, crops need an ample N-supply. Demands of leguminous crops can usually be met by fixing atmospheric N_2, but non-leguminous crops depend on available N in the rooted soil layer. In San Camilo, 200-240 kg N/ha was absorbed by a high-yielding crop of potato, 250-300 kg by maize and even up to 400 kg during a summer period of Rhodes grass. In all these cases, the bulk of the uptake took place over a period of 80 to 100 days. In general, the N-supplying capacity of soils cannot meet such demands and use of chemical N fertilizers is indispensable. This certainly holds for San Camilo with its sandy soils of low organic matter content. Therefore, high expenditures are required and for the farmers this is difficult to realize, apart from the problem of actually obtaining the fertilizer.

There are two ways in which these N fertilizer requirements could be reduced in the San Camilo situation. First, attention should be given to an optimum exploitation of the N-supplying capacity of alfalfa, which is able to fix about 700 kg N/ha annually in San Camilo (Section 3.4.2.3). Of this about 150 kg/ha remains in the roots and a substantial part of that is available for a following crop. Thus, well-irrigated maize produced 21 tons of dry forage without N fertilization, when sown after phoughing-in of a three year old alfalfa stubble (Fig. 6.9b). The traditional rotation system including alfalfa has used this natural N-supplying capacity for many years. Even so, the quantitative insights are insufficient to determine its most optimal exploitation. This aspect certainly deserves more attention in future agricultural research in the region.

A second way to reduce the fertilizer needs, is to improve the efficiency and uptake by split applications coinciding with the greatest demand of the crop, i.e. the period of active growth. No explicit experimentation was carried out, but there are strong indications (Section 4.4.2 and 5.3.2) that in such a way high N recovery will be possible. So far no systematic attention has been given to this subject, but it would seem to be a worthwile area of experimentation.

7.1.3 *Mechanical soil resistance*

A factor that unexpectedly influenced the growth of maize significantly, was the mechanical soil resistance to root development (Section 6.4.3). Well-fertilized maize, growing on clay loam produced twice as much dry matter as equally well-fertilized maize growing on a non-subsoiled sandy pampa soil. Sub-soiling these sandy soils prior to planting approximately halved the difference. The sensitivity to mechanical soil resistance varied substantially among crops. Rhodes grass for example showed no reaction to sub-soiling, but normally deep-rooting crops such as alfalfa and sunflower were, like maize unable, to grow roots below 45 cm in non-subsoiled fields. Nevertheless, the increase in forage yield due to sub-soiling was only about 10% for alfalfa, much less than for maize and probably mainly as a result of smaller water losses due to drainage below the more deeply rooted soil layer. The stronger response of maize suggests that the higher soil resistance in the non-subsoiled fields affected the absorbtion capacity of the maize roots, an effect that seemed virtually absent in alfalfa.

It may be expected that mechanical soil resistance will cause even more severe problems in the stonier soils of some other pampas, like those in the Majes and Siguas regions. Sub-soiling, choice of less susceptible crops and increased irrigation frequency are the actual available practical options for a reduction of the problem, but experimental results are as yet not available for more specific recommendations. Highly problematic soils could be made suitable for drip-irrigated orchards, after careful preparation of planting-holes. The first results in this respect obtained by an Israeli-Peruvian cooperation programme seemed encouraging (Van de Meer et al., 1983). The mechanical resistance as a growth-limiting factor certainly deserves further attention by continued research and experimentation.

7.1.4 *Timing of the growing season*

The choice of sowing date in relation to the subsequent growing season appeared to be very critical for maize, and this will probably hold for other thermophile crops, especially C_4 crops. At first impression, the climatological conditions of the pampas seem favourable for crop growth throughout the year, with high solar radiation, absence of frost and favourable temperatures during daytime. According to criteria suggested by FAO (1978, 1981), the average temperatures, even during the coldest months should be suitable for thermophile crops, leading to average linear growth rates of about 160 to 200 kg/ha.d. However, measured growth rates during these months in maize and Rhodes grass were less than half these values, probably as a result of damage to the photosynthetic system caused by night temperatures below 10 °C, in combination with high irradiance during the day (Hilliard & West, 1970; West, 1973).

Photoperiod is another sowing date-related factor that could significantly influence crop behaviour. The different growth patterns of spring-planted and autumn-planted potatoes, as observed by Van de Meer et al. (1983) may have been caused by this factor. So far, no systematic research has been carried out with respect to the sowing time sensitivity of most of the annual crops in the region and attention for this aspect is recommended.

7.1.5 *Cutting and grazing management*

A judicious cutting and grazing regime of forage crops and pastures is essential for obtaining both high yields and good feeding quality. For the pampas, only alfalfa grazing management is actually of relevance, as other pastures are not used in practice. The general practice of cutting or grazing the alfalfa about once a month during the six warmest months and once every six weeks in the colder period (coinciding with approximately 10% flowering) appeared most favourable as concluded from the experimental evidence obtained during the project period (Section 3.4.3). Even so, farmers' yields are generally much lower than those obtained at the experiment station. Two major factors may explain this difference. The irregular supply of irrigation water has already been discussed. The other factor may be related to the grazing management practised by the farmers. As the stocking rate is generally too high, the alfalfa fields are overgrazed as a rule, leaving only a little green stubble. Moreover, the fields are often further grazed by small ruminants and other animals, directly after removal of the cattle herd. Consequently, leaf area as well as bud number and reserve levels are negatively affected, which may cause a much slower recovery after exploitation, reducing the overall yield. The quantitative consequences of different exploitation intensities, however, cannot be discussed in detail as no experimental results are available.

7.1.6 *Cultivar characteristics*

The ultimate yield of a certain crop is, in addition to environmental conditions and management regime, determined by cultivar characteristics such as harvest index, growth duration, pest and disease resistance, photoperiod-sensitivity etc. In our experiments in San Camilo, locally selected cultivars or ecotypes of maize, alfalfa and potato, generally performed better than cultivars introduced from elsewhere. Several characteristics, however, seem potentially amenable to improvements by breeding and selection. In maize, for example, decreased sensitivity to low night temperatures and mechanical soil resistance would be very desirable. As another example, both alfalfa cultivars tested in our experiments seem to use a very large share of the assimilates for building and maintaining an extensive root system (Section 3.3.1.3 and 3.3.4.5). Cultivars that would have a different partitioning pattern, more favourable to the above-ground parts, such as found in cultivars adapted to more temperate climates (Sibma, unpublished results), would probably show a much larger yielding ability. The first indications in this respect, obtained from some recently introduced foreign alfalfa cultivars were not encouraging, as yields were not improved and they did not match the good persistence of the local cultivar Tambo. The local potato cultivar, Revolución, also showed a higher total dry matter production capacity than the Dutch cultivar Désirée. Even so, the tuber yield of Revolución was not higher, as it produced three times as much foliage as Désirée. Thus, also in this case a more favourable distribution of biomass may potentially increase yields.

The above examples show that cultivar characteristics are a key factor in determining the ultimate economic yield. Compared to introductions from abroad, local cultivars performed very well, although several characteristics can be improved. Cultivar testing therefore remains an important part of practical research and the unrestrained introductions of so-called improved foreign cultivars by merchants, as is being done with alfalfa during the past years, should be viewed with concern.

The research carried out in the irrigated pampas in southern Peru has shown that high yields can be obtained, per unit area as well as per unit of irrigation water, so long as the factors discussed are taken into account. Some of these, like proper N fertilization and the choice of an adequate sowing time, are under control of individual farmers and useful recommendations can already be made at this stage. Several of these factors still need additional research, much of which can be carried out with the available facilities and manpower. However, a point like the improvement of cultivars by a special breeding programme, is time-consuming and expensive, and is probably not a realistic possibility for the experiment station in San Camilo. An important factor like the improvement of the water supply, is technically simple to solve, but organizational and political consequences are far-reaching and, therefore, virtually no progress has been made in this respect during the past few years. However, an effective registration of the actual use of irrigation water by individual farmers, who on the other hand should have more flexibility to use the water as they wish, seems to be a key factor for the increase of yield per unit irrigation water.

