Hierarchical levels in agro-ecosystems:

selective case studies on water and nitrogen

Promotor:

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hoogleraar in de plantaardige produktie systemen, met bijzondere aandacht voor de (sub-)tropen

Hierarchical levels in agro-ecosystems: selective case studies on water and nitrogen

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van de Landbouwuniversiteit Wageningen,
dr C.M. Karssen,
in het openbaar te verdedigen
op vrijdag 14 maart 1997
des namiddags te vier uur in de Aula

Cover design:
Henk Hoonhout
Editing assistance:
Drs JS Drijver-de Haas

CIP-gegevens Koninklijke Bibliotheek, Den Haag

Ridder, N. de, 1997.

Hierarchical levels in agro-ecosystems: selective case studies on water and nitrogen / N. de Ridder.
Thesis Agricultural University Wageningen. - With ref. - With summary in Dutch
ISBN 90-5485-657-2
Subject headings: agro-ecosystems; hierarchical levels; spatial and temporal scales; transfer functions; emerging properties; spatial up-scaling.

STELLINGEN

1. De voortdurende discussie of water dan wel bodemvruchtbaarheid (met name het voedingselement stikstof) de beperkende factor is voor plantengroei in de Sahel kan worden beëindigd indien ruimte- en tijdschalen nader worden gespecificeerd.

- Penning de Vries, F.W.T., and M.A. Djitèye (eds), 1982. La productivité des pâturages sahéliens: une étude des sols, des végétations et de l'exploitation de cette ressource naturelle. Agric Res Rep 918. Pudoc, Wageningen.

2. Voor een beter inzicht in het duurzame karakter van agro-ecosystemen dienen deze niet alleen te worden bestudeerd op de juiste tijd- en ruimteschaal, maar ook in relatie tot elkaar en op verschillende hiërarchische niveaus.

- Fresco, L.O. and S.B. Kroonenberg, 1992. Time and spatial scales in ecological sustainability. Land Use Policy 9:155-168.

3. De bewering dat gewasgroeimodellen ontwikkeld en geschikt zijn voor de ruimtelijke schaal van een akker, is onjuist, omdat deze modellen in veel opzichten nog één-dimensionaal zijn.

- Bouman, B.A.M., 1991. Linking X-band radar backscattering and optimal reflectance with crop growth models. Proefschrift Landbouwuniversiteit Wageningen.

4. Het gebruik van landeenheden voor de bepaling van het landbouwkundige potentiëel, die alleen zijn vastgesteld op basis van bodem- en klimaatskaarten, gaat voorbij aan de ruimtelijke configuratie van deze eenheden in het landschap en is daarom fout.

- Driessen, P.M. and N.T. Konijn, 1992. Land-use systems analysis. WAU/INRES, Wageningen.

5. Wil de 'harvest index' in de toekomst bruikbaar zijn bij de veredeling van (tropische) voedselgewassen, dan dient deze parameter niet alleen te worden gezien als een expressie van genetisch potentiëel maar ook van groei beperkende en reducerende omgevingsfactoren.

- Wallace, D.H., J.L. Ozbun and H.M. Menger, 1972. Physiological genetics of crop yield. Adv. Agron. 24:97-146.

6. Verkennende landgebruiksstudies die gebruik maken van 'Interactive Multiple Goal Lineair Programming' leiden tot misleidende ruimtelijke allocatie van landgebruik.

- WRR, 1992. Grond voor keuzen: vier perspectieven voor de landelijke gebieden in de Europese Gemeenschap. Rapporten aan de regering 42, Den Haag.

7. Ogenschijnlijk zinloze wetenschappelijke debatten, zoals die aan het begin van deze eeuw plaatsvonden over de vraag of een vegetatie als een organisme kan worden beschouwd, kunnen toch de wetenschap vooruit helpen.

-Cooper, W.S., 1926. The fundamentals of vegetational change. Ecology Vol. 7, no. 4:391-413.

-Tansley, A.G., 1935. The use and abuse of vegetational concepts. Ecology Vol. 16, no. 3:284-307.

NN08201, 2233.

8. Aangezien groen papier en een gesloten groene vegetatie dezelfde NDVI-waarden (Normalized Difference Vegetation Index) geven, kunnen via satellieten verkregen NDVI-waarden niet als direkte maat worden gezien voor de fotosynthetische activiteit van een vegetatie.

- *Tucker, C.J., C.L. Vanpraet, M.J. Sharman and G. van Ittersum, 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980-1984. Remote Sensing of Environment 17:233-249.*

9. De herinvoering van het uit de middeleeuwen stammende 'meester-gezel' systeem draagt meer bij tot kwaliteit en efficiëntie van onderwijs aan de Landbouwuniversiteit dan het handhaven van de Richtingonderwijscommissies (ROC's).

10. Met recht achten donoren het sociaal-economische onderzoek van belang voor de verdere ontwikkeling van Sahellanden, maar ten onrechte wordt een lagere prioriteit gegeven aan het biofysische onderzoek.

11. De met de plannen voor een Kennis Centrum Wageningen gepaard gaande reorganisatie geeft aan dat in deze weinig is geleerd van de ervaringen van het romeinse leger aan het begin van onze jaartelling.

- *Gaius Petronius (66 AD).*

- *Peper, B.P., 1996. Duurzame kennis, duurzame landbouw. Een advies aan de Minister van Landbouw, Natuurbeheer en Visserij over de kenisinfrastructuur van de landbouw in 2010.*

12. Ook een stelling is maar een rek.

Behorende bij het proefschrift:
Hierarchical levels in agro-ecosystems: selective case studies on water and nitrogen.

Nico de Ridder
Wageningen, 14 maart 1997

"..... the concatenation of events is always more complicated and inexplicable than we like to imagine. We must remember that a pattern - whether of the past or the future - is always arbitrary or partial in that there could always be a different one or a future elaboration of the same one. In the end we have to make a guess ......"

"..... de aaneenschakeling van gebeurtenissen is altijd ingewikkelder en onverklaarbaarder dan we willen geloven. We mogen niet vergeten dat een patroon - of het nu in het verleden of in de toekomst ligt - altijd willekeurig en onvolkomen is, in de zin dat het altijd kan veranderen, of een uitbreiding van het oorspronkelijke kan zijn. Uiteindelijk moeten we toch gokken ......"

Charles Palliser, 1993. The Quincunx: the inheritance of John Huffam.
Viking, England.

Preface

Nearly five years ago, I was invited to apply for a job at the former department of Tropical Crop Science of the Agricultural University in Wageningen. To be a PhD-graduate was one of the requirements for an acceptable candidate, a requirement I was not able to meet at that time. Since my MSc-graduation in 1979, I had worked at several research institutes and projects. Being such a scientific nomad, I had never found the tranquillity (or should I say: I was never given the opportunity?) to concentrate on a PhD-thesis. At that particular meeting of the interview panel Prof. Dr. Ir. L.O. Fresco did not make an issue of this shortcoming, simply stating that I would be able to obtain a PhD-degree in the following years. Her limitless faith in my capacities and continued day-to-day support, has kept me going and allowed me to finish this last remaining and highest formal education objective in life. Louise, I sincerely thank you!

Trying to capture my scientific development during the 18 years of my professional life in a PhD-thesis may be considered as a virtually hopeless task. So much the more it will be to acknowledge all the people who have placed significant sign posts on the road and made my adventurous journey through time possible. Nevertheless, I will take the risk of forgetting someone along the road. To my relief, people knowing me will remember that this is not on purpose but rather due to my absent-mindedness.

Two late professors played an important role during my MSc-study in preparing me on my scientific career: Prof. Dr. Ir. C.T. de Wit and Prof. Dr. R. Brouwer. Both would have enjoyed seeing me obtain my PhD-degree. Others were important as well during this period, but I can only mention a few. Wim Elberse patiently taught me the first principles of writing scientific reports, surely a skill one cannot do without. Furthermore, Henk Breman, Jan Krul, Frits Penning de Vries and Leo Stroosnijder, all scientists at the former PPS-project in Mali, have contributed to my development during my MSc-study as well as later in my career, whenever we met again: I owe you all a great dept of gratitude.

My first job was in Israel, where I was appointed at the Hebrew University of Jerusalem. No'am Seligman, Roger Benjamin and Herman van Keulen, you are gratefully acknowledged for your support at that time. Our cooperation resulted in a few publications, of which I have included one (Chapter 2) in this thesis. If the methodology in this chapter is carefully evaluated, one would agree that I have to express my thankfulness to those who have executed the tedious and precise hand-work. A. El Mageed Abu Abed, G. El-Rantisi, Niek van Duivenbooden, Iet Olieman, Pauline Wijnmalen en Anneke Jeeninga, I still do not understand how we convinced

you to do this crazy job!
My second job brought me back to Mali. Leo Stroosnijder taught me to reduce the complex scientific results of the PPS-project to the basic principles which subsequently had to be transferred to young engineers from all Sahelian countries. Leo, you also advised me on the tricks of project management and budgeting: it was just what I needed in my jobs to come. I received warm hospitality of all the colleagues at the former department of "Theoretische Teeltkunde", being my home base during this period: thank you all, it was a great time!
The International Livestock Center for Africa was my next employer. Many colleagues at this CGIAR institute have contributed to my scientific development, but I want to especially express my sincere gratitude to Klaas Wagenaar. Together we have written the publication, that I inserted as Chapter 3 in this thesis.
In the following three years I was employed by the former Center for Agro-biological Research (CABO; nowadays AB-DLO). From the publications that appeared in that period, I used two for my thesis (Chapter 4 and 5). It was a great experience to assist in the development and writing of a manual for evaluating Sahelian pastures. Many colleagues have worked on the final publication of this book, but I want to thank in particular Henk Breman and Peter Uithol for their stimulating cooperation in this period. Together with Herman van Keulen, I have condensed a chapter from this book into a publication, which I have inserted as Chapter 5. The publication on the role of organic matter in the semi-arid tropics of West Africa (Chapter 4) was written in harmonious collaboration with Herman van Keulen, for which he is acknowledged in all sincerity.
The two years in Burkina Faso were a break in terms of my scientific career. I learned to supervise the construction of a laboratory for ecology at the university of Ouagadougou under the highly appreciated guidance of Karel Erkelens. I also appreciate the administrative support I received from the former rector of this university, Alfred Traore. Jelte van Andel posed as my sounding-board in the background. Jelte, thank you for your contribution to my professional development.
My latest job, and so far the longest, is at the Agricultural University in Wageningen, at the former department of Tropical Crop Science, which later became the Plant Production Systems section within the Agronomy department. To finish a PhD-thesis on top of the regular work at the department is highly demanding, not only for the one trying to do so, but certainly also for his colleagues. I thank all my colleagues of the Agronomy department, who, in some way or another, have contributed to an environment in which I could manage the job.
However, some of you have to be mentioned in particular. Tjeerd Jan Stomph contributed to the Chapters 7 and 8, as well as to the general introduction (Chapter

1) and the general discussion (Chapter 9). Tjeerd, I owe you a great dept of gratitude and I appreciate the fruitful discussions we have had. I earnestly hope that our collaboration will continue for the foreseeable future. With Simône Radersma, I worked on the publication appearing as Chapter 6 in this thesis. Simône, it was a smooth cooperation and I am grateful you permitted me to include our publication in my thesis. Daniel van Kralingen is acknowledged for his support in getting started with the programming of the model as published in Chapter 7. Annemarie Rozema, at that time a student at our department, assisted with inclusion of the nitrogen balance in this model (Chapter 8). The discussions with Free de Koning contributed to what finally became the general introduction (Chapter 1) and general discussion (Chapter 9). Thank you Free, and that you may follow soon! The assistance by Egbert Westphal and Jan Wienk in formulating the propositions is highly appreciated, whereas Joost Bouwer is acknowledged for editing this preface. Unexpected and not foreseen assistance came from Wampie van Schouwenburg during the evenings I was desperately trying to get the prints ready before the deadline. Wampie, thank you very much for your help!

The C.T. de Wit graduate school created discussion groups for PhD-students. I had the fortunate opportunity to participate in the group on methodology during the last two years.

I have appreciated this initiative of the graduate school and will remember with great pleasure the in-depth discussions with the participants in our group.

My research program is part of the so-called VF-program entitled "Sustainable land use in the tropics". Thanks to the colleagues in this program I was able to do part of the research presented in this thesis.

Furthermore, I wish to express my appreciation to Martin van Itterssum of the department of Theoretical Production Ecology. Together we have developed the course "QUASI" and have given this course several times. Without asking, he has taken more than his share to relieve me in the last months of the preparation of my thesis.

The cover of this thesis was designed by Henk Hoonhout. It is a hell of a job to express all the rather abstract thoughts of this thesis into one single page. Henk, I am much obliged to you.