7.2 MODELLING AND SIMULATION IN AGRICULTURE

Following its success in the technical sciences, the development of dynamic models for the simulation of agrobiological processes has created expectations that such models might lead to a better insight in the quantitative relations among fundamental processes in plant and crop physiology. This could result in more effective problem-oriented research. In addition, it is also hoped that such models, given some basic data, may become sufficiently accurate for adequate predictions to be made about growth and production of certain crops in different climatic regions before growing them. The research carried out in Southern Peru offered the opportunity to test and possibly evaluate these prospects, utilizing the simulation models of agrobiological systems made principally by the "Wageningen croup" (De Wit, 1970; Van Keulen, 1975; De Wit et al., 1978; Penning de Vries, 1982a).

7.2.1 *Simulation as a tool for research in developing countries*

Modelling in sciences like biology, plant physiology and agriculture has partly been initiated to provide a link between the detailed analytical research in the laboratory under controlled conditions and the problems in the field. The models developed for this goal should therefore contribute to our understanding of the system in the field, integrating knowledge about the individual relevant processes. The models should thus function as a bridge between areas and levels of knowledge and as a basis for generalization. Simulation should also lead to the formulation of hypotheses and new ideas for experiments to test them (De Wit, 1975; Penning de Vries, 1977). This view on modelling suggests that experimental research combined with simulation may be an effective method for the aquisition of thorough knowledge of an agricultural system, offering therefore better options for optimal exploitation.

This desired close connection between experimental research and modelling is in practice, however, limited to a relatively small part of the agricultural research carried out in the world and particularly in developing countries. Firstly, modelling is a highly specialized field of activity with still only a limited number of people involved. In addition, a scientifically interesting model is often too detailed and not sufficiently documented to be handled by outsiders, so that only those who are actively involved in its development, are able to maintain fruitful contacts with interested users. In fact insufficient efforts have been made sofar to advance models to a level where they can easily be applied by others with limited computer facilities. The experience within the FAPROCAF project has shown that such contacts need to be intensive to be fruitful and that they are also rather time-consuming. When the site of field research is far away from the place where the modelling is done, adequate communication is, in practice, almost impossible. During the FAPROCAF project only once, when one of the researchers was on home leave, could such contact be established. An unattractive consequence of this is that the simulation activities in that case have generally little or no active participation from the counterparts from the developing countries. As a result of the difficult communication and the lack of manpower at the backing institutes, most of the modelling work with respect to FAPROCAF was carried out after the termination of the project, with little or no feedback to further experimentation. This points to a second limitation: parallel modelling and research activities should extend over several cycles and no real progress can be expected on a short-term basis. Therefore, the experimental results and subsequent modelling activities obtained during FAPROCAF were only sufficient for the identification and quantification of several interesting phenomena. However, the many necessary assumptions need further experimentation before reliable conclusions can be drawn. The fact that the latter will probably not be carried out, leaves the value of the simulation efforts in doubt.

The question whether agricultural research in combination with modelling is really helpful in developing countries to provide the data they most urgently need, is also of importance. The generally large gap between actual and attainable yield in most cases does not need simulation support for identification and further quantification of the most important limiting factors. For example, modelling as such is not helpful to the research necessary to formulate recommendations for the elimination of most of the yield-limiting factors in the San Camilo region discussed in the previous section, such as fertilization efficiency, rotation, sowing periods, etc. For these types of experiments enough insight can be gained if, during the investigations, adequate additional information is obtained from, for example, chemical plant analyses, periodic harvests and observations on phenological development. Such experiments are often also attractive for demonstration purposes to farmers or to the agricultural extension service, a characteristic that is lacking with many of the research executed mainly for scientific and modelling objectives.

During the execution of the FAPROCAF project, the benefit from simulation as such has been rather limited and was confined to the modelling activities of Van Keulen and Zipori (unpublished results) on the growth of alfalfa. However, this conclusion does not do justice to the continuous support of the Centre for Agrobiological Research (CABO) and the Department of Theoretical Production Ecology of the Agricultural University, both in Wageningen, and the Hebrew University in Rehovot, which was often based on simulation experience from earlier experiments. These contacts frequently resulted in the quantitative interpretation of the results obtained and also in ideas for further experimentation. The hierarchical approach used in this report, starting from a potential yield level and subsequently investigating the most important constraints influencing actual production in a more fundamental way, has been inspired by the modelling approach followed in these institutes. In that way, the results may be used for extrapolation to other areas and other conditions.

An additional benefit of the simulations using the existing comprehensive models BACROS and PHOTON after termination of the project was that some improvements could be introduced to the models, whilst some weak areas were highlighted. The adaptation of the ARID CROP model for alfalfa growth under different cutting regimes, must be considered as preliminary and still requires considerable experimentation and further model development.

On the whole, it would seem that, as for FAPROCAF, simulation as such is not a tool that makes most types of research in and for developing countries more effective. However, sufficient attention to relevant underlying processes (sometimes indicated by modelling-oriented research elsewhere), can be very fruitful. A well-thought out planning and organization of the experiments and a "quantitative attitude" should then suffice for the production of the relevant data in an efficient way.

7.2.2 *Simulation as a tool for prediction of potential growth*

The possibility of accurately predicting the yield of crops under the specific conditions of a region would be an attractive facility for the analysis of regional agriculture and the development of options for its improvement. Agro-technical models that can be used in combination with socio-economic models for planning and policy evaluation purposes are actually developed with this in mind (SOW, 1980). In these models, the hierarchical approach as indicated in Section 1.5, is followed. The starting point is the estimation of potential production, i.e. crop production that is only dependent on irradiance and temperature, as all other possible constraints are assumed to have been effectively eliminated. Subsequently, the influence of various production factors such as water availability, nutrient supply and the influence of weeds, pests and diseases, is evaluated. The lower one gets into the hierarchy, the more complex and less accurate the quantitative descriptions are and hence the less reliable the results. Models for level 1 (potential growth) and level 2 (only water limiting) are well-developed, as the underlying knowledge is sufficiently advanced. However, much knowledge about the factors involved in the lower levels is still lacking and modelling, therefore, is still in a preliminary stage (De Wit & Penning de Vries, 1982).

The potential production is thus a logical starting point for the analysis of a specific situation. It shows the scope for improvements from an agro-technical point of view and as such it also serves as a yardstick for the evaluation of locally obtained experimental results. As can be deduced from Section 7.1, the potential production level is of particular interest for irrigation projects, because at or near this level maximum efficiency of the use of irrigation water is obtained.

Although comprehensive models such as BACROS are developed principally as tools for analysis and explanation at the plant physiological level, the expectation that such models also have prediction value often provides a strong motivation for their development (Penning de Vries, 1982a). Therefore, that model was chosen to simulate the potential growth of maize and Rhodes grass in the San Camilo situation (Sections 5.4 and 6.5). The results of these simulation experiments showed that for accurate predictions, a fairly large number of crop (or even cultivar) specific factors in relation with the growing site must be provided, usually estimated from experimental data. For new areas such information is by definition not available and then independent estimates must be made, which may strongly influence the ultimate results. Some of these factors are indicated below:

- Simulation of leaf area development. In BACROS the incorporation of a forcing function of leaf area development into the model is preferred, although often such a function is not available. In some cases a direct relation between total above-ground dry weight and leaf area appears to yield satisfactory results (Dayan et al., 1981b). Alternatively, a partitioning function for dry matter may be defined, in dependence of for instance accumulated temperature and the leaf area may be calculated from an average, crop-specific leaf weight to area ratio. Partitioning patterns are, however, highly cultivar-specific and may be influenced by photoperiod or other environmental factors. Furthermore, an assumption has to be made with regard to leaf death, which is also crop and cultivar-dependent. For the ultimate result, however, leaf area plays a key role, as it defines the proportion of available irradiance effectively used for photosynthesis. An accurate prediction of leaf area development is especially important in situations where during a substantial part of the growing cycle the crop does not form a closed cover.

- Simulation of the distribution of biomass over various plant parts, as this largely determines economic yield. The distribution pattern is a cultivar characteristic, for which firm data are seldom available.
- The value for the maximum assimilation rate of a single leaf at light saturation must be estimated. Often values of 40 and 70 kg CO_2/ha.h are taken for C_3 and C_4 crops, respectively, but sometimes lower or higher values are taken to obtain a good fit with measured data. For example in Zambia for wheat (Van Keulen & De Milliano, 1984) and in Mali for maize (Penning de Vries, 1982b and personal communication), values of 30 and 90 kg CO_2/ha.h were used. Evidently such adaptations have a significant influence on the results.
- The value of the reference temperature, chosen for the calculation of maintenance respiration. Van Heemst (1984a) gives approximate values for the relative maintenance respiration rate of grains of 0.015 g carbohydrate per g dry matter per day, at a temperature of 20 °C, whereas Van Keulen et al. (1982) take the same value with 25 °C as basis for the calculation of maintenance respiration of wheat in Zambia. As temperature stimulates maintenance respiration by a factor two per 10 °C, calculated growth rates could be considerably higher if the standard value is defined at a higher reference temperature. Penning de Vries & Van Laar (1982) suggested to take a reference temperature to which the crop is adapted. Such a statement, however, leaves considerable room for variations in prediction.

Taking into account these causes of variations in prediction, it is not surprising that comprehensive computer models for the simulation of potential growth often do not have better predictive value as simplified summary models (Penning de Vries, 1982a). Step-wise calculations using a pocket calculator and time intervals of 10 days will also suffice in most cases and even still simpler calculations such as used by the Agro-ecological Zones Project (FAO, 1978; 1981) give similar potential yield predictions, as is shown by Versteeg & Van Keulen (in preparation).

It can be concluded that the advantage of computer simulation models is more confined to predictions and judgements in complex situations where many variables are involved, such as quantifying the impact of pests and diseases and the desirability of control measures, or the influence of policy measures on regional or national economy. However, even in highly developed countries limited use is made of this tool and the results are still under debate. If they become of practical importance in the future, for most of the less developed countries they may be relevant mainly for rather exceptional cases, like for example for large scale, estate type of agriculture.

SUMMARY

THE SIGNIFICANCE OF RESEARCH TO POTENTIAL AGRICULTURAL PRODUCTION IN IRRIGATED DESERT AREAS

Thirty-six per cent of the world's land surface is situated in arid and semi-arid regions in which regular and high crop yields can only be assured by irrigation. Actually, only about one-seventh of the area is used for agriculture, one-seventh of which is irrigated. In irrigated areas in less developed countries, crop yields are, on average, less than half those in developed countries, and often less than one-third. That means that half to two-thirds of the irrigation water applied is not used for crop production and, in fact, that water is often lost. This loss can effectively be reduced by aiming at the highest possible yield per unit irrigated area. A more efficient use of water absorbed by the plant will barely influence the efficiency of irrigation-water utilization and will sometimes even decrease it.

In this thesis, the results are presented of research aimed at identifying and quantifying the most important factors for high crop yields in the irrigated plains around San Camilo (16 °S, 71 °W) in Southern Peru. Another aim of the study was to improve existing simulation models and to test their capacity to improve research planning or extrapolate research results. The investigations were limited to four crops, viz. alfalfa, potato, Rhodes grass and maize, as examples of perennial and annual C_3 and C_4 crops, respectively.

The project-history, the present agricultural system in the region, the irrigation water supply, the climate, soil conditions and the measuring techniques used are described.

ALFALFA

Well-irrigated alfalfa reached an annual yield of about 27 t/ha with ten cuttings per year. Following a relatively short lag period after cutting, a season-dependent maximum linear growth rate of 125 to 225 kg/ha.d was reached, but after two to three weeks, the growth rate of the aerial parts decreased drastically and often (depending on season and cultivar) growth ceased completely. The foliage was then still green and no indications of decreased photosynthesis were obvious. Alfalfa grown at higher latitudes shows a much longer linear growth period during spring, but during late summer and autumn this stage is usually also rather short. Cultivar-specific photoperiod-sensitivity seems to play a role. In Peru, there were strong indications that aerial growth is closely associated with the size and growth of the root system. At an early stage in the regrowth cycle, a large proportion of the assimilates produced is translocated below-ground. At low cutting frequencies this leads to the build-up of a large mass of roots (up to 25 t/ha). However, at high cutting frequencies, the quantity of roots was only one tenth.

The conditions in San Camilo allowed a high nitrogen fixation, estimated at about 700 kg N/ha annually. Even so, high N fertilization produced a small (8-13%) but significant increase in forage yields. This might be explained by the higher respiration costs of N_2 fixation, compared to NO_3 assimilation.

The influence of cutting frequency on plant density seems to be related to the sensitivity of the crowns to mechanical damage during cutting, and striking differences between cultivars were observed. In one of the experiments, dry matter yield was higher in non-weeded fields, but

digestibility and palatability were hardly affected and remained at an acceptable level. Even so, care must be taken to prevent the invasion of Bermuda grass (*Cynodon dactylon*) and Kikuyu grass (*Pennisetum clandestinum*), which crowd out alfalfa by aggressive sod formation.

K fertilization did not result in higher forage yields and only in sporadic cases were responses obtained from P fertilization. Because of the large variations in forage-P and K concentrations not related to the level of supply, but caused by factors such as age of the sward and regrowth, season and cultivar, such concentrations are only useful to identify very approximate critical ranges. Results of soil analyses in San Camilo cannot serve as a basis for fertilizer recommendations, as soil variability is very large. Because of the type of parent rock material, the grazing system practised and the mineral influx in irrigation water, no economic fertilizer responses are expected with alfalfa in the San Camilo region in the early stages of settlement.

Computer simulations of photosynthesis using the comprehensive model PHOTON resulted in over- and under-estimations of 20 to 25% for alfalfa assimilation as measured in the greenhouse in the Netherlands.

The simulation model ARID CROP was adapted to an alfalfa cutting-management model. Its results approached reasonably the strongly varying results with respect to forage yield, level of reserves and root mass, obtained at different cutting intervals in the field. The model adaptation was based on the hypothesis that, at an early stage in the regrowth cycle, alfalfa translocates a large proportion of its photosynthates to the root system, to establish a pool of reserves. After cutting, these reserves are partly translocated to the regrowing stubble and simultaneously, root structural material dies off. These processes cease as soon as photosynthesis is restored to some degree. The reverse assimilate transport then starts again.

POTATO

Experimental results from a Peruvian (Revolución) and a Dutch (Désirée) cultivar indicate, that with proper sprinkler irrigation 70 to 80 t/ha of potatoes can be produced. The Peruvian cultivar exhibited a total dry matter growth rate of 270 kg/ha.d, but the duration of the linear growth stage was shorter than that usually found in more temperate regions. The harvest index was also rather low, so that final tuber yield was not higher than the potential established in temperate regions. Désirée exhibited a 20% lower total dry matter growth rate but, because of a higher harvest index, a comparable tuber yield was attained. Revolución produced 2.5 to 3 times more leaf area than Désirée, but that did not lead to more efficient light interception.

The NPK uptake pattern showed that split N and K fertilization can increase fertilizer recovery. Split applications result in different mineral concentrations in the foliage, as well as in deviating NO_3-concentrations in the petioles, compared to a single dressing. Therefore, no comparisons with published tissue concentrations could be made, as usually fertilizer applications are not split. However, the final tuber NPK concentration and the yield indicated that the crop did not suffer from nutrient shortage.