The first years of my life I have spent abroad. First, five years in the former Dutch colony, Indonesia, followed by another three and a half years in a small village called Seroei situated on the island of Yapen in the Geelvinkbaai, Nieuw Guinea. In Seroei I reached school age. Since neither a Dutch school nor teachers were available in such an out-of-the-way corner of the world, my mother taught me to 'read and write'. My parents did not only build the foundations of my education, but also gave me

their full support in my subsequent education. This goes part of the way to explaining my great gratitude and respect I have for them.
Finally, I want to thank my children, Ellen and Jorn, who followed me around the world, sometimes grumbling but mostly cheerfully.
All this having been said, I am not able to express my sincere gratitude to the most important person in my life, because she does not want to be mentioned at all ......

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General introduction

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General introduction

1.1 Changes in agronomic research

The evolution of agronomy dates back to the first agricultural practices by Man. Through trial and error Man developed new agricultural technologies (e.g. seed selection, tillage, manipulation of nutrients and water, weeding, harvesting and conservation). In the eighteenth century, agronomy developed as a formal science, when, at least in Europe, the first professors in agriculture were nominated at universities in Scotland and Italy (Struik and Fresco 1993).[1]
Experimental research on agricultural stations started in 1834 in France and 1843 in England (Salmon and Hanson 1964). The publication of Von Liebig's law of the minimum (1855) was a landmark in agricultural research. In previous centuries, farmers had to rely on techniques as shifting cultivation, rotations with legume crops and use of organic manure and waste of cities to maintain soil fertility (De Vries and Van der Woude 1995; Slicher van Bath 1987). In the decades after Von Liebig's publication, the insight evolved that soil fertility also can be maintained and even upgraded by the use of chemical fertilizers. This is further illustrated by other publications on production functions in relation to nutrients (Liebscher 1895; Mitscherlich 1924). The main stream in agricultural research thus focussed on experiments studying dosage-effect relations. Experimentation was done on special plots, under the assumption that these plots were representative for larger units such as farmer's fields. After the Second World War, results of agricultural research in general, but in particular those of studies on dosage-effect relations, have contributed enormously to the increase in productivity per unit area. Of course, this was only possible with a simultaneous, economic development in societies, creating an increasing demand in agricultural products (De Wit and Van Heemst 1976; Greenland et al. 1994).
The successful application of production functions in relation to nutrients in daily

[1] Agriculture is a generic term, including at once the science, the art and the process of supplying human wants by raising the products from the soil, and by associated industries. It implies amongst other things the cultivation of soil, the production and harvesting of crops, and the care and breeding of livestock. Agronomy is a more restricted term, generally seen as the application of scientific principles to the cultivation of land. In this thesis the meaning of agronomy is limited to the application of scientific principles of natural sciences in the management of agro-ecosystems. It implies the study of effects of management practices, such as cultivation practices, on biophysical processes determining the performance of agro-ecosystems. Agro-ecosystems are in principle ecosystems, but managed by Man to obtain arable and livestock products.

agriculture introduced object changes in research. Since high production was in principle guaranteed through use of manure and fertilizers, yield limiting and yield reducing factors became topics of research to obtain potential production levels. The interest in breeding increased - first in temperate agriculture, but in the sixties also in the tropics -, followed by attention paid to pests, diseases and water management. Agronomic research evolved to technology development, focusing on partial processes in agriculture. During this period many specialism developed from the original comprehensive science of agronomy i.e. plant breeding, entomology, phytopathology, nematology, soil tillage, soil conservation, irrigation, etc. (Struik and Fresco 1993).
During the 1960s and the 70s this unbridled technology development created public concern. Unexpected negative side effects like persistent biocides and excessive use of manure and fertilizers created a general awareness of the environmental costs of intensive agriculture. Furthermore, in the tropics the Green Revolution, characterized by the introduction of high yielding varieties, induced new issues such as inequality in income and loss of work in the agricultural sector. As a reaction to the analytic and reductionistic approach in agronomic research and the worries about the negative side effects of the new technologies, a more integrative system analysis was called for. This resulted, amongst others, in the Farming Systems Research approach. The focus in agronomic research switched to *agro-ecosystem analysis*, a more holistic approach, which enables inclusion of (negative) side effects - also considered as outputs of the agricultural system -, in studying agriculture (Fresco 1995a).
As a result of the Conference of Environment and Development in Rio de Janeiro in 1992 Agenda 21, of which Chapter 14 deals in particular with sustainable[2] agriculture and rural development, the environmental issues of pollution, degradation and depletion of natural resources in agriculture are recently placed in a global perspective. Furthermore, the world population growth induced an intensified competition for land between agriculture and other land use forms (Waggoner 1994) and emphasized the need for land use planning (Fresco et al. 1994). These changes in view have caused yet another shift in the agronomic research agenda.
Today, agronomic research faces the challenge to develop knowledge and insight to manage agro-ecosystems, which are inherently sustainable, diminish the undesirable side effects and meet the increasing demand of food of a still growing world population, without claiming all the available land. Trade offs have to be made clear between objectives of sustainability, the unavoidable, negative side effects of agriculture and the growing demand for food. In addition,

[2] The term "sustainability" is defined as the way in which resources can be used to meet changing future needs without undermining the natural resource base (TAC/CGIAR 1989).

agronomic processes, so far studied at the plot level, have to be studied and applied at larger entities such as toposequences, watersheds, river systems, continents and even the entire globe, and over longer time periods if we want to take sustainability seriously (Fresco and Kroonenberg 1992). Sound management of agro-ecosystems is not solely a matter of the individual farmer anymore, nor of only field and farm level. Local, national and international policy levels demand guidance from the agricultural research community in management of the natural resources.

1.2 Agro-ecosystem analysis

Agriculture is a complex process, even if it can be described in simple terms as "the human activity that transforms solar energy at the earth's surface into useful (edible) chemical energy by means of plants and animals" (De Wit and Van Heemst 1976) or as "an activity (of Man), carried out primarily to produce food and fibre (and fuel, as well as many other materials) by deliberate and controlled use of (mainly terrestrial) plants and animals" (Spedding 1979). One needs a unifying concept to study this complex process, even more so if the negative side effects of agricultural practices have to be considered as well. Systems theory provides such an unifying concept, in which the system takes up the central position.

Tansley (1935) was probably the first to introduce the term "ecosystem" in ecology, defining it as the whole of all plants and animals interacting with the complex of physical factors forming the environment. The ecosystem is the central concept of system analysis in the biological and ecological realm, but is also widely used in agronomy. However, agro-ecosystems differ from ecosystems through the impact of Man, resulting in more open systems (energy and mass flows leave the system through e.g. harvest, nutrient leaching, erosion; and enter the system through e.g. fertilizers), use of auxiliary energy sources (human and animal labour and fossil energy), reduced diversity of species (e.g. uniform crops, avoiding weeds), and fewer natural feedbacks (replacement of natural feedbacks through external control by Man) (Mannion 1995).

According to the systems theory, a system comprises five elements: components, interactions between components, boundaries of the system, inputs and outputs (Odum, 1983). Depending on the objectives of study, a choice has to be made which components, interactions between components, inputs and outputs have to be considered in the specific analysis of a system:

> Let us introduce an example of an agro-ecosystem: a farmer's field, situated on a slope. The farmer cultivates an annual crop on this field. We can consider this field as a system. It now depends on the objectives of the system analysis, which components have to be considered. If the objective is to analyze crop growth and production in relation to water and nutrient availability, we have to consider the crop and the rooting zone in

the soil as the main components. These two components can be further divided into different parts of the crop (roots, stems, leaves, reproductive organs) and soil characteristics (physical characteristics for water availability and chemical characteristics for nutrient availability). Furthermore, we have to decide which relationships between the components will be included. It is evident in our example, that we will include relationships between e.g. water availability and plant growth on the one hand and nutrient availability and plant growth on the other. Finally, we have to decide which inputs and outputs are included in the study. Generally, the harvestable part of the crop is considered to be the single output of the system, but other outputs have to be considered as well e.g. leaching of nutrients and erosion. The inputs depend on the components and relationships included in the system analysis. Weather influences plant growth mainly through radiation (photosynthesis and energy balance), temperature (transpiration, crop development) and rainfall (water availability). Agronomic practices of the farmer can also be considered as inputs: through his manipulations the farmer influences, directly or indirectly, plant growth conditions. If he uses manure and fertilizers, these will affect plant growth through nutrient availability. Ploughing the field changes the structure and density of the soil, affecting root development, water availability and nutrient availability for plant growth. If the objectives of study change, e.g. we want to study the effect of a particular pest on crop growth, the population of the organism causing the pest (a component) and exogenous factors (inputs) affecting the population growth have to be considered as well. Thus, the elements to be included in a system analysis depend on the *objectives* of study.

This example shows that agro-ecosystem analysis can never include all elements, which can be distinguished in natural systems. We mentally isolate and delimit parts of natural systems, nature itself being far too complex to be studied as a whole.

This delimitation of parts of nature can be seen as one of the three aspects in the definition of the boundaries of the system to be studied and refers to an organization structure in nature (Allen and Hoekstra 1990). For each system to be studied, also an appropriate time and spatial scale have to be defined.

The boundaries, determined by the elements to be included in the system analysis, are always artificial and are defined in accordance with the objectives of the system analysis. Fortunately, nature itself seems to have an organization structure[3].

In our example, the farmer's crop on the field is composed of single plants, each plant is composed of different organs and each organ is composed of cells. The farmer's field is part of a larger landscape unit such as a toposequence, which in itself is part of a watershed.

Because each of the sub-systems is part of a larger system, which in its turn is

[3] The question whether this organization structure really exists in nature (Milsum 1972) or is by itself again a mental product of Man, is left aside (Allen and Hoekstra 1990).

part of an again larger system, we can apparently distinguish a certain hierarchical organization.

1.3 Hierarchies

The word "hierarchy" originates from Greek: *hieros* means sacred and *arkhes* means ruler. The word originally relates to the priestly government with the hierarch as the chief priest or archbishop. According to Webster's Dictionary (1990) it referred to "a group of priests holding high office within an organized religion and having graded authority to govern the organization". Nowadays, the principle of ranking receives a more general purport and is used for any graded organization. Concrete examples from daily life are e.g. command structures in armies, administrative structures of a state or company, and distribution systems of water and energy supply. Abstract hierarchies are found in the organization of a book, a library system or in computer software. For example, the hierarchy of a book is:

word ⇒ sentence ⇒ paragraph ⇒ section ⇒ chapter ⇒ part.

An important property of hierarchies is the inequality or asymmetry in relationships: a lower unit is subordinate to a higher. When units are ordered and ranked accordingly, levels emerge. Within a level, units are not subordinate to each other. Higher levels rule or constrain and often contain lower levels. In general, the number of units increases downwards, and units become smaller in size and less complex, whereas they act on a shorter time period. If higher levels contain lower levels, we speak of nested hierarchies (Klijn 1995).

Examples of hierarchical concepts in science are old and well known e.g. in taxonomy of plants and animals. However, the General System Approach in ecology has to be credited with introducing hierarchy as a concept (Von Bertalanffy 1950 and 1972; Odum 1983). Ecosystem analysis uses the ecosystem as the organization unit. According to O'Neill et al. (1986), this point of view evolved to the so-called Population-Community approach and led to the hierarchy of:

individual ⇒ population ⇒ community.

Here the biota[4] are the ecosystem, whereas abiotic components (e.g. soils) tend to be regarded as external influences. In other words, the organism is the fundamental unit.

However, other ecologists (e.g. Evans 1956) recognized that both biotic and abiotic components should be included in the fundamental unit. In their view, the ecosystem is defined as a system composed of components related by physical-chemical-biological processes within a space-time unit. In this Process-Functional approach energy and mass flows become important study objects, sometimes

[4] Biota include both the flora and the fauna (Holmes, 1979).

even to the extent that individual species are not distinguished at all. It also leads to a different hierarchy (O'Neill et al. 1986):

functional component ⇒ ecosystem ⇒ biosphere.

These approaches are rarely strictly adhered to by ecologists. It depends on the specific issue of interest which approach is emphasized and which system is defined and which observation sets have to be used to explain system behaviour. To put it simply, the distinction between the approaches lies in the extent to which the environment is taken as an internal or external parameter or part of the system.

Agronomy, the science studying management of agro-ecosystems through cultivation practices, is pre-eminently a systems science. Agriculture, being a complex process, implies that many specialism have to be integrated (Van Dyne and Abramsky 1975; Spedding 1979; Leffelaar 1992). The external control by Man, i.e. cultivation practices, creates an important difference between the functioning of hierarchies in ecology and agronomy. In ecology higher organization levels in the hierarchy constrain lower levels. For example, an individual species in a community is constrained in complete occupation of space through the mechanism of competition at the higher organization level of the community. In agronomy, many of such constraints are removed artificially and replaced by human control.

> In our example, constraints avoiding one species to completely occupy space at the community level, i.e. that of the crop on the farmer's field, are replaced by the farmer by weeding or use of herbicides, and at the organism level, i.e. the individual plants of the crop, by introduction of (improved) seed or planting material.

Although hierarchical concepts are used in agronomy, they generally do not extend to higher levels than cropping systems. A hierarchy commonly used is:

(cells) ⇒ organs ⇒ plants ⇒ crops ⇒ cropping systems[5].

> In our example the farmer has of course more fields, but these will be situated on other slopes and may be even in another watershed. Cropping systems imply organization of the farmer to rotate different crops over the years and over the fields. The next step in the hierarchy will then be the farm, the unit at which labour organization and economics can be analysed.

In climbing up in the hierarchy, a breaking point is introduced after cropping systems. In the lower levels, a biological hierarchy is followed, but at the point of

[5] The cropping system is a land use unit comprising soil, crop, weed, pathogen and insect subsystems, that transform solar energy, water, nutrients, labour and other inputs into food, fuel, fibre and pharmaceuticals. An important characteristics of the cropping system is the sequence of cropping, or cropping and fallow, on a given piece of land (Fresco and Westphal 1988).

the farm level socio-economic factors come into play. The hierarchy becomes administrative e.g.:

farm ⇒ village ⇒ department ⇒ province ⇒ country.

As is clear from ecosystem analysis, the hierarchical approach can be used, but there is no single hierarchy which fits all the needs. The definition of a hierarchy depends on the issue addressed, what systems are defined and which observation sets are needed. Thus, if the biological processes are the focus of study, the following hierarchy may be appropriate:

organs ⇒ plants ⇒ crops ⇒ cropping systems.

However, this hierarchy is not suitable if spatial aspects of water and nutrient flows are studied.

> In our example of the farmer's field on a slope, water and nutrients will flow into and from his field from and into adjacent fields, which most likely are cultivated by another farmer.

The next hierarchical level can not be the farm. We have to include all fields (possibly owned by different farmers) making up the larger system of a toposequence:

plot/field ⇒ toposequence ⇒ valley ⇒ watershed ⇒ river system ⇒ continents.

However, this hierarchy will not work for studies of e.g. CH_4-emissions or CO_2-fixation, because the processes involved will follow other spatial system boundaries.

In land use studies, in which agronomy becomes more and more involved, a hierarchy of land use systems can be used. This hierarchy combines bio-physical and socio-economical variables/processes with the purpose to understand land use changes and the possible effects of these changes on the environment (Figure 1.1). Here an attempt is made to combine two hierarchies, one related to bio-physical and the other related to socio-economical variables/processes. This approach indicates that bio-physical and socio-economic variables/processes have to be studied each following their own hierarchies, before results can be combined into land use systems (Stomph et al. 1992). In this thesis we only deal with the left side of the figure.

All approaches have in common, that at each hierarchical level, systems have to be defined with specific spatial and temporal scales in mind (O'Neill et al. 1986).

1.4 Scales and scaling

Only two meanings of the word scale are of interest in agro-ecosystem analysis.

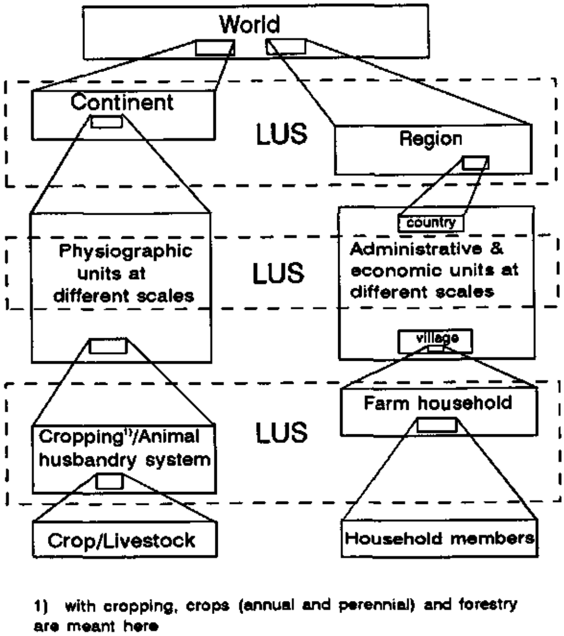

FIGURE 1.1 Hierarchies in agro-ecosystems according to Stomph et al. (1992). LUS stands for Land Use System, the combination of bio-physical and social/economic aspects of a system.

One meaning refers to series or degrees, a ladderlike arrangement or classification, a graded system. In system analysis scales can thus be interpreted as the levels of organization in a hierarchy of systems. Since the word scales is also used in system analysis in a second meaning, it would be preferable to avoid the use of scales whenever the organization levels of a hierarchy are meant. However, in general scales and hierarchies are used interchangeably.
The second meaning refers to numbers: a ratio of reduction or enlargement, a ruler. *In system analysis this meaning refers* to the quantification of specific spatial and time scales of the system to be studied.
Measurements of time and space itself follow a hierarchy. Time is conceptualized by as:

seconds ⇒ minutes ⇒ hours ⇒ days ⇒ weeks ⇒ months ⇒ years ⇒ etc,

and space as, for example (cubic or square):

mm ⇒ cm ⇒ dm ⇒ m ⇒ km

Thus in fact three aspects can be distinguished in all hierarchies: time, space, and organization level. Examples are manifold, in which scientists have tried to relate these three aspects. Such an attempt for hydrological processes at a range of characteristic time-space scales is given by Blöschl and Sivapalan (1995). Other examples are found in ecophysiology (Osmond et al. 1980), in classifying streams (Frissell et al. 1986), and land use processes (Fresco and Kroonenberg 1992). As appears from such attempts, organization levels cover a range of temporal and spatial scales.

> Returning to our example, a field is considered as an organization level in a hierarchy, but such a field can be defined over a range of time and spatial scales depending on the characteristics of the crop cultivated on the field and the objectives of study. Planting the field with a perennial or annual crop will alter the temporal scale to consider. With a perennial crop we have to consider a longer time span than with an annual crop. Changing the subject of study from relations between nutrient and water availability and crop growth to the relation between pest dynamics and crop production will change the space to consider. In that case the spatial distribution of the pest has to be considered, commonly resulting in a larger spatial entity than the field on which the crop is cultivated.

Thus, boundaries between organization levels are diffuse and overlapping and can hardly be expressed unequivocally in discrete ordinal numbers of time and space.

The organization level at which we want to analyze a specific system is the explanatory level. Processes functioning at a lower organization level are used to describe processes occurring at this explanatory level, whereas processes one step higher in the hierarchy can guide us to define the system at the explanatory level and show us how the specific system studied at the explanatory level is embedded in the higher hierarchical level. Sometimes one has to move even further down or upwards in the hierarchy (Jarvis 1995). Sustainability of agro-ecosystems in its simplest sense can be interpreted as no net loss of nutrients (e.g. Smaling 1993). This interpretation of sustainability is of course a disputable simplification, but if we do so we have at least to consider, as in our example, the farmer's field as a part of a toposequence. We have, for example, to take into account not only a loss of water and nutrients through run-off, but also an enrichment with water and nutrients by run-on on the field from adjacent terrain situated higher up the slope. And, soil physics of water retention curves at the underlying level will explain the water available for uptake by the crop at the explanatory level. This three level, or sometimes even multi-level approach, means that we have to move between hierarchical levels, implying also that we have to "scale".

Two types of scaling can be distinguished. Scaling literally means to reducing or increasing in size or in time, the first type. The second type refers to transfer of information between hierarchical levels. In the case of the latter type, up-scaling refers to transferring information from a lower hierarchical level to derive processes at a higher level, whereas down-scaling refers to transferring information from a higher hierarchical level to a lower.

> In our example we deal with the process of up-scaling if information on e.g. transpiration and photosynthesis at the level of leaves (plant organs) is transferred to the level of crops to obtain photosynthesis and transpiration i.e. production of the crop. The process of down-scaling is necessary if we do not have a meteorological station next to our farmer's field. We then have to rely on meteorological stations in the region, giving the average climatic and weather data from the region, which we have to downscale to our farmer's field. This is usually done implicitly i.e. without taking into account the temporal and spatial variability in weather data.

In agronomy we also will come across scaling in the literal meaning of the word. This is the case if we want to apply information obtained from a plot to the entire field of the farmer in our example, thereby increasing the size from several square meters to may be a hectare and assuming that the plot is representative for the entire field in all its characteristics. The latter assumption is somewhat premature, because there will be variation in the characteristics within the farmer's field. But even when this variation is taken into account by distinguishing different units, aggregation and summation of aggregates may not lead to the correct answer. The research carried out by Yair and Lavee (1985) illustrates this. The authors measured run-off at a slope with a total planimetric area of 907 m^2, which was divided in three subplots. One plot (307 m^2) contained the colluvial slope, another plot (161 m^2) the upper slope and the third plot (439 m^2) the entire slope. Run-off per unit area of the entire slope (11.7 dm^3 m^{-2}) is almost equal to the run-off per unit area of the colluvial slope (13.3 dm^3 m^{-2}), whereas the runoff per unit area of the upper slope is much higher (33 dm^3 m^{-2}). It is evident, that taking simply the mathematical average or the summation of the run-off per unit area of the two individual land units as being valid for the entire slope would clearly lead to an overestimation of run-off. Apparently, run-off per unit area is decreasing with increasing spatial scale, which proves the existence of scale effects. However, these spatial scale effects can not only be explained by the most likely existing increase in variation with increasing spatial scale. Yair and Lavee also showed, through simulation, that run-off per unit area of a piece of land, homogeneous in infiltration characteristics, decreases with the increase in length of the slope.

Scaling is not, at least not necessarily, a matter only of summation, averaging and aggregation if we move between hierarchical levels. At different organization levels, different processes may occur. An example is the mutual relationship between climate, soil and vegetation. At the global level, vegetation belts reflect the climatic zones. At the plot level, vegetation is a function of weather and soils. At that same level, vegetation in turn influences both microclimate and soil through evapotranspiration and the breakdown of its biomass. At the intermediate level of landscape, vegetation patterns shape the hydrology and the meso-climate, but together these aggregate to factors such as surface roughness, albedo and evapotranspiration that ultimately affect global climate (Fresco 1995b). Thus, by increasing the temporal and spatial scales of the system, thereby ultimately also moving to higher hierarchical levels, properties of a system may change. These emerging properties of systems imply a discontinuity in system characteristics.

1.5 Spatial up-scaling in agronomy

SPATIAL UP-SCALING IN RELATION TO CROP GROWTH FACTORS

In management of agro-ecosystems three basic types of practices can be distinguished: interventions to control growth defining factors, growth limiting factors and growth reducing factors (De Wit and Penning de Vries 1982; further developed by Rabbinge and Van Ittersum 1994). Growth defining factors are, next to crop characteristics (physiology, phenology and canopy architecture), radiation, temperature and CO_2. Crop characteristics can be manipulated through breeding, but management of the other factors is limited to greenhouses. Growth limiting factors are water and nutrients and growth reducing factors are weeds, diseases, pests and pollutants. These factors can be manipulated to a large extent by yield increasing measures (irrigation and application of fertilizers) and yield protecting measures (weeding, use of biocides).

For each type of these interventions, numerous different research fields have contributed to the issue of spatial up-scaling. It is not the purpose to present here a comprehensive overview, but a few examples are given as an illustration.

In relation to growth defining factors, much attention has been given to the spatial up-scaling of processes from the individual organs to canopy. An early example is the up-scaling of photosynthesis from leaves to canopies (De Wit 1965). Spatial up-scaling of CO_2 assimilation (e.g. Goudriaan and Van Laar 1978) and transpiration (e.g. McNaughton and Jarvis 1983) are similar examples. Spatial aspects of root growth in relation to possible uptake of water and nutrients is an example of spatial up-scaling of individual plant roots to crops (e.g. De Willigen and Van Noordwijk 1987).

In relation to growth reducing factors the basis for spatial modelling of competition between single plants in a crop is given by De Wit (1960), later developed further into competition between weeds and crops (e.g. Spitters and Van den Bergh 1982). The combination of population dynamics of a pest or disease with temporal and spatial crop characteristics (e.g. Rabbinge et al. 1990) is another example related to growth reducing factors.

Spatial up-scaling of processes related to water and nutrient availability, the growth limiting factors, are mainly dealt with by soil scientists and agro-hydrologists. An example at a detailed level is the up-scaling in soil aggregates of aeration and denitrification (e.g. Leffelaar 1977). An early example related to nutrient availability in space at field level is the physical theory on placement of fertilizers by De Wit (1953). New developments in site-specific management yield geo-referenced soil data on the spatial variation in water and nutrient availability for plant growth explaining the large differences in yields within a field (e.g. Bouma et al. 1995).