A line-source sprinkler irrigation experiment provided good insight in water utilization of the potato. Potatoes take up only a small portion of the water supplied, but this water is used efficiently for dry matter production. Therefore, it seems possible to reach potentially high water utilization figures for potatoes, if irrigation techniques can be adapted to the low uptake capacity. Water stress delays tuber initiation through its effect on the moment that a threshold quantity of foliage is produced. This threshold appeared much lower for Désirée than for Revolución, so that the first cultivar is preferable in the case of an unreliable water supply.

RHODES GRASS

No data were available in the project area on Rhodes grass (*Chloris gayana*) and use was made of experimental and modelling data obtained in Israel. With a sufficient N supply, the annual cumulative experimental production was slightly higher in Peru (44 t/ha) than in Israel (38 t/ha). This was caused by a longer period of favourable temperatures during the year and by a longer continuation of the linear growth stage. On the other hand, the linear growth rates obtained in Israel were higher and the exponential stage before the period of linear growth was shorter. Growth in autumn, winter and spring in Peru was less than expected on the basis of average temperatures and irradiance. This was confirmed by simulation results obtained using the model BACROS, which had produced reliable predictions for the Israeli situation. For San Camilo, the simulated results were only similar to the ones measured during the summer period; the simulated yields for autumn/spring and winter exceeded the measured yields by 50 and 100%, respectively. On an annual basis, the simulated production was more than 50% higher than the actual harvest. The low night temperatures during the cool periods are probably the cause of permanent damage to the chloroplasts, especially when irradiance during daytime is high.

There were indications that with Rhodes grass very high N fertilizer recoveries can be obtained.

MAIZE

Growth of well-irrigated and fertilized maize was strongly determined by sowing time. In early spring (September), initial growth was very slow, so that the linear growth stage occurred during summer. During that period a high linear growth rate of 330 kg/ha.d and a high final production of 26 t/ha was obtained. Sowing two months later, resulted in accelerated initial growth, while linear growth still took place during the summer months. A similar high growth rate and final production were therefore obtained. Sowing in early summer (January) resulted in even faster initial growth, but now most of the linear stage occurred during autumn, with relatively many cold nights. Apparently under those conditions, this C_4 crop also suffered permanent damage to the chloroplasts, because the linear growth rate was only 145 kg/ha.d and final production decreased to about 12 t/ha. Cultivars from the Netherlands and Israel yielded less than local hybrids. During exponential growth, a similar correlation between crop height and dry matter weight was found for all cultivars. The influence of mechanical soil resistance on maize growth was striking. Sub-soiling increased rooting depth from about 35 to 70 cm and increased the linear growth rate from 175 to 330 kg/ha.d. Furrows filled with clay loam from the near-by Tambo valley, increased the linear growth rate even further to 500 kg/ha.d, resulting in a final dry matter production of about 36 t/ha. These results show that to obtain potential growth it is not enough to supply a healthy crop with sufficient water and nutrients; soil physical factors should also permit unrestricted utilization of these growth factors.

After a preceding crop of alfalfa, non-fertilized maize produced 21 t/ha dry matter, which was 80% of the yield obtained with ample N fertilization.

As for Rhodes grass, the maize growth rates simulated with BACROS were too high during autumn and early spring, probably because of damage in the field to the leaf photosynthetic apparatus due to low night temperatures. The extremely high summer growth rates in Tambo clay loam, could only be simulated using physiological assumptions, for which there was no basis in fact.

THE MOST IMPORTANT FACTORS FOR IRRIGATED CROP PRODUCTION

Maximum utilization efficiency of irrigation water is obtained by supplying an optimally growing crop with just enough water to attain maximum yield. This includes measures for the regulation of the water supply, as well as optimization of the other growth conditions.

Improvements in the crop water supply in the area are hampered by two conditions, viz. lack of efficient monitoring of actual water use by the individual farmer and the irregular water supply throughout the year. Especially in crops which lose much water due to soil evaporation (incomplete soil cover) or to percolation (low uptake capacity), a low production per unit applied irrigation water is easily obtained.

With respect to other growth conditions around San Camilo, an insufficient N supply to non-leguminous crops is probably the main reason why actual production usually remains far below the potential. However, other crop-specific factors such as low night temperatures for both maize and Rhodes grass, and mechanical soil resistance of many pampa soils for maize, may also significantly influence production. There are also indications that the grazing system practised by many farmers often leads to over-grazing and decreased alfalfa yields. Finally, cultivar characteristics appeared to be important for the ultimate yield. Local cultivars generally showed the best performance, although several characteristics, such as harvest index (alfalfa and potato), cold-tolerance and sensitivity to mechanical soil resistance (maize) could probably be improved.

USE OF SIMULATION FOR RESEARCH AND PREDICTION IN AGRICULTURE

Within agricultural research, simulation models are developed mainly to increase insight in biological systems and on that basis to predict agricultural production from fundamental knowledge of basic processes. Therefore, close contact and long interaction between modelling and experimentation is a primary prerequisite for succesful implementation. Due to the short duration of the FAPROCAF project and the long distance between the sites of experimentation and modelling, little direct inpact from simulation was obtained during the project period. Even so, it benefitted from the knowledge and experience of the backing institutes, which is partly based on earlier simulations.

For accurate predictions of, for example, potential production possibilities, actual available simulation models still need a considerable amount of specific information, such as leaf area development, dry matter partitioning, level of assimilation at light saturation and reference temperature for the calculation of the maintenance respiration. The influence of such information on the final result is so large, that simplified calculation methods produce equally accurate predictions compared to more sophisticated computer simulations, if the same specific data are available.

FACTOREN DIE DE PRODUKTIE VAN GEIRRIGEERDE GEWASSEN IN ZUID PERU BEINVLOEDEN, GERELATEERD AAN VOORSPELLINGEN DOOR SIMULATIEMODELLEN

SAMENVATTING

DE BETEKENIS VAN ONDERZOEK NAAR POTENTIELE PRODUKTIE IN GEIRRIGEERDE WOESTIJNGEBIEDEN

Zes en dertig procent van het landoppervlak op aarde bevindt zich in de aride en semi-aride gebieden. Alleen met irrigatie kan hier een regelmatige en hoge landbouwopbrengst worden verkregen. Momenteel is ongeveer 1/7 van dit areaal in gebruik voor de landbouw en wederom ruwweg 1/7 hiervan wordt geïrrigeerd. Gemiddeld liggen de gewasopbrengsten in de geïrrigeerde arealen van de derde wereld op minder dan de helft van vergelijkbare opbrengsten in de ontwikkelde landen en in veel landen ligt het niveau zelfs op minder dan eenderde hiervan. Dit betekent dat ongeveer de helft tot tweederde van de hoeveelheid irrigatiewater op een akker niet wordt gebruikt voor gewasproduktie en vaak gaat dit water verloren. Deze verliespost kan belangrijk worden tegengegaan indien een zo hoog mogelijke opbrengst per eenheid geïrrigeerde oppervlakte wordt verkregen. Het zoeken naar een efficiënter gebruik van door de plant zelf opgenomen hoeveelheid water zal nauwelijks effect hebben op een efficiënter gebruik van het irrigatiewater en kan soms zelfs leiden tot een verslechtering van deze efficiëntie.

In dit proefschrift worden de resultaten van onderzoek behandeld, dat het identificeren en quantificeren van de belangrijkste factoren voor een hoge gewasproduktie in de geïrrigeerde vlakten rond San Camilo (16 °S, 71 °W) in Zuid-Peru tot doel had. Een nevendoelstelling daarbij was om bestaande simulatiemodellen van gewasgroei te toetsen op hun effectiviteit om de onderzoeksdoelstellingen sneller en/of beter uit te voeren en deze zo nodig te verbeteren. Het onderzoek spitste zich toe op de gewassen luzerne, aardappel, Rhodesgras en maïs, als voorbeelden van meerjarige en eenjarige C_3 en C_4 gewassen.

De voorgeschiedenis van het project, het projectgebied, het aanwezige landbouwsysteem, de watervoorziening, het klimaat, de bodemgesteldheid en de gebruikte meettechnieken worden beschreven.

LUZERNE

Een goed geïrrigeerd gewas luzerne bereikte in San Camilo een gemiddelde jaaropbrengst van rond 27 t/ha bij tien sneden per jaar. Na het snijden werd snel de maximale liniaire groeisnelheid (van tussen 125 en 225 kg/ha.d) bereikt, maar na twee tot drie weken liep deze drastisch terug en vaak (afhankelijk van seizoen en ras) kwam het tot een groeistilstand. Het bladerdek was dan nog volledig groen en er werden geen aanwijzingen gevonden voor afnemende fotosynthese. Op hogere breedtegraden heeft de luzerne in het voorseizoen een veel langere liniaire groeifase, maar bij gelijke daglengte in het naseizoen is deze ook daar een stuk korter. Ras-specifieke fotoperiodische gevoeligheid lijkt hierbij een rol te spelen. In Peru werden aanwijzingen verkregen dat de bovengrondse groei sterk wordt beïnvloed door de omvang en de groei van het wortelstelsel. Hierbij lijkt al vroeg een groot deel van de gevormde assimilaten naar het wortelstelsel te worden verplaatst. Als gevolg hiervan werden bij een lage snijfrequentie grote hoeveelheden wortelmassa gevonden (tot 25 t/ha ondergrondse droge-stof), terwijl bij een kort snij-interval de wortelmassa tienmaal zo klein was.

Door gunstige milieu-omstandigheden in San Camilo vond er een hoge stikstofbinding plaats. Deze werd berekend op ongeveer 700 kg N/ha.j. Hoge

N- bemesting gaf een kleine (8-13%), maar duidelijk significante meeropbrengst. Deze kan worden verklaard door de hogere ademhalingskosten van de stikstofbinding, vergeleken met die van de nitraatassimilatie.

De invloed van de snijfrequentie op de dichtheid van het gewas leek verband te houden met de gevoeligheid van de kronen voor mechanische schade bij het snijden, welke op zijn beurt sterk afhankelijk was van het ras.

In een proef zonder onkruidbestrijding bleek het onkruidenbestand de droge-stofopbrengst te verhogen, zonder dat een schadelijke vermindering van de verteerbaarheid en de smakelijkheid voor het vee optrad. In de praktijk dient echter gewaakt te worden voor het binnendringen van Bermudagras (*Cynodon dactylon*) en Kikuyugras (*Pennisetum clandestinum*), die door agressieve zodevorming de luzerneplanten te sterk verdringen.

Kaliumbemesting verhoogde de opbrengst niet en slechts in sporadische gevallen werd een positief effect van fosfaatbemesting gevonden. Het P- en K-gehalte in de plant was, vanwege de variabiliteit hierin, slechts bruikbaar ter indicatie van een gevarenzone. Hierbij bleek dat, behalve de bodembeschikbaarheid van de betreffende elementen, ook de ouderdom van de zode, de leeftijd van de hergroei, het seizoen en het ras van invloed te zijn op het gehalte. Door de grote variatie in de bodemgesteldheid in San Camilo zijn bodemanalyses geen juiste basis voor bemestingsadviezen. Gezien de aard van het moedergesteente, het toegepaste beweidingssysteem en de mineralenaanvoer door het irrigatiewater, zal er rond San Camilo in de meeste gevallen voorlopig nog geen economisch bemestingseffect bij luzerne te verwachten zijn.

Simulaties met het gedetailleerde model PHOTON van in Nederland uitgevoerde fotosynthesemetingen aan in kassen opgegroeide luzerne, resulteerde in afwijkingen van 20-25%, zowel boven- als onder de meetresultaten.

Het simulatiemodel ARID CROP werd aangepast tot een luzerne snijmodel dat de sterk verschillende meetresultaten van diverse snijfrequenties, ten aanzien van ruwvoederopbrengst, reservegehalte en wortelmassa, redelijk benaderde. De modelaanpassing berustte hoofdzakelijk op de hypothese dat luzerne in een vroeg stadium grote hoeveelheden fotosyntheseprodukten naar het wortelstelsel transporteerde voor de opbouw van een reservevoorraad. Na het snijden worden de reserves gebruikt voor de bovengrondse spruiten, waarbij simultaan structureel wortelmateriaal afsterft. Deze processen stoppen zodra de fotosynthese enigszins is hersteld. Daarna gaat het assimilatentransport naar de ondergrondse delen weer van start.

AARDAPPEL

Onderzoek met een Peruaans (Revolución) en een Nederlands ras (Désirée) toonde aan, dat met een goede beregening 70-80 t/ha aardappelen kon worden geproduceerd. Hierbij werd door het Peruaanse ras een groeisnelheid van 270 kg totaal droge stof/ha.d behaald. De duur van de liniaire groeifase was korter dan wat doorgaans onder koelere klimaatomstandigheden wordt gevonden. Bovendien was de oogstindex aan de lage kant, zodat de uiteindelijke knolopbrengst niet hoger was dan wat potentieel in gematigde klimaatomstandigheden kan worden geproduceerd. Désirée had een 20% lagere totaal droge-stofgroeisnelheid, maar door een hogere oogstindex werd uiteindelijk een vergelijkbare knolopbrengst verkregen. Revolución vormde bijna 2,5-3 maal zoveel bladoppervlak als Désirée, maar dit gaf geen duidelijk verschil in effectieve lichtonderschepping.

Het NPK opname-patroon toonde aan dat gedeelde kunstmesttoediening tot een verhoogde efficiëntie kan leiden. In vergelijking met eenmalig toegediende kunstmestgiften gaven gedeelde giften sterk gewijzigde N- en

K-gehalten in het loof, evenals afwijkende NO_3-N-gehalten in de petiolen. Hierdoor waren vergelijkingen met elders gepubliceerde gehaltes niet goed mogelijk, omdat meestal geen gedeelde giften werden toegepast. Uit de knolopbrengst en het NPK gehalte in de knollen kon echter worden afgeleid, dat de nutriëntenvoorziening van het gewas voldoende was geweest.

Uit een proef met geleidelijk afnemende beregeningsintensiteit kon een goed inzicht worden verkregen in het watergebruik van de aardappel. Hierbij bleek dat slechts een relatief klein deel van het toegediende water door de plant wordt opgenomen, maar dat dit efficiënt wordt benut. Hierdoor lijkt het mogelijk dat met aangepaste irrigatietechnieken potentiëel hoge watergebruiksefficiënties bereikt kunnen worden. Door watergebrek werd de aanleg van knollen vertraagd, totdat een bepaalde drempelhoeveelheid loof was gevormd. Deze drempel bleek bij Dësirée veel lager te liggen dan bij Revolución, zodat het eerste ras de voorkeur verdient als de watervoorziening onzeker is.

RHODESGRAS

Over de groei van Rhodesgras (*Chloris gayana*) bestonden in het projectgebied geen gegevens. Bij het onderzoek van dit meerjarig tropische C_4 gras werd daarom veel gebruik gemaakt van onderzoeks- en simulatiegegevens uit Israël. Wanneer er voldoende stikstof werd toegediend bleek de som van de produkties van de afzonderlijke sneden door het jaar heen in Peru een iets hoger totaal (44 t/ha) te geven dan in Israël (38 t/ha). Dit werd veroorzaakt door het langere groeiseizoen en ook door de langere duur van de liniaire groeifase. Daarentegen waren in Israël de liniaire groeisnelheden gedurende het seizoen meestal hoger en duurde de exponentiële fase in het begin korter. De groei in herfst, winter en lente was in Peru lager dan op de grond van lichtintensiteit en temperatuur verwacht werd. Dit bleek ook uit de simulaties uitgevoerd met het BACROS model, dat voor situaties in Israël goede voorspellingen had opgeleverd. De simulaties voor San Camilo waren alleen gedurende de zomermaanden overeenkomstig de gemeten produkties; voor de winter- en de lente/herfstperioden lagen deze ruwweg 100% respectievelijk 50% boven de gemeten opbrengsten. De totale jaarproduktie werd zodoende met ruim 50% overschat. Vermoedelijk is dit te wijten aan een permanente beschadiging van chloroplasten, veroorzaakt door koude nachttemperaturen, vooral na dagen van hoge instraling.