All these examples are used as information to describe processes at the explanatory level of the crop or field, implying up-scaling from individual to population level (crop oriented) or from point to spatial components (soil oriented). Thus, there seem to be two approaches (Figure 1.2). The first takes the

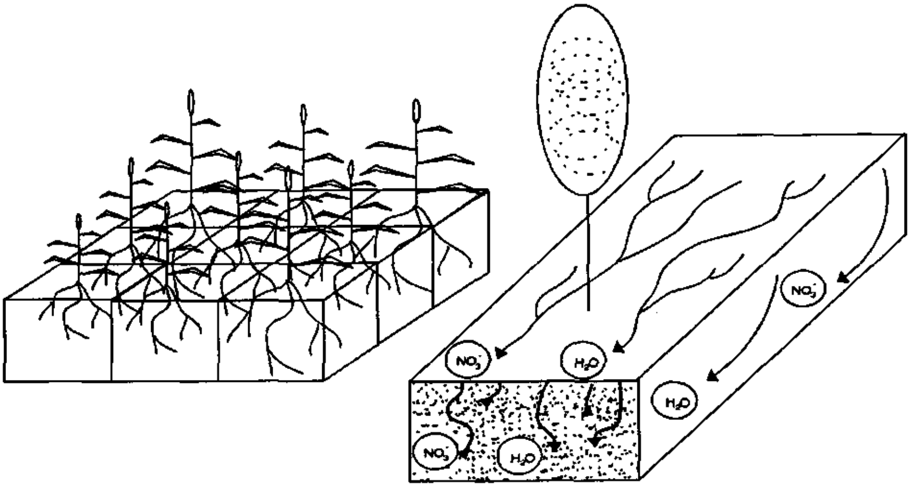

FIGURE 1.2. Two approaches in up-scaling: from individual to population level (crop *oriented) and from point to spatial components (soil oriented).*

crop as starting point: spatial up-scaling of processes from individual organs and plants to the crop is considered, while the soil compartment is a black box regarding its spatial aspects. The second approach takes the soil as starting point, with an inverse result: spatial aspects of up-scaling from individual organs and plants to crops are considered as a black box while spatial up-scaling of processes related to water and nutrient flows are explicitly taken into account.

SPATIAL UP-SCALING TO HIGHER HIERARCHICAL LEVELS

Spatial up-scaling in agronomy does not stop at the hierarchical level of crops. It is practiced up to regional and the global level. Two examples are given to illustrate common up-scaling procedures; the first relates to up-scaling of crop production and the second to up-scaling of nutrient balances. To assess the potential world food production, Penning de Vries et al. (1995) used crop growth

models to calculate crop production in 15 different agro-ecological zones of the world. For each agro-ecological zone yields were calculated for small units of this zone, which are characterized by specific combinations of soil and climate. Subsequently, these yields are aggregated to obtain production levels for a specific agro-ecological zone. To assess nutrient balances in Africa at regional level (sub-Saharan Africa) and at district level (Kisii District in Kenya), Smaling (1993) distinguishes land-water classes. These classes are characterized by soil and climate at one hand and crop performance at the other. For each of these classes, the inputs and outputs of the major nutrients are estimated and the results aggregated to obtain nutrient balances at higher hierarchical levels.
Both approaches have in common that spatial variation is taken into account by an appropriate aggregation strategy, but water and nutrient flows and their availability for plant growth are assumed to be spatially independent.

1.6 Structure of this thesis

Since my graduation in 1979, I have worked at several research institutes and projects. Each new job also appeared to be a change in research subject, but somehow agro-ecosystem analysis was always a basic element in the research approach followed. As my awareness of hierarchical levels and issues related to scales and scaling became stronger, I consciously focused on these issues thereby exploring higher hierarchical levels. Papers which have appeared during this period and which are presented as cases of agro-ecosystem analysis, reflect this development. They deal with different hierarchical levels of agro-ecosystems and come across several aspects of agro-ecosystems analysis. In Figure 1.3, these hierarchical levels are indicated as well as the main issues of agro-ecosystem analysis per chapter. They have in common that water and nitrogen run through the papers like a continuous thread. As such they all follow a Process-Functional approach (O'Neill et al. 1986).
At the hierarchical level of the plant (and crop) reproductive ratios of annual pasture species, defined in two ways, are compared (Chapter 2). In Chapter 3, productivity of ranching and traditional livestock systems in Botswana are compared, whereas the role of organic matter in the viability of arable farming systems in West Africa is treated in Chapter 4. Next, two examples are given to transfer information of lower to higher hierarchical levels. One makes use of transfer functions (Chapter 5), the other extrapolates information to higher levels, showing emerging properties when moving to a higher hierarchical level and thereby increasing the time and spatial scales (Chapter 6). The following two chapters cover the hierarchical level of watersheds. They show the effects on system behaviour if the spatial processes of water and nitrogen flows are explicitly taken into account. Chapter 7 considers the possible effect of up-scaling in space of the processes of infiltration and run-off to the level of a watershed,

whereas Chapter 8 elaborates its consequences if land use changes.
The thesis ends with a general discussion and conclusions on three issues of agro-ecosystem analysis at different hierarchical levels (Chapter 9). These issues are:

(1) the interdependence between objectives and agro-ecosystem boundaries (Chapters 2, 3 and 4);
(2) sustainability in relation to hierarchical levels (Chapters 4, 7 and 8);
(3) up-scaling, in particular:
    (i) transfer functions to transfer information to higher hierarchical levels (Chapter 5)
    (ii) emerging properties (Chapter 6)
    (iii) spatial up-scaling of the water balance (Chapter 7)
    (iv) integrated up-scaling of soil and crop processes (Chapter 8).

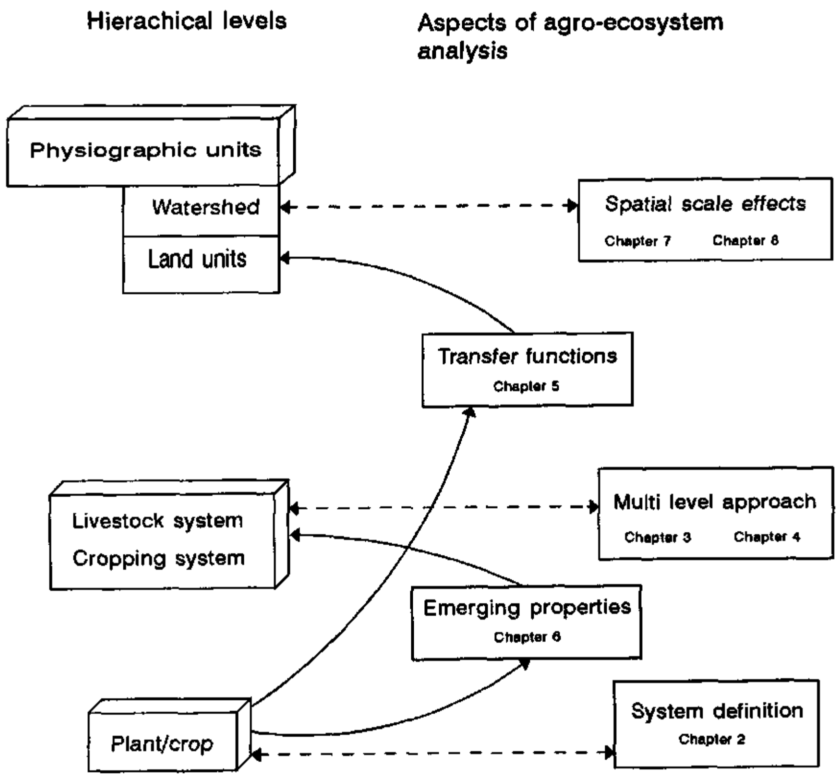

FIGURE 1.3 The hierarchical levels dealt with in this thesis, as well as the main aspects of agro-ecosystem analysis per chapter.

Chapter 2

Analysis of environmental and species effects on the magnitude of biomass investment in the reproductive effort of annual pasture plants.

This chapter has appeared as:

De Ridder N, NG Seligman and H van Keulen 1981. Analysis of environmental and species effects on the magnitude of biomass investment in the reproductive effort of annual pasture plants. *Oecologia* 49:263-271

Chapter 2

Analysis of environmental and species effects on the magnitude of biomass investment in the reproductive effort of annual pasture plants

N. de Ridder, N.G. Seligman and H. van Keulen

2.1 Introduction

Total biomass production of annual pastures in semi-arid regions has received considerable attention in recent years. The growth processes have been studied in fair detail, but the vegetation dynamics and the fate of the seed crop after maturity have received considerably less attention. This does not seem fully justified, since in most semi-arid regions, including the Mediterranean zone, the dry season is longer than the green season and the amount of biomass available at the beginning of the dry season and its quality will to a large extent determine the potential animal density that can be maintained.
It has often been reported, that the amount of dry matter and of plant nutrients in the pasture vegetation at the onset of the dry season is much lower than at the peak of the growing season. Gutman (1978) found a decrease of about 30 percent in the standing crop, directly after drying, in a transitional Mediterranean steppe in North-Israel. Van Keulen (1975) recorded losses of 35, 28 and 15 percent of the peak biomass, in three successive years in Migda, South-Israel (Figure 2.1). Both Van Keulen and Gutman suggest that this decline in standing crop may be attributed to shedding of seeds and dead leaves.

This process is of great practical importance. When such a large proportion of the biomass consists of reproductive structures, which are inevitably lost at maturity, less material will be available for intake by grazing animals in the dry season. Cattle especially, but also sheep and goats may have difficulty in collecting the dispersed material, some of which is buried in the soil and some blown away. Moreover, the competition for this material between the domesticated animals on the one hand and other animals such as birds (Gaston 1976), insects (Green and Palmbald 1975; Janzen 1969) and rodents etc. on the other hand, increases.
The effect of this decrease in the quantity of available biomass is often aggravated by the very low quality of the remaining material. The reproductive

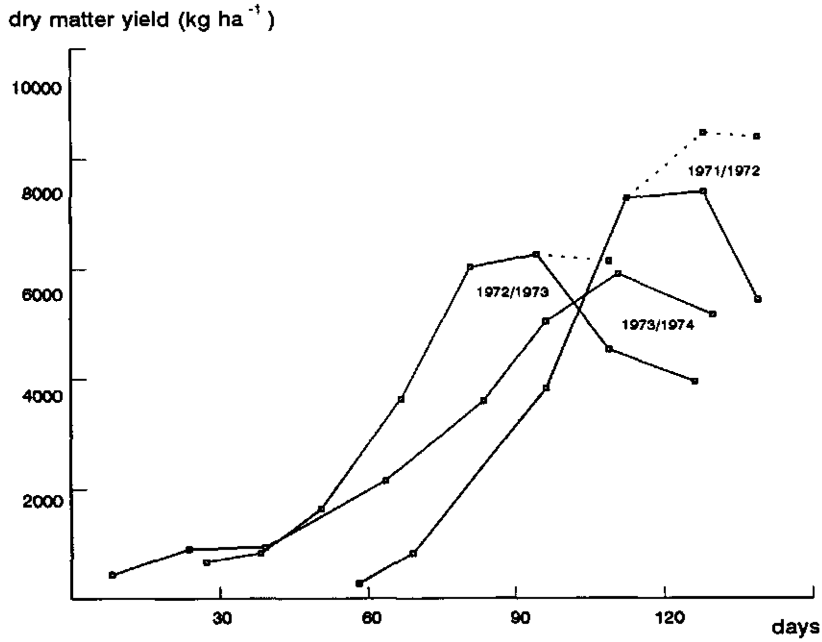

FIGURE 2.1 *Recorded losses of peak biomass of an annual pasture in three successive years in Migda, South Israel. (Source: Van Keulen 1975)*

organs are in general a strong sink for nutrients. Under limiting conditions by far the largest part of especially nitrogen is accumulated in the seeds at maturity. Loss of this material therefore results in a sharp decrease in protein content and hence in digestibility of the standing crop.

This study concentrates on the question whether the amounts of dry matter involved may be partly or completely explained by seed fall or shedding of the total reproductive structure of plants, including those parts produced for seed protection and dispersal, such as awns, glumes etc. The harvest index (HI) which in seed crops is defined as the proportion of harvestable seed in relation to the total biomass produced, is a good reflection of the reproductive effort in crop plants. In dealing with wild species, where a large part of the reproductive effort is often invested in structures intended for protection and dispersal of the true seeds, it is useful to distinguish between the ratio of all reproductive tissues to the total biomass (reproductive ratio or RR) and the ratio of true seed to the total biomass (seed ratio or SR). In principle, the total biomass term should also include the root material. However in most studies, including the present one, root weights have not been determined, because of the laborious methodology involved and the uncertainty in interpreting the data obtained.