Indicaties werden verkregen dat met Rhodesgras in Peru een hoge stikstof-bemestingsefficiëntie kan worden bereikt.

MAIS

De groei van goed geïrrigeerde en bemeste maïs in San Camilo werd sterk bepaald door het zaaitijdstip. In de vroege lente (september) was de start bijzonder traag, waardoor de liniaire groeifase in de zomer plaatsvond. In deze periode werd een hoge groeisnelheid van 330 kg/ha.d en een hoge eindopbrengst van 26 t/ha droge stof gehaald. Door twee maanden later in te zaaien werd de beginsgroei sneller en vond de liniaire groeifase nog volledig in de zomer plaats. Daardoor werden ook hier een vergelijkbaar hoge groeisnelheid en eindopbrengst gehaald. Inzaai in de vroege zomer leverde een nog snellere aanvangsgroei op, maar nu viel het grootste deel van de liniaire groeifase in de herfstperiode, met een groot aantal koude nachten. Vermoedelijk werd hierdoor ook bij dit C_4 gewas blijvende schade toegebracht aan de chloroplasten. Het gevolg was dat de liniaire groeisnelheid werd gehalveerd tot 145 kg/ha.d en de eindopbrengst uitkwam op ongeveer 12 t/ha droge stof.

De uit Nederland en Israël geïmporteerde rassen vertoonden een duidelijk afwijkende groei van die van de lokale hybriden en haalden een lagere opbrengst. Onafhankelijk hiervan, was er tijdens de exponentiële groeifase een, voor alle rassen gelijk, verband tussen lengte en droge-stofopbrengst. Frappant was de invloed van mechanische bodemweerstand op de groei van maïs in de pampa. Diepploegen verbeterde de bewortelingsdiepte van ongeveer 35 tot 70 cm en verhoogde de liniaire groeisnelheid van 175 tot 330 kg/ha.d. Inzaai in geulen gevuld met lemige klei uit de naburige Tambo vallei deed de groeisnelheid zelfs toenemen tot 500 kg/ha.d en de eindopbrengst tot 36 t/ha droge stof. Deze resultaten tonen aan dat voor het verkrijgen van potentiële groei het niet voldoende is om te zorgen voor een gezond gewas en een goede water- en nutriëntenvoorziening, omdat ook bodemfysische eigenschappen de opname van deze groeifactoren kunnen beperken. Door een luzerne voorvrucht kon niet van stikstof voorziene maïs 21 t/ha ruwvoer produceren; dit is ongeveer 80% van de opbrengst gehaald door ruim met stikstof bemeste maïs.

Net als bij Rhodesgras werd ook voor maïs de groei in de herfst en het vroege voorjaar door het BACROS simulatiemodel overschat, vermoedelijk door de beschadiging van het fotosynthese-apparaat als gevolg van koude nachttemperaturen. De extreem hoge zomergroei met Tambo klei kon alleen worden gesimuleerd met behulp van fysiologische hypothesen, waar feitelijk geen gegevens over zijn.

DE BELANGRIJKSTE FACTOREN VOOR GEIRRIGEERDE GEWASSENPRODUKTIE

Maximale benutting van het irrigatiewater wordt verkregen door een optimaal groeiend gewas juist voldoende water te geven om tot een maximale opbrengst te komen. Dit houdt maatregelen in ter regulering van de hoeveelheid water, alsmede ter optimalisering van de overige groeivoorwaarden.

Ten aanzien van de watervoorziening wordt een verbetering in het projectgebied sterk belemmerd door twee aspecten, te weten de afwezigheid van controle op het feitelijke watergebruik door de individuele boer en de onregelmatige watervoorziening gedurende het jaar. Vooral bij gewassen waar veel water wordt verloren aan bodemevaporatie (slechte grondbedekking) of percolatie (zwakke beworteling), leidt dit snel tot slechte opbrengsten per m^3 irrigatiewater.

Wat betreft de overige groeivoorwaarden, bleek dat rond San Camilo een gebrekkige stikstofvoorziening bij niet-leguminozen vermoedelijk de belangrijkste reden is dat het hoge opbrengstpotentieel, vaak niet gehaald wordt. Echter ook meer gewas-specifieke factoren kunnen een belangrijke invloed hebben, zoals koude nachttemperaturen op de groei van maïs en Rhodesgras en de mechanische bodemweerstand op de groei van maïs. Ook werden aanwijzingen verkregen dat de door veel boeren toegepaste overbeweiding de opbrengst van luzerne verlaagt. Ten slotte bleken de raseigenschappen belangrijk voor de uiteindelijke opbrengst te zijn. Lokale rassen en hybriden voldeden vaak het best, hoewel een aantal eigenschappen zoals oogstindex (luzerne en aardappel), koudetolerantie en groeipotentieel op gronden met een hoge mechanische weerstand (maïs), waarschijnlijk kunnen worden verbeterd.

HET NUT VAN SIMULATIE VOOR ONDERZOEK EN VOORSPELLING IN DE LANDBOUW

Simulatiemodellen worden in het landbouwkundig onderzoek ontwikkeld om het inzicht in biologische systemen te vergroten en te relateren aan fundamentele kennis van deelprocessen. Hiervoor is een nauw contact en een langdurige wisselwerking tussen simulatie en onderzoek een eerste vereiste.

Het FAPROCAF project heeft door de korte tijdsduur en de grote afstand tussen de plaats van het veldonderzoek en die van de simulatie, weinig direct nut van het simuleren ondervonden. Wel heeft het kunnen profiteren van de inzichten en ervaringen van de begeleidende instituten in Nederland en Israel, welke voor een deel met simulatietechnieken zijn verkregen.

Om tot betrouwbare voorspellingen van bijvoorbeeld het opbrengstpotentieel te kunnen komen, hebben de nu ter beschikking staande simulatiemodellen vrij veel specifieke informatie nodig, bijvoorbeeld ten aanzien van bladontwikkeling, droge-stofverdeling, assimilatieniveau bij lichtverzadiging en referentietemperatuur bij de onderhoudsademhaling. De invloed van deze specifieke gegevens is dermate groot, dat sterk vereenvoudigde berekeningen vergelijkbare voorspellingen geven als computersimulaties, indien over dezelfde specifieke informatie wordt beschikt.

RESUMEN

LA SIGNIFICACIÓN DE LA INVESTIGACIÓN EN LA PRODUCCIÓN POTENCIAL EN AREAS DESÉRTICAS IRRIGADAS

El treinta y seis por ciento de la tierra en el mundo se encuentra en areas áridas y semi-áridas. Sólo con la irrigación es posible llegar a producciones altas y regulares. En este momento aproximadamante una séptima parte de las tierras se usa para la agricultura, de la cual otro séptimo esta bajo riego. En tierras regadas de los paises en desarollo, los rendimentos son, en promedio, menos de la mitad que en los paises desarollados y en muchos de ellos aún menos de una tercera parte. Eso quiere decir, que aproximadamente de 1/2 a 2/3 de la cantidad del agua de riego no es usada y muchas veces esta agua se pierde. Se ha demostrado que se puede disminuir efectivamente esta perdida, buscando un rendimiento mas alto por unidad de area irrigada. La investigación de una mayor eficiencia en el agua absorbida por la planta misma, no mejoraría mucho la eficacia del uso de agua de irrigación y a veces la disminuiría.