Some values reported for RR and SR are presented in Tables 2.1a and 2.1b. These already give an indication of the magnitude of the reproductive effort in various annual species grown under widely varying conditions. The data show that the SR of cultivated monocotyledons varies from 0.13 to 0.57 and the RR from 0.33 to 0.66. The SR of cultivated dicotyledons varies from 0.05 to 0.67 and the RR from 0.16 to 0.67. For the wild species the SR of monocotyledons varies from 0.05 to 0.54 and their RR from 0.19 to 0.67. The SR of Sahelian monocotyledons varies from 0.01 to 0.17. In one of the species *(Diheteropogon hagerupii)*, the RR can be higher: 0.19 to 0.34. The SR for Sahelian vegetation found by Gaston (1976) is also quite high: 0.25 to 0.38. The RR would of course be considerably higher than that. Estimation of the reproductive effort of wild species growing in their natural habitat, is difficult because flowering, fruit setting and seed dispersal continue simultaneously over prolonged periods. This in contrast to cultivated species which have been bred for resistance to seed shedding and for synchronized maturation.
The SR and RR values of wild species may be at the same level as those of

TABLE 2.1a The seed ratio (SR) and reproductive ratio (RR) of some cultivated species

	SR	*RR*	*Author*
MONOCOTYLEDONS			
Hordeum vulgare	0.13 - 0.57	0.33 - 0.66	Van Dobben 1965b; Donald & Hamblin 1976; Spitters 1979
Zea mays	0.21 - 0.49	-	Donald & Hamblin 1976
Avena sativa	0.29 - 0.53	0.43 - 0.56	Van Dobben 1962, 1965a; Donald & Hamblin 1976
Oryza sativa	0.13 - 0.56	-	Donald 1962; Donald & Hamblin 1976
Secale cereale	0.31 - 0.36	-	Van Dobben 1962, 1965a
Sorghum bicolor	0.13 - 0.51	0.64	Anonymous 1968; Hodges et al. 1979; Donald & Hamblin 1976
Triticum vulgare	0.15 - 0.54	0.35 - 0.50	Anonymous 1968; Kagan & Ephrat 1974; Campbell & Davidson 1979; Passioura 1977; Van Dobben 1965a; Donald & Hamblin 1976
DICOTYLEDONS			
Carthamus tinctorius	0.05 - 0.25	-	Beech & Norman 1963; Stern & Beech 1965
Cicer arietum	0.67	-	Anonymous 1968
Helianthus annuus	-	0.16 - 0.35	Gaines et al. 1974
Phaseolus vulgaris (mean of 26 varieties)	0.46	-	Rettig 1979
Arachis hypogea	0.22 - 0.29	0.36 - 0.41	Goldin 1966 and unpublished data

TABLE 2.1b The seed ratio (SR) and reproductive ratio (RR) of some annual wild species.

	SR	*RR*	*Author*
1 Sahelian species			
MONOCOTYLEDONS			
Aristida funiculata	0.09	-	Bille 1977
Aristida mutabilis	0.04	-	Bille 1977
Brachiaria ramosa	0.02	-	Bille 1977
Cenchrus biflorus	0.03	-	De Ridder 1976
Chloris prieurii	0.03	-	Bille 1977
Diheteropogon hagerupii	0.01	-	Bille 1977
Diheteropogon hagerupii	-	0.19 - 0.34	Penning de Vries (personal communication)
Echinochloa colona	0.06	-	Bille 1977
Panicum leatum	0.05	-	Bille 1977
Panicum humile	0.02	-	Bille 1977
Pennisetum pedicellatum	0.03	-	Bille 1977
Schoenfeldia gracilis	0.01	-	Bille 1977
Schoenfeldia gracilis	0.17	-	De Ridder 1976
DICOTYLEDONS			
Zornia glochidiata	0.05	-	Bille 1977
Blepharis linariifolia (+ *Polycarpea*)	0.05	-	Bille 1977
Annual Sahelian vegetation (Chad)	0.25 - 0.38	-	Gaston 1976
2 Non-Sahelian species			
DICOTYLEDONS			
Astragalus cibarius	0.22	0.67	Green & Palmbald 1975
Astragalus utahensis	0.24	0.50	Green & Palmbald 1975
Chenopodium rubrum	0.47 - 0.54	-	Cook 1975
Polygonum cascadense	-	0.38 - 0.58	Hickmann 1975
Polygonum cascadense	0.55	-	Hickmann 1977
Polygonum douglasii	0.15	-	Hichmann 1977
Polygonum kellogii	0.65	-	Hickmann 1977
Polygonum minimum	0.10	-	Hickmann 1977
Senecio sylvaticus	0.06 - 0.12	0.19 - 0.20	Van Andel & Vera 1977
Veronica peregrina	0.38 - 0.43	-	Linhart 1974

their cultivated congeners. This could be inferred from data by Harper and Ogden (1970) who concluded that in that respect only small differences existed between *Avena fatua* (wild oats), *Avena sativa* (cultivated for grain) and *Avena strigosa* (cultivated for forage) (Table 2.2).

TABLE 2.2 The seed ratio (SR) and reproductive ratio (RR) of three *Avena spp.* (calculated from data by Harper and Hogden (1970) for above ground material assuming that 25 percent of the total biomass presented belongs to the root system).

	SR	*RR*
Avena fatua	0.34 - 0.37	0.56 - 0.61
Avena sativa	0.43 - 0.45	0.54 - 0.56
Avena strigosa	0.29 - 0.31	0.45 - 0.47

Likewise, in a test with wild relatives of wheat growing under low soil fertility conditions, harvest index values of 0.39 for *Triticum monococcum*, 0.43 for *Triticum spelta* and 0.44 for *Triticum dicoccum* were obtained (Zeven, personal communication). In the long-term Broadbalk experiments (Garner and Dyke 1969) on the non-fertilized plots the harvest index does not show a consistent change and the values found in 1966/67 are identical to ten-year averages obtained at the end of the last century (0.44). The general picture arising from these data is indeed that wild species or old varieties growing under conditions to which they are adapted, invest about the same proportion of their total production in reproductive tissue as do the modern varieties growing under present-day conditions.

The variability within one species can be quite considerable, owing to environmental conditions during the growing cycle. The decisive influence of these conditions in determining the seed yields of cultivated crops is well-known (*cf.* Spiertz 1977). In the semi-arid Northern Negev in Israel, where studies on annual pastures have been conducted since 1962 (Tadmor et al. 1974), biomass losses from seed dispersal and predation were observed repeatedly. However, no reliable information is available on the actual seed yields produced under grazing on fertilized and non-fertilized pastures under semi-arid conditions. It was, therefore, considered worthwhile to estimate the *RR* and *SR* of species of these natural pastures. This study is related to a more comprehensive study on seed production and seed survival in annual semi-arid pastures (Loria 1979).

2.2 Materials and Methods

Plants were sampled at two sites in Israel: the Tadmor Experimental Farm in Migda (1978 and 1979) and the Berurim seed farm (1978). The growing season in this Mediterranean type climate extends from approximately November till April. The year 1978 refers here to the 1977/1978 growing season; 1979 to the 1978/1979 growing season. Migda is situated near Beersheva in the Northern Negev desert in Israel (34° 25' EL, 31° 22' NL). The average rainfall in the area is 250 mm per year. The region consists of slightly undulating plains composed of a 10-20 m thick mantle of löss overlying deposits of eocene chalk. Berurim is situated about 40 km south of Tel Aviv in an area with an average rainfall of 450-500 mm per year. The deep vertisol and an intensive crop rotation create very favourable growing conditions.
Because of the difficulties connected with the determination of the reproductive effort of wild species, special care was taken in this study to develop a consistent, albeit laborious, methodology. The methods used in the two years were different. Both will be described in detail.
In 1978 individual plants were harvested carefully, on different dates, to obtain plants at different degrees of maturity. To ensure that complete plants were obtained, only those were chosen, that grew in relatively isolated positions, so that all shedded leaves, seeds and/or fruits could be collected. At Migda, plants were sampled from relatively wet as well as relatively dry sites. The wet sites were, in general, depressions where run-on from surrounding areas created more favourable moisture conditions. The dry sites were areas from which run-off water was probably lost.
All plants were separated into fruits or ears and vegetative parts and dried in an oven for 48 hours at 70 °C.
The individual samples of each plant were weighed: the mean weight of fruits or ears and the mean weight of vegetative parts provide the RR per species. Counting of the total number of fruits or ears per sample also enabled calculation of the mean fruit or ear weight. From the fruits or ears a subsample was taken and the seeds were separated from the rest. Both components were weighed and the fraction of seeds calculated. A relationship was thus established between the total dry weight of the reproductive organ and the associated fraction of seeds in the sample. Using this relationship, the fraction of seeds was estimated from the main sample, which yielded the seed weight and, hence, the SR.
In 1979 randomly selected quadrats of 20 * 20 cm were harvested instead of individual plants. The fields sampled, representing the different treatments, and the number of samples collected per field are summarized in Table 2.3.
The quadrats were harvested at the moment when the plants started to mature

at the end of the growing season, about one week after the last rain. The samples were separated into the main species present. All species samples were used for separation of vegetative and reproductive components, except those of *Schismus arabicus* of which only two or three of the samples of Fields 1, 11 and 12 were used for this purpose. The different components of the species were dried in an oven at 70 °C for 24 hours and the dry weight determined. The reproductive components were used for estimation of the potential SR and RR assuming that all flowers present at the moment of harvesting would produce seeds, that no more flowers would develop and that all still unripe seeds would mature.

TABLE 2.3 Summary of the samples collected in the 1978/1979 growing season (Field 1 continuous grazing; Field 11 and Field 12 deferred grazing; Field 13 ungrazed).

	Fertilizer application kg ha^{-1}			*Stocking rate sheep ha^{-1}*	*Number of samples*
	N	P	K		
Field 1					
1977-1978	60	-	-	3.3	single plants
	60	-	-	0	single plants
1978-1979	-	18	-	3.3	10
	-	18	-	0	15
Field 11					
1977-1978	60	-	-	10.0	single plants
	60	-	-	0	single plants
1978-1979	-	18	-	10.0	10
	-	18	-	0	15
Field 12					
1977-1978	60	-	-	15.0	single plants
	60	-	-	0	single plants
1978-1979	-	18	-	15.0	10
	-	18	-	0	15
Field 13					
1977-1978	100	28	310	0	single plants
	-	28	310	0	single plants
1978-1979	100	28	310	0	30
	-	28	310	0	30

Different methods of measuring and counting were applied for the various species, as described below. The species were identified according to Zohary (1977).

A MONOCOTYLEDONS

Phalaris minor

1. The total number of inflorescences per sample in all samples was counted.
2. The inflorescences of all samples were then pooled and 20 complete inflorescences (or as many as could reasonably be analyzed) were collected at random.
3. For each of these inflorescences the total number of flowers was counted. All seeds and flowers were removed and the empty inflorescences weighed.
4. A sample of 200 seeds was taken at random, including mature and immature seeds, and weighed. This was assumed to represent the situation of seed production at the date of sampling. Next 200 mature seeds (consisting of caryopsis and palea) were counted and weighed.

Hordeum leporinum

1. and 2. As for *Phalaris minor.*
3. For each inflorescence the total number of dispersal units was counted: one dispersal unit has three spikelets, but only one spikelet produces a seed. Each inflorescence was weighed.
4. Samples of 200 mature seeds, 200 mature dispersal units without seeds and 200 mature and immature dispersal units were taken at random, counted and weighed.

Schismus arabicus

1. As for *Phalaris minor.*
2. The inflorescences of all samples were pooled and ten complete inflorescences were taken at random.
3. For each inflorescence the total number of spikelets was counted, six spikelets were removed, two from the apex, two from the middle and two from the bottom position of the inflorescence, and the number of flowers per spikelet was counted.
4. The flowers and seeds from all spikelets of each inflorescence were collected. The empty inflorescences were than weighed.
5. A sample of 1 000 mature and immature seeds and a sample of 1 000 mature seeds were taken at random. The samples were weighed. (From the quadrats taken from the grazed treatments of Fields 1 and 11 only 250 mature seeds were collected).

Stipa capensis

1, 2 and 3. As for *Phalaris minor.*

4. Samples of 200 mature seeds and their awns and 200 mature and immature seeds (consisting of caryopsis and palea) and their awns were taken at random, counted and weighed.

B DICOTYLEDONS

Erucaria boveana

1. The number of fruits and flowers per quadrat sample was counted.
2. All fruits from all quadrat samples were pooled and 20 fruits were collected at random. From each fruit the number of seeds was counted.
3. Samples of 200 fruits, 200 mature seeds and 200 mature and immature seeds collected at random, were counted and weighed.

Asphodelus tenuifolius

1. As for *Erucaria boveana*.
2. Every pod contains six seeds.
3. Samples of 200 mature seeds and 200 empty pods were counted and weighed. The plants were almost completely mature, therefore immature seeds were not taken into consideration.

Trigonella arabica

1, 2 and 3. As for *Erucaria boveana*.

The originally oven-dried samples were stored for two months before processing. The weights given are those obtained after the storage period on an analytical balance with an accuracy of 0.001 g. Using the weight of mature seeds and the weight of a mixture of mature and immature seeds respectively for seed weight, potential and actual SR and RR are calculated as follows:

1. Actual (or potential) seed weight * total number of seeds per m^2 = total actual (or potential) weight of seeds per m^2 (S).
2. Weight of empty inflorescence or fruit * total number of inflorescences or fruits per m^2 = total weight of empty inflorescence or fruits per m^2 (E)
3. Weight of above ground vegetative components per m^2 + total actual (or potential) weight of seeds per m^2 + total weight of empty inflorescences or fruits per m^2 = total biomass per m^2 (B).

4a. SR = S/B
4b. RR = (S + E)/B

2.3 Results

The results of the year 1978 are presented in Figures 2.2 and 2.3 and Tables 2.4a and 2.4b. Figures 2.2 and 2.3 show that the proportion of seeds in ears or fruits increases as their weights increase, up to maximum value which varies per species. This relationship reflects the process of seed maturation, as the lighter fruits and ears are generally immature.

The differences between species are evident with respect to their SR, but less so for their RR (Tables 2.4a and 2.4b): the lowest SR is found for *Erucaria* (0.01) and the highest for *Trigonella* (0.42). The RR of all species may reach a value of 0.50 or more up to the exceptionally high value of 0.80 for *Trigonella*, under certain conditions (single, widely spaced plants growing and maturing over a short period late in the season).

The dry and wet sites do not show a significant difference in RR or SR, although there is a tendency for higher values of the two indices in the dry sites for *Erucaria* and *Plantago*, which may be partly due to the fact that towards the end of the growing season, the plants on the wet sites were still green in parts and had more immature pods and seeds than those growing on

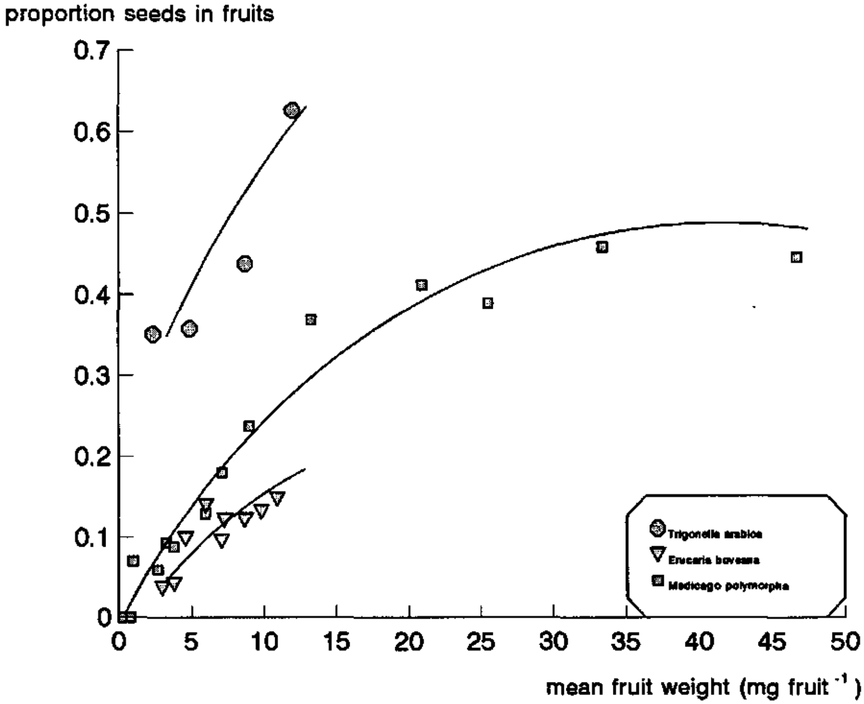

FIGURE 2.2 The proportion of seeds in fruits in relation to the mean fruit weight.

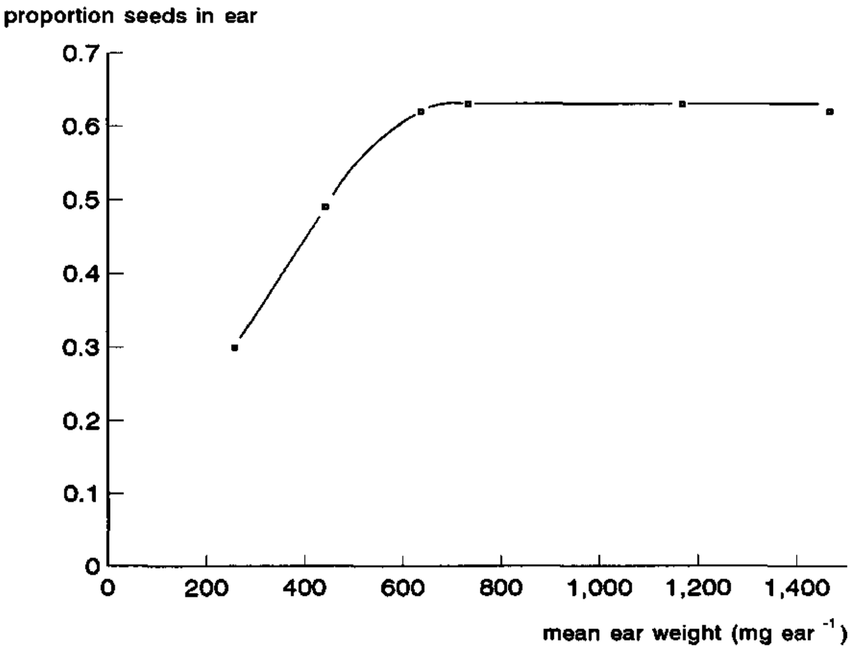

FIGURE 2.3 The proportion of seeds in ears in relation to the mean ear weight.

TABLE 2.4a Vegetative and reproductive characteristics of the species sampled in 1978. DWP=dry weight plants; DWF/E=dry weight fruits or ears; MWF/E=mean dry weight fruits or ears.

Species	Site	Sampling date	Nr of plants	DWP ($mg\ plant^{-1}$)		DWF/E ($mg\ plant^{-1}$)		MWF/E ($mg\ fruit^{-1}$ or ear^{-1})	
				Mean	SE	Mean	SE	Mean	SE
Triticum sativum	Dry-3	April 5	5	1 020	67	458	69	458	68.9
cv Miriam	Wet-3	April 10	14	3 961	615	2 140	353	1 304	182.7
Erucaria boveana	Dry-221	April 10	4	1 852	240	795	88	9.4	0.13
Coss.	Dry-165	May 1	7	2 540	524	1 034	249	8.8	0.47
	Dry-4	May 1	6	1 913	332	953	177	8.8	1.10
	Wet-221	April 10	3	6 200	2 490	2 183	1 253	7.3	0.70
	Wet-165	April 18	2	7 629	2 766	1 812	1 037	4.3	0.48
	Wet-4	May 1	2	21 830	13 760	7 150	4 250	6.8	0.68
Glaucium corniculatum L. Rudolph	Dry-165	May 1	2	3 615	2 695	1 765	1 285	289.4	49.4
Medicago polymorpha	Dry-8	April 10	3	603	273	197	145	19.6	8.6
L. (smooth bur)	Dry-165	May 1	5	1 944	543	1 218	348	28.5	3.2
	Wet-8	April 10	4	685	121	303	49	24.0	2.4
	Wet-165	May	3	290	64	128	56	26.1	2.0
	Berurim	May 1	2	22 541	1 676	14 448	1 583	25.2	1.6
Medicago polymorpha	Dry-8	April 10	5	184	50	58	33	12.5	1.4
L. (spring bur)	Dry-165	May 1	8	841	134	448	87	27.2	4.3
	Wet-8	April 10	3	1 397	257	557	267	17.7	6.9
Medicago polymorpha L. *cv* 50/5	Berurim	May 1	2	47 022	12 903	32 503	8 413	96.0	5.5
Plantago lagopus L.	Dry-221	April 10	6	396	153	241	99	47.3	10.3
	Dry-165	May 1	5	2 790	1 614	1 460	767	55.1	13.0
	Wet-221	April 10	3	5 557	-	1 470	407	55.7	8.0
	Berurim	April 10	1	2 270	-	560	-	70.0	-
Trigonella arabica	Dry-221	April 5	4	171	48	73	18	7.9	1.70
Del.	Dry-165	May 1	5	876	439	710	354	12.3	1.25
	Wet-221	March 28	8	1 234	323	696	193	6.9	0.76

TABLE 2.4b The reproductive ratio (RR) and seed ratio (SR) of species sampled in 1978.

Species	*Site*	*RR*		*Seed fraction in ears/ fruit*	*SR*
		Mean	*SE*		
Triticum sativum	Dry-3	0.45	0.04	0.50	0.32
cv Miriam	Wet-3	0.50	0.03	0.64	0.32
Erucaria boveana	Dry-221	0.43	0.03	0.14	0.06
Coss.	Dry-165	0.41	0.02	0.13	0.05
	Dry-4	0.50	0.04	0.13	0.06
	Wet-221	0.35	0.08	0.11	0.04
	Wet-165	0.24	0.06	0.05	0.01
	Wet-4	0.35	0.02	0.11	0.04
Glaucium corniculatum (L.) Rudolph	Dry-165	0.50	0.02	0.24	0.12
Medicago polymorpha L.	Dry-8	0.33	0.14	0.37	0.12
(smooth bur)	Dry-165	0.61	0.03	0.41	0.25
	Wet-8	0.46	0.05	0.40	0.18
	Wet-165	0.44	0.09	0.40	0.18
	Berurium	0.64	0.02	0.40	0.26
Medicago polymorpha L.	Dry-8	0.32	0.10	0.30	0.10
(spring bur)	Dry-165	0.52	0.03	0.41	0.21
	Wet-8	0.40	0.12	0.35	0.14
Medicago polymorpha L. cv 50/5	Berurium	0.69	0.01	-	-
Plantago lagopus L.	Dry-221	0.58	0.02	-	-
	Dry-165	0.52	0.02	-	-
	Wet-221	0.26	0.02	-	-
	Berurium	0.25	-	-	-
Trigonella arabica Del.	Dry-221	0.45	0.03	0.46	0.21
	Dry-165	0.80	0.02	0.52	0.42
	Wet-221	0.55	0.02	0.43	0.24

the dry sites. Hence, the effect of moisture availability on the SR and RR values is not too clear. The variation of SR and RR within one species can also be quite considerable (e.g. the SR of *Erucaria* varies from 0.01-0.06 and the RR from 0.24-0.50). In 1978 only individual plants were collected, many of them in very sparse stands. When the plant density is low, SR is generally higher.

The results for 1979 are presented in Tables 2.5a and 2.5b. Table 2.5a summarizes some characteristics of the reproductive organs of the species sampled in 1979, together with the treatment of the fields. Table 2.5b gives both the potential and the actual values for RR and SR. In reality, the harvest indices will lie between the potential and actual values.

The SR and RR values of *Erucaria,* which were determined in both years, are reasonably consistent. In the 1979 data there were large differences in SR

TABLE 2.5a Some characteristics of the reproductive organs of the species sampled in 1979

Species	*Treatment*	*1000-seedweight (mg)*		*Nr of seeds* $(10^3/m^2)$	*Nr of fruits or ears per* m^2	*Weight of empty fruits of ears per* m^2	$\bar{x}$ *of (nr of fruits or ears/weight of vegetative components)* $\pm$ *SE of* $\bar{x}$
		potential	*actual*				
Schismus arabicus Nees.	NPK	72	17	117.4	418	10	35±5
	PK	79	20	68.0	300	8	53±4
	F_1-grazed	69	55	826.4	3,545	6	49±12
	F_1-ungrazed	76	49	1,409.9	6,791	5	35±5
	F_{11}-grazed	62	64	1,220.2	6,048	8	42±1
	F_{11}-ungrazed	76	67	1,691.4	10,443	8	35±5
	F_{12}-grazed	68	64	570.3	2,628	9	41±12
	F_{12}-ungrazed	76	76	2,172.5	8,324	9	35±5
Hordeum leporinum Link (formerly Hordeum murinum)	NPK	2,380	2,250	1.1	40	12	8±2
	F_1-grazed	1,700	136	3.4	163	38	13±3
	F_1-ungrazed	1,979	292	1.6	87	35	8±2
	F_{12}-grazed	2,700	2,700	0.8	70	54	6±2
	F_{12}-ungrazed	2,476	2,476	0.7	28	69	8±2
Phalaris minor Retz	NPK	1,560	340	19.3	143	47	8±3
	PK	1,310	270	3.1	47	25	9±1
	F_1-ungrazed	1,700	630	6.1	48	45	8±3
	F_{12}-ungrazed	1,800	1,350	4.2	32	65	8±3
Stipa capensis Thunb.	F_{11}-ungrazed	300[a] + awns: 1,560	300 + awns: 2,410	7.3	183	10	22±7
Erucaria boveana Coss.	NPK	200	172	18.4	2,149	4	(58±12)[b]
	PK	289	339	7.6	805	4	-[c]
	F_1-grazed	170	160	6.5	878	6	-[c]
	F_1-ungrazed	230	190	7.3	1,094	5	(58±12)[b]
	F_{12}-ungrazed	240	270	2.0	267	6	(58±12)[b]
Asphodelus tenuifolius Cav.	NPK	1,310	1,310	11.4	1,904	4	74±9
	PK	1,210	1,210	17.8	2,963	3	110±8
Trigonella arabica Del.	PK	1,070	890	1.5	272	3	135±26

[a] This is about 4x lower than other data on Stipa capensis and may be due to the fact that the dispersal units weighed may have consisted of emtpty glumes.
[b] Values from one bulked sample
[c] Not determined