En esta tesis seran presentados los resultados de la investigación para la identificación y la cuantificación de los factores más importantes para un rendimiento alto en las áreas irrigadas de la región de San Camilo (16 °S, 71 °W), en el Sur de Perú. Otro objetivo fue mejorar modelos existentes de simulación y de comprobar su capacidad para mejorar la planificación de la investigación agricola o para extrapolar sus resultados. La investigación se limitó a cuatro cultivos: la alfalfa, la papa, el pasto Rhodes y el maíz, como ejemplos de cultivos perennes y anuales del tipo C_3 y C_4.

Los antecedentes del proyecto, el sistema agrícola existente, el abastecimiento de agua de irrigación, el clima, las condiciones del suelo y los métodos de medición son descritos.

ALFALFA

Alfalfa bien irrigado llegó a una producción anual de unas 27 t/ha, con diez cortes por año. Inmediatamente después del corte la máxima tasa de crecimiento lineal de 125 a 225 kg/ha.d fue alcanzada, pero al cabo de 2 o 3 semanas el crecimiento de la parte aérea diminuyó bastante y muchas veces (dependiendo de la época y del cultivar) terminó por completo. No obstante, el follaje estaba verde todavía y no habían indicaciones de que la fotosíntesis hubiera disminuido. En latitudes más altas, la alfalfa muestra épocas de crecimiento lineales mucho más largas durante la primavera, pero durante el otoño y la última parte del verano el periodo de crecimiento lineal es en general también bastante corto.

La sensibilidad al fotoperiodo, dependiente del cultivar, parece tener una influencia importante. En el Perú habían indicaciones claras de que el crecimiento de la parte aérea esta en estrecha relación con el volumen y el crecimiento del sistema radicular. Poco tiempo después del rebrote, la mayor parte de los productos de asimilación es translocada hacia el sistema radicular. Bajo un régimen de cortes muy espaciado, grandes cantidades de raíces fueron formados (hasta 25 t/ha). Por otro lado, con cortes frecuentes, la cantidad de raíces fue diez veces menos.

Las condiciones ambientales en San Camilo fueron favorables para una alta fijación de nitrógeno, que se calculó llegaba hasta 700 kg N/ha.año aproximadamente. No obstante, una alta fertilización en N produjo una pequeña (8-13%), pero significativa, alza en el rendimiento de forraje, causado probablemente por los costos de respiración más altos en la fijación del N_2 en comparación con la asimilación de NO_3.

La influencia de la frecuencia de los cortes sobre la densidad de plantas de alfalfa fue relacionado a la sensibilidad de las coronas a los daños mecánicos durante el corte, y grandes diferencias entre cultivares fueron notadas. En uno de los experimentos el rendimiento de materia seca fue mas alta en parcelas sin deshierbe, mientras que la digestibilidad y la sapidez no fueron afectadas substancialmente y quedaron a un nivel aceptable. No obstante se debe cuidar de prevenir el establecimiento de pasto Bermuda (*Cynodon dactylon*) y Kikuyu (*Pennisetum clandestinum*), que atropellan las plantas de alfalfa por formación agresiva de céspedes.

La fertilización K no resultó en rendimientos más altos y sólo en algunos casos respuestas positivas de fertilización fueron obtenidas. Por la alta variabilidad de las concentraciones de P y K en el forraje la cual no es relacionada con el nivel de abasticemiento, pero que es causada por factores como la edad del campo y del follaje, la época y el cultivar, dichas concentraciones sólo sirven para identificar rangos criticos muy aproximados. Los análisis del suelo en San Camilo no son una buena base para recomendaciones de fertilización dada la variabilidad del suelo. Por el tipo de roca materna, el presente sistema de pastoreo y el aprovisionamiento de minerales a través del agua de irrigación, respuestas económicas de fertilización en la alfalfa no son muy probables a corto plazo alrededor de San Camilo.

El modelo de simulación Arid Crop fue adaptado a un modelo de manejo de corte para la alfalfa, con el cual satisfactoriamente fueron simulados los distintos resultados obtenidos con diferentes regímenes de corte en cuanto al rendimiento de forraje, al contenido de reservas y a la cantidad de raices. La adaptación de este modelo fue en base a la hipótesis, que muy pronto la alfalfa transporta gran parte de los productos de fotosíntesis al sistema radicular para establecer un "pool" de reservas. Después del corte, estas reservas son translocadas hacia el rebrote, mientras al mismo tiempo material radicular estructural desaparece por necrosis. Estos procesos terminan en el momento en que la fotosíntesis empieza de nuevo. Después el transporte de productos de asimilación se realiza en dirección contraria hacia el sistema radicular.

PAPA *(Solanum tuberosum)*

Los resultados experimentales obtenidos con un cultivar peruano (Revolución) y otro holandés (Désirée) demuestran que se pueden producir 70-80 t/ha de papas con apropiado riego por aspersión. El cultivar peruano llegó a una tasa de crecimiento en materia seca total de 270 kg/ha.d, pero la duración de la fase de crecimiento lineal fue más corto de lo que se encuentra generalmente en regiones de clima templado. Asimismo, el índice de cosecha fue bastante bajo, resultando en un rendimiento final de papas similar a los rendimientos potenciales obtenidos en regiones de climas templados. Désirée llegó a una tasa de crecimiento de materia seca total de approximidamente 20% mas bajo, pero a causa de índices de cosecha más altos, se llegó a un rendimiento de papas comparable. Revolución desarrolló de 2,5 a 3 veces más area foliar que Désirée, pero no llegó a una mejor captación de luz. El patrón de absorción NPK mostró que aplicaciones divididas de N y K pueden aumentar la recuperación de la fertilización. Aplicaciones divididas influyen fuertemente en la concentración de minerales en el follaje, como también en la concentración de NO_3 en los pecíolos de las hojas en comparación con aplicaciones únicas. Por esta razón comparaciónes relevantes con concentraciones publicadas en otros sitios no fueron posibles, porque generalmente los fertilizantes fueron dados en aplicaciones únicas. No obstante, el alto rendimiento y la concentración NPK en los tubérculos indicaron que el cultivo en San Camilo no ha sufrido déficit de nutrientes. Un experimento de riego según el método de fuente lineal resultó en un buen entendimiento del uso de agua en este cultivo. Las papas sólo pueden absorber una pequeña parte del agua aplicada, pero esta agua se usa eficientemente para la producción de materia seca. Por esto parece posible de llegar a altas utilizaciones del agua de riego si se puede adaptar la técnica de la irrigación en función de la débil capacidad de absorción de agua de este cultivo. El déficit de agua demoró la formación de tubérculos hasta que se hubo producido una cierta cantidad de follaje. Este valor umbral fue mucho más bajo con Désirée que con Revolución, de modo que es preferible escoger el primer cultivar en casos de abastecimiento de agua inseguro.

PASTO RHODES

No habían datos en la area del proyecto sobre pasto Rhodes (*Chloris gayana*) y hemos usado mucho los datos experimentales y de simulaciones conseguidos en Israel. Con suficiente fertilización N la producción experimental acumulativa de un año resultó un poco más alta en el Perú (44 t/ha) que en Israel (38 t/ha). Esto fue causado por una mayor duración tanto del periodo favorable para el crecimiento, como también durante el año por una más larga continuación de la fase de crecimiento lineal. Por otro lado, las tasas de crecimiento lineales conseguidas en Israel eran más altas y el periodo exponencial antes de la fase de crecimiento lineal fue más corto. El crecimiento durante el otoño, el invierno y la primavera en el Perú fue más bajo de lo esperado a base de la irradiación solar y de la temperatura promedia, lo que se confirmó con la simulación efectuada con el modelo BACROS, que había producido buenos pronosticos para la situación en Israel. Para San Camilo sólo los resultados medidos en la época de verano fueron parecidos a las simulaciones. En comparación con los resultados medidos, las simulaciones del otoño y de la primavera los excedían en un 50% y la del invierno fue 100% más alta. Tomando el promedio de un año completo, la producción simulada fue más del 50% por encima de lo que fue cosechado en la realidad. Es muy probable que las temperaturas bajas en las noches durante las épocas frias causen daños permanentes a los cloroplastos, especialmente después de dias de alta irradiación solar. Se han obtenido indicaciones de que con pasto Rhodes se puede llegar a recuperaciones de fertilización N muy altas.