TABLE 2.5b The reproductive ratio (RR) and seed ratio (SR) of the species sampled in 1979

Species	*Treatment*	*Total Yield (g m⁻²)*		*RR*		*SR*	
		potential	*actual*	*potential*	*actual*	*potential*	*actual*
Schismus	NPK	32.6	26.1	0.39	0.24	0.26	0.08
arabicus Nees.	PK	15.2	11.2	0.51	0.34	0.35	0.12
	F_1-grazed	150.6	139.1	0.52	0.48	0.38	0.33
	F_1-ungrazed	232.9	194.8	0.65	0.53	0.46	0.35
	F_{11}-grazed	269.7	272.2	0.46	0.47	0.28	0.29
	F_{11}-ungrazed	386.1	370.9	0.55	0.53	0.33	0.31
	F_{12}-grazed	131.6	129.3	0.47	0.47	0.30	0.28
	F_{12}-ungrazed	433.6	433.6	0.55	0.55	0.38	0.38
Hordeum leporinum	NPK	23.9	23.8	0.13	0.13	0.11	0.11
Link (formerly	F_1-grazed	23.4	18.1	0.51	0.37	0.25	0.03
Hordeum murinum)	F_1-ungrazed	16.3	13.5	0.39	0.26	0.20	0.04
	F_{12}-grazed	41.7	41.7	0.14	0.14	0.05	0.05
	F_{12}-ungrazed	14.7	14.7	0.25	0.25	0.11	0.11
Phalaris minor Retz	NPK	87.2	63.7	0.42	0.21	0.34	0.10
	PK	11.7	8.5	0.45	0.24	0.35	0.10
	F_1-ungrazed	35.7	29.2	0.35	0.21	0.29	0.14
	F_{12}-ungrazed	21.1	19.2	0.46	0.41	0.36	0.30
Stipa capensis Thunb.	F_{11}-ungrazed	24.0	29.7	0.55	0.66	0.09	0.07
Erucaria boveana	NPK	49.0	48.4	0.25	0.24	0.08	0.07
Coss.	PK	17.8	18.2	0.31	0.32	0.12	0.14
	F_1-grazed	21.1	21.0	0.30	0.30	0.05	0.05
	F_1-ungrazed	20.8	20.5	0.34	0.34	0.08	0.07
	F_{12}-ungrazed	20.8	20.9	0.10	0.10	0.02	0.03
Asphodelus	NPK	52.9	52.9	0.43	0.43	0.28	0.28
tenuifolius Cav.	PK	62.3	62.3	0.49	0.49	0.35	0.35
Trigonella arabica Del.	PK	5.0	4.7	0.48	0.45	0.31	0.28

between species: the lowest potential SR is found for *Erucaria* (0.02) and the highest for *Schismus* (0.46). The value for *Schismus* (0.4), found by Loria and Noy-Meir (1980), obtained in a much drier environment, is similar to the value found in our study. The potential RR varies from low (0.10) for *Erucaria* to high (0.65) for *Schismus.*

Differences between the treatments with and without nitrogen supply, and between grazed and non-grazed are small, but the values tend to be higher without nitrogen (compared to with nitrogen supply) and without grazing (compared to with grazing). Exceptions are *Phalaris,* where nitrogen fertilization does not affect the SR and *Hordeum*, where grazing affects the SR in Fields 12 and 1 differently: Field 12 with a lower and Field 1 with higher SR than in the non-grazed plots. The treatment effects (nitrogen fertilizer and grazing) are statistically significant (F = 4.9, P = 0.001) when measured as inflorescences or fruits per unit of vegetative biomass (Table 2.5a). The differences between the treatments persist when measured as SR and RR but are not significant owing to the additional variation accumulated during the seed ripening and dispersal period.

2.4 Discussion

The results obtained in this study indicate that in annual wild species 10-80 percent of the total biomass produced during the growing period is eventually invested in the reproductive organs which include seeds as well as subsidiary protection and dispersal structures. Mean values, taken over all treatments and over two years of observation, range between 26 and 60 percent (Table 2.6) and cover the range for annual cultivated species. Such behaviour is appropriate for species that have to rely on their seed stock for survival from year to year. In some cases, the major part of the total effort is invested in subsidiary structures for protection and dispersal, rather than in true seeds (*e.g. Stipa, Erucaria)*. These include thickened seed coats (*e.g. Asphodelus)* which have a protective or other (germination inhibition) function. In *Erucaria* the seeds remain on the skeleton of the dead plant which protects them till they become detached by mechanical disturbance. In that sense, the entire dead plant participates in the protection and dispersal of the seed.

The magnitude of the losses of biomass towards the end of the growing season reported for natural vegetation could thus be explained by dispersal of part or all of the reproductive structures produced. As shown in Figure 2.1, the losses may vary from year to year, owing to variations in the botanical composition and/or different environmental conditions from one year to another. As the SR and RR vary per species (Tables 2.1, 2.4 and 2. 5), variation in botanical composition may thus change the SR and RR of the total canopy. The amount of standing biomass lost may then be further modified since the proportion of the produced dry matter of seeds and reproductive structures that is shed, differs from species to species: there is almost no shedding of seeds and reproductive structures from *Erucaria* until late in the dry season. Only from *Phalaris* and *Asphodelus* the seeds fall, whereas from *Schismus, Hordeum* and *Stipa* most of the reproductive parts are dispersed.

The wide range of year to year SR values can be represented as a function of the mineral, mainly nitrogen (and phosphorus?), translocation to the seeds. It has often been noted that uptake of nitrogen after flowering is negligible, unless extra nitrogen is applied as a late top-dressing (Anonymous 1968; Van Dobben 1962; Gmelig-Meyling and Van Dobben 1965). Nitrogen for the developing seeds, S, and associated reproductive structures has to be supplied mainly by translocation from the vegetative tissue, V, (Sinclair and De Wit 1976). The SR is then dependent on the concentration of nitrogen in the seeds, N_s, and the difference in the nitrogen concentration of the vegetative tissue between flowering, N_f and maturity, N_m. Thus,

$$V\,(N_f - N_m) = SN_s \text{ and}$$

$$SR = S / (V + S) = N_f - N_m / (N_s + N_f - N_m) = D_{fm} / (N_s + D_{fm})$$

in which D_{fm} is the difference (or depletion) in nitrogen concentration of the vegetative tissue between flowering and maturity. The response surface of this function is given in Figure 2.4.

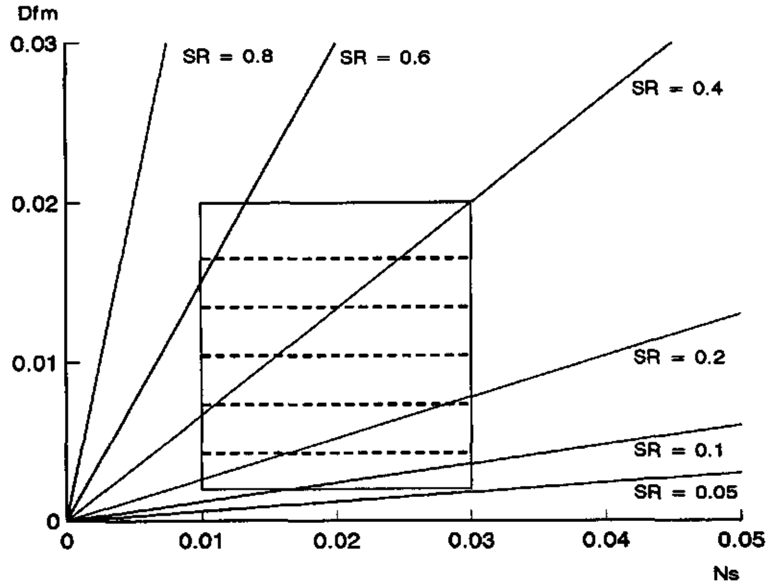

FIGURE 2.4 The response surface of seed ratio, SR, as a function of nitrogen concentration of the seed, N_s, and the dilution of nitrogen in the vegetative pools, D_{fm}, between flowering and maturity. The shaded area indicates the main range of variation in most of the species studied.

As the N_s *values generally fall between 0.01 and 0.03 and* D_{fm} values between 0.002 and 0.02, it is possible to obtain SR values anywhere between 0.05 and 0.67. The actual values achieved will depend on genetic characteristics that strongly affect N_s, and environmental factors, mainly nitrogen economy, that largely affect D_{fm}. These effects were reflected in this study but can be traced in literature as will be discussed in the following.

1. Nitrogen application generally results in a decrease in SR (Van Andel and Vera 1977; Campbell and Davidson 1979; Kagan and Ephrat 1974; Anonymous 1968; Donald and Hamblin 1976). On the other hand increasing values have also been reported (Van Dobben 1992; Gmelig-Meyling and Van Dobben 1965; Anonymous 1968).
The decrease occurs when D_{fm} / N_s decreases and indeed, in non-depleted agricultural fields, in grain N_s can increase considerably in relation to D_{fm} with increasing fertilizer application. In wheat, N_s can increase from 0.018 to 0.025, whereas N_f and N_m tend to increase together, thus diminishing the effect of added nitrogen on D_{fm} (Ellen and Spiertz 1980).
The harvest index should increase if D_{fm} increases in relation to N_s. This is possible under two different circumstances:

a. there is additional uptake of nitrogen during seed fill, and ripening conditions are favourable and long enough for seed fill to utilize the extra assimilates.
   This can occur as senescence of the vegetative parts is delayed by more available nitrogen (Van Dobben 1962; Spiertz 1977);
b. under conditions of severe nitrogen deficiency where N_f can be as low as 0.006 and N_m and N_s are around 0.003 and 0.010 respectively (Penning de Vries et al. 1980).
   Under such conditions, moderate application of nitrogen can increase the SR mainly by increasing D_{fm}. Deviations from this pattern can occur as seed-set and seed-fill can be strongly affected by environmental conditions, including pollination disturbances, grazing, plant disease, drought and other depredations.

2. Species and varietal effects. Differences in SR between species can be partially related to differences in N_s. Seeds with a high N_s tend to have a low SR (H. Breman, personal communication). However, where the seeds constitute only a small part of the dispersal unit (*e.g. Hordeum leporinum* and *Stipa capensis*) it is more appropriate to use RR when comparing reproductive efforts. In these cases the morphological differences in dispersal units override the translocation limitations in determining seed ratios. But, as the nitrogen concentration in the dispersal and protective structures is low, the nitrogen concentration of the dispersal unit is also low, generally around 0.01. If this is taken as N_s, then RR (instead of SR) rises steeply to 0.6 while D_{fm} increases to 0.015 (see Figure 2.4). This covers the range of values found in this study.

Varietal differences in the harvest index of cultivated crops appear to be inversely related to N_s (Kramer 1979, 1980). These varietal differences are generally maintained at different nitrogen availability levels. The data of Warren and Johnston (1967), describing a change in variety in the continuous barley experiment in the Rothamsted Hoosfield, show that the harvest index of Plumage Archer, grown from 1917 onwards is equal to that of Maris Badger, a modern variety, at all levels of nitrogen availability. At the low soil fertility level the total yield of the older variety is higher, which seems to be the result of a higher nitrogen uptake. A similar result was obtained by Hiltner and Lang (1912) who compared an improved rye variety (Petkuser) with a traditional one at different fertility levels. At the low fertility level the traditional variety yielded more, but the harvest index was identical for both. At the higher fertility levels, the total production was higher for the improved variety, but the harvest index changed for both in the same way.
The results of Sandfaehr et al. (1965) for a number of barley varieties, ranging in year of introduction between 1904 and 1954, were different only in that the newer varieties have a higher harvest index at all N levels tested. A similar conclusion was reached by Van Dobben (1962) for wheat. At high fertility levels the harvest index ranged from 0.34 to 0.40 for varieties introduced between 1900 and 1950. The modern varieties maintained a higher harvest index at higher N levels than the older varieties. At lower nitrogen levels, the harvest indices were higher for all varieties.
Generally, it may be concluded, that the influence of plant breeding in small grains has mainly been in counteracting the negative effects of high nutrient availability on the seed/straw ratio. This, however, was achieved at the cost of a lower N_s (Kramer 1980). N_s appears to be genetically determined, as the higher harvest indices are maintained in relation to older varieties even under low fertility conditions.

3. Plant density influences the harvest index: the lower the plant density, the higher the harvest index (Linhart 1974; Stern and Beech 1965; Goldin 1966; Hickmann 1975; Donald and Hamblin 1976), although Donald and Hamblin found that for maize the harvest index decreases again at very low plant density. Darwinkel (1978, 1979) found such an optimum curve also for wheat. This is apparently caused by poor seed production on tillers that are produced late under very low density conditions.