MAÍZ

El crecimiento del maíz propiamente irrigado y fertilizado, fue determinado en gran parte por la época de siembra. Al inicio de la primavera (Septiembre), el crecimiento inicial es muy lento, de modo que la fase de crecimiento lineal ocurre durante el verano. Durante esta época altas tasas de crecimiento lineal (330 kg/ha.dia) y producciones finales (26 t/ha) fueron alcanzadas. Sembrando 2 meses más tarde se aceleró el crecimiento inicial, mientras que el crecimiento lineal sucedió todavia durante los meses de verano, causando que fueron obtenidas similares tasas de crecimiento y producciones finales. Sembrando al inicio del verano (enero) resultó en un crecimiento inicial aún mas acelerado pero la mayor parte de la fase lineal ocurrió en otoño, con muchas noches frias. Aparentemente también este cultivar C_4 sufrió daños permanentes en los cloroplastos porque la tasa de crecimiento lineal fue reducido a la mitad, hasta 145 kg/ha.d, y la producción final disminuyó hasta unas 12 t/ha.

Cultivares de Holanda y de Israel tenían un comportamiento diferente y rindieron menos que los híbridos locales. No obstante, durante el crecimiento exponencial, en todos los cultivares fue encontrado una correlación similar entre altura de planta y peso seco. Sorprendente fue la influencia de la resistencia mecánica del suelo en el crecimiento de maíz. La subsolación permitió profundizar las raices de aproximadamente 35 hasta 70 cm y aumentó la tasa de crecimiento lineal de 175 a 330 kg/ha.d. Incorporación al suelo de San Camilo de arcilla limosa del cercano valle de Tambo aumentó aún más la tasa de crecimiento lineal hasta 500 kg/ha.d, lo que resultó en una producción final de materia seca de cerca de 36 t/ha. Estos resultados demuestran que no es suficiente el suministrar bastante agua y nutrientes a cultivos sanos para obtener rendimientos potenciales, porque también hay factores físicos del suelo que pueden limitar la absorción de estos factores de crecimiento considerablemente. Después de una rotación con alfalfa, maíz no fertilizado era capaz de producir 21 t/ha de forraje seco obteniendo así el 80% del rendimiento con amplia fertilización.

Igual a pasto Rhodes, BACROS simuló una tasa de crecimiento demasiado elevado para el maíz durante el otoño y la primavera, problablemente como resultado de daños en la capacidad fotosintética de la hoja durante noches frias. Las tasas de crecimiento extremadamente altas durante el verano con el suelo arcillo limoso de Tambo solamente podía ser simulado con suposiciones fisiológicas para las cuales no existen fundamentos.

LOS FACTORES MÁS IMPORTANTES PARA LA PRODUCCIÓN EN CULTIVOS IRRIGADOS

La máxima utilización del agua de riego se obtiene aplicando justo suficiente agua para llegar a rendimientos máximos en cultivos que crecen bajo condiciones óptimas de suministro de nutrientes, sanidad vegetal, etc. Esto incluye medidas de control del agua de riego, así como la optimización de los otros factores de crecimiento.

La mejora en el suministro de agua a los cultivos en la región es impedido por dos factores: (1) ausencia de un control eficaz del actual uso de agua por el agricultor individual y (2) el suministro irregular de agua durante el año. Especialmente los cultivos que pierden mucha agua por evaporación de suelo (cobertura incompleta del follaje) o por percolación (sistema de raices débil), llegan facilmente a producciones bajas por m^3 de agua de riego. Respecto a las otras condiciones de crecimiento, el insuficiente suministro de N a cultivos de no leguminosas, problemente es la razón principal de que la producción actual alrededor de San Camilo quede generalmente muy por debajo del rendimiento potencial. Sin embargo, otros factores más específicos del cultivo también pueden tener efectos importantes, como la presencia de temperaturas bajas en la noche sobre el crecimiento de maíz y pasto Rhodes y la alta resistencia mecánica de muchos suelos de las pampas sobre el crecimiento de maíz.

También habían indicaciones de que el sistema de pastoreo, como es practicado por muchos agricultores, llega muchas veces al sobrepastoreo y disminuye los rendimientos de alfalfa. Finalmente, las caracteristicas del mismo cultivar resultaron importantes para el rendimiento final. Cultivares locales demostraron generalmente el mejor comportamiento, aunque varias caracteristicas como el índice de cosecha (alfalfa y papa), la resistencia al frio, y la sensibilidad a la resistencia mecánica del suelo (maíz) pueden ser mejoradas probablemente.

USO DE SIMULACION EN LA AGRICULTURA PARA FINES DE INVESTIGACION Y DE PREDICCION

Modelos de simulación son desarollados en especial en la investigación agrícola para aumentar el entendimiento de sistemas biológicas y para relacionar la producción agrícola con el conocimiento fundamental de procesos básicos. Para este fin un contacto estrecho y una interacción continua entre simulación y experimentación es un primer requisito. Debido a la corta duración del proyecto FAPROCAF y a la larga distancia entre las sedes de experimentación y de simulación, no se han obtenido muchos beneficios directos de la simulación durante el proyecto. No obstante, el proyecto se ha aprovechado del conocimiento y de la experiencia presente en los institutos cooperantes de Holanda e Israel, parcialmente en base a simulaciones anteriores.

Para predicciones exactas de, por ejemplo, los rendimientos potenciales posibles, los modelos de simulación existentes necesitan todavia una gran cantidad de información específica como el desarollo del área foliar, la partición de la materia seca, el nivel de asimilación a saturación de luz y la temperatura de referencia para cálculos de la respiración de mantenimiento. La influencia de esta información sobre el resultado final es tan importante, que métodos de calculación simplificados producen predicciones igualmente exactas como simulaciones por computadora, cuando se dispone de los mismos datos específicos.

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Curriculum Vitae

Mark Nicolaas Versteeg werd geboren op 10 februari 1946 te Delft. Vanaf 1958 volgde hij als intern een opleiding HBS-B aan het Canisius College te Nijmegen, waar in 1963 het einddiploma werd behaald. Hierna begon hij zijn studie aan de Landbouwhogeschool te Wageningen. In september 1971 werd het ingenieursdiploma behaald in de richting tropische plantenteelt, verzwaard met onkruidbestrijding en met als verdere specialisatie de plantenveredeling en de algemene plantenziektenkunde. In november 1971 trad hij in dienst van de Directie Internationale Technische Hulp van het Ministerie van Buitenlandse Zaken, ten dienste van het COPERHOLTA project in Tarapoto, in noord-oost Peru. In 1978 trad hij als gewasonderzoeker in tijdelijke dienst van het Centrum voor Agrobiologisch Onderzoek (CABO), ten behoeve van het Nederlands-Israelisch-Peruaanse samenwerkingsproject "FAPROCAF" in zuid-Peru, waar hij tevens verantwoordelijk was voor de dagelijkse leiding. Na afloop van het dienstverband in 1983, heeft hij gastvrijheid genoten bij het CABO in Wageningen, waar de in Peru verzamelde gegevens werden verwerkt tot een proefschrift. Voor het Directoraat Generaal Internationale Samenwerking werden korte missies uitgevoerd in Colombia, Israel en Peru en voor het adviesbureau Euroconsult werd in 1984 een missie in Guinée volbracht.