4. Water stress generally increases the harvest index (Passioura 1977; Hodges et al. 1979, Gaston 1976; Donald and Hamblin 1976). This could be related to the fact that waterstressed plants tend to have higher N_f values. If subsequent growth is relatively unstressed, N_m and N_s will hardly be affected

and, consequently, SR will increase. However, water stress after flowering causes the harvest index to drop, so that N_s will then invariably be higher. A striking example was observed in wheat growing at the Migda site in the 1979-80 growing season. Abundant rains early in the season resulted in luxurious vegetative growth (10-12 tons dry matter per ha). From early on in the reproductive phase a prolonged dry period together with hot dry winds from the desert ("chamsien") caused rapid drying of vegetation and soil, resulting in shrunken seeds and low grain yields (±3 ton per hectare) with HI around 0.2. The N_s of such shrunken seeds may typically be well above 0.03.

5. Beech and Norman (1963) found that the harvest index of short-day plants strongly decreases at long days.

6. Light intensity affects the harvest index. Donald and Hamblin (1976) recorded that lower levels of irradiance decrease the harvest index.

7. The effects of multiple stress conditions may counteract each other or they may work in the same direction, as illustrated by the results of Campbell and Davidson (1979). Water stress in an early stage of development of wheat well supplied with nitrogen tended to counteract the negative effect of nitrogen supply on the harvest index, whereas water stress in a later stage enhanced the unfavourable effect.

In general, these effects may be understood on the basis of dry matter production in the different phases. There are also indications however, that stresses during flowering and fertilization may have strongly adverse effects on seed setting. In the later stages of development the capacity of these seeds to store reserve substances may be the limiting factor. Under such conditions a low harvest index may be found, which is not correlated to the dry matter production in the two major growth phases.
The influences of especially moisture availability, nitrogen supply and plant density on the SR and RR are also noted in the results obtained in this study on semi-arid annuals in field conditions. The environmental differences here are not statistically significant because the sample sizes were too small in relation to the large degree of heterogeneity in both soil properties and plant characteristics under the field conditions of the study area.

2.5 Conclusions

The results of this study and those of related work show that the magnitude of the reproductive effort in many wild annual pasture species is similar to that of cultivated annual crop plants. It is proposed that the ratio seed/total biomass is closely related to nutrient translocation processes from the vegetative parts to the reproductive parts. An analysis based on the nitrogen content of the vegetation at flowering and maturity and on the nitrogen concentration of the seeds appears to apply equally well to both wild and cultivated, including highly bred, species. Most of the environmental effects on harvest indices (or seed ratios) can also be interpreted in terms of their effects on the nitrogen concentrations mentioned above. In view of these conclusions, it is clear that the reproductive effort of annual pasture species is a major factor in determining the quantity and quality of the biomass available for grazing, especially after plant maturity. Understanding these relationships can contribute to more rational management of such pastures.

Chapter 3

Energy and protein balances in traditional livestock systems and ranching in eastern Botswana.

This chapter has appeared as:

De Ridder N and KT Wagenaar 1986. Energy and protein balances in traditional livestock systems and ranching in eastern Botswana. *Agricultural Systems* 20:1-16

Chapter 3

Energy and protein balances in traditional livestock systems and ranching in Eastern Botswana

N. de Ridder and K. T. Wagenaar

3.1 Introduction

Most of Botswana is covered with natural rangeland where cattle production is the major activity. Only a small part of the country is cultivated. Nevertheless, arable farming is important as a subsistence activity for much of the rural population. Farming is concentrated in the eastern and southern parts of the country, where most of Botswana's people live. In these arable areas, as well as in nearby areas of rangeland, the supply of cattle to provide draught power is an important aspect of production. In pastoral areas both meat and milk are important products.

Research in the 1970s indicated that productivity in the traditional livestock systems, expressed in terms of weight of weaner calf per cow per year, was significantly lower than productivity on experimental ranches under reasonably acceptable levels of management (Rennie et al. 1977). The experimental ranches had management systems similar to those on commercial ranches in other parts of southern Africa.

This research implied that land would be more productive if it were allocated for ranching and if cattle were managed for beef production. Two further considerations, however, suggest that the real situation is not as clear-cut as was thought. These considerations are:

1. While the weight of weaner calf per cow per year is an adequate parameter for expressing the productivity of commercial beef production systems, in multi-goal traditional production systems draught power and milk production for human consumption also need to be taken into account, since both affect the potential beef production and are themselves valuable outputs.
2. The productivity *per animal* may be higher in ranching systems, but this does not necessarily mean higher productivity *per hectare.*

De Ridder and Wagenaar (1984) compared the productivity of both systems on a per hectare basis, taking draught power and milk production into account. They concluded that traditional systems in eastern Botswana were as much as 95 percent more productive than ranching in terms of live weight production equivalents (Table 3.1). The average values of production parameters used to compile Table 3.1 were assessed from data reported in literature.

TABLE 3.1 Productivity of traditional and ranching systems in eastern Botswana (De Ridder and Wagenaar 1984)

Production parameters	*Traditional systems*	*Ranching systems*
Cows and calves		
Calving rate (%)	50.0	74.0
Mortality (%)	12.0	8.5
Weaning rate (%)	44.0	67.7
Weight of 12-month calf (kg)	132.5	200.0
Weight of 12-month calf (per cow yr^{-1})(kg)	58.3	135.4
Stocking rate (LSU ha^{-1})	0.167	0.08
Cow Stocking rate (cows ha^{-1})	0.112	0.037
Weight of 12-month calf (ha^{-1} yr^{-1}) (kg)	6.53	5.01
Milk offtake		
Lactating cow stocking rate (cows ha^{-1})	0.049	0.025
Offtake (kg cow^{-1} yr^{-1})[a]	162.0	-
Offtake (kg ha^{-1} yr^{-1})	7.94	-
Live weight equivalent (kg ha^{-1} yr^{-1})	2.22	-
Draught power		
Stocking rate (oxen ha^{-1})	0.037	0.009
Draught energy (MJ $oxen^{-1}$ yr^{-1})	338.0	-
Draught energy (MJ ha^{-1} yr^{-1})	12.5	-
Live weight equivalent (kg ha^{-1} yr^{-1})	0.65	-
Total live weight equivalents (kg ha^{-1} yr^{-1}) [b]	9.40	5.01

[a] 25 % of total milk production: 180 (days) * 3.6 (kg day^{-1}) * 0.25.

[b] Weight of a 12-month calf plus live weight equivalents for milk and draught.

In Table 3.1 growth and mortality for the different age classes of animals older than one year were not considered. It will be shown later that when this is done, the differences between traditional systems and ranching are reduced.

It is commonly believed that, besides having higher productivity, ranching systems are more efficient in converting forage energy and proteins into human food. Ranching is also thought to guarantee better range conditions, avoiding degradation, and to be a less risky enterprise in environments where rainfall, and hence forage availability, are highly variable.

Several authors have pointed out that, to test these beliefs and to assess the advantages and disadvantages of each system, all the outputs of the two systems must be taken into account. Furthermore, productivity on both the per animal and per hectare basis should be included if a fair comparison is to be made (Cruz de Carvalho 1974; Behnke 1985). Energy flows and balances have been suggested (Western 1982) and used (Cruz de Carvalho and Vieira da Silva 1973; Ellis et al. 1979; De Felice-Katz 1980) as a tool to compare systems comprehensively. This paper compares the complete gross energy (GE) and crude protein (CP) balances in traditional livestock systems and ranching.

3.2 Materials and methods

The stocking rate and production values presented in Tables 3.l and 3.2 were used to calculate the amounts of GE and CP consumed for maintenance and for the indicated production on a per hectare basis in both systems.

TABLE 3.2 Live weight at beginning (LW_1) and end (LW_2) of the indicated growth periods[a] and the stocking rate of each animal category in traditional livestock systems and ranching.

	Traditional system			*Ranching system*		
	LW_1 (kg)	*LW_2 (kg)*	*Stocking rate (LSU ha^{-1})* [b]	*LW_1 (kg)*	*LW_2 (kg)*	*Stocking rate (LSU ha^{-1})*
Cows (> 4 years)	325	325	0.081	425	424	0.035
Heifers (1-4 years)	135	325	0.002	200	425	0.014
Calves (0-1 year)	26	135	0.010	31	200	0.006
Young bulls (1-3 years)	135	330	0.003	540	540	0.001
Bulls (> 3 years)	425	425	0.003	540	540	0.001
Bullocks (1-3 years)	135	330	0.016	200	450	0.014
Oxen (> 3 years)	425	425	0.031	540	540	0.009

[a] Growth period is 1 year (calves), 2 years (young bulls and bullocks) and 3 years (heifers)
[b] 1 LSU = 450 kg. Stocking rates, expressed in animals per ha, were converted to LSU ha^{-1}, thus: 0.112 cows ha^{-1} * 325 kg/450 kg = 0.08 LSU cows in LSU ha^{-1}
(Source: De Ridder and Wagenaar 1984).

Following the calculations of the GE and CP requirements of animals, the amounts of available GE and CP in pastures were estimated. Two separate cases were considered: in Case I the availabilities of GE and CP in the pastures of both the traditional and ranching systems were assumed to be equal, while, in Case II, the availabilities of GE and CP in traditionally managed pastures were assumed to be lower because of higher stocking rates.

CALCULATION OF GE AND CP REQUIREMENTS FOR MAINTENANCE AND PRODUCTION

The *metabolizable energy* (ME) and *digestible crude protein* (DCP) requirements for maintenance per animal per year, based on the average live weights of each stock category (Table 3.2), were estimated from NRC (1976) tables. The DCP requirements for maintenance of calves were estimated from Roy (1980).
Production was defined as the annual live weight gain of animals from both sexes in the different age classes (Table 3.2), plus the milk off-take and output of draught power given in Table 3.1. ME and DCP requirements for the first-year live weight gain of calves were obtained from Roy (1980). The ME requirements for the average annual live weight gain of heifers, bullocks and young bulls were obtained from ARC (1980), while the DCP requirements were taken from NRC (1976) tables. The ME and DCP requirements for the production of 1 kg of milk were 5.4 MJ (ARC 1980) and 0.06 kg (NRC 1976) respectively.
The efficiency with which ME is transformed into NE for draught power was considered to be equal to that of maintenance, i.e. 0.64 (ARC 1980). The maintenance and production requirements per animal category were converted to a per hectare basis by using the livestock unit (LSU) conversion factor and the stocking rate of each category (Table 3.2).
Addition of all the ME and DCP maintenance and production requirements for each animal category gave the total maintenance and production requirements per hectare per year. The average digestibility over the whole year was estimated at around 0.50 (Pratchett 1983). Metabolizability was assumed to be 0.81 (Konandreas and Anderson 1982). Thus, conversion of ME to GE was by dividing the ME requirements by 0.405 (0.81 * 0.50 = 0.405). The equation used to estimate DCP from CP:

$$\text{DCP}\ \% = 0.9\ \text{CP}\ \% - 3.25 \qquad (3.1)$$

was derived from Van Niekerk et al. (1967) and Milford and Minson (1965). The mean CP percentage in the diet was estimated at 7.5 percent (Pratchett 1983). Thus, the conversion factor for CP to DCP is 0.47.

CALCULATIONS OF GE AND CP AVAILABLE IN PASTURES

Data on peak dry matter (DM) production and the GE and CP available in pastures in Botswana are insufficient, although APRU (1977) reported an average peak biomass of 1900 kg DM per hectare on seven ranches over a two-year period, at an average rainfall of about 450 mm. The long-term average peak biomass was therefore estimated from rainfall.
There are a few references indicating a lower DM production at higher stocking rates. For example, at the Morale research station in Botswana, McKay (1968)

found that after the pastures had been grazed for eight years at high and moderate stocking rates, DM production at an average rainfall of 300 mm was 400 and 1360 kg per hectare respectively. In a comparable climatic zone in southeastern Zimbabwe, Kelly and Walker (1976) measured less herbaceous biomass in systems under intense utilization than in those that were moderately stocked: the averages over two years were 745 and 1275 kg DM per hectare respectively. However, no consistent data are available to relate stocking density to biomass production. The following equation was therefore used to estimate long-term average biomass production via the nitrogen balance:

$N_b = 0.0083\ R / f - 0.12$ (after De Wit and Krul 1982) (3.2)

in which N_b is the amount of nitrogen in the above-ground biomass at flowering (kilogram per hectare); R is the average rainfall per year (mm) and f is the fraction of N_b which disappears annually through grazing, volatilization and fire.

This equation is based on data collected from a transect in the Malian Soudan and Sahel zone over four years. They included data on DM production, N content and estimates of N_b losses by grazing, volatilization and fire. The annual rainfall in this transect ranged from 1100 mm in the south to 350 mm in the north.

The advantage of this equation is that biomass can be related to rainfall (R) and exploitation intensity (f), but a precondition for its use is that, with a rainfall not much below the average, the availability of N is the first limiting factor for plant growth. Nitrogen-limited plant growth is indicated by a minimal average N percentage (1 percent) and a higher than minimal P/N ratio (>0.04) at flowering stage. The average N and P percentages in natural pastures were found to be 1 percent and 0.08 percent respectively (APRU 1975, 1977), giving a P/N ratio of 0.08. Further indication that N is the first limiting factor for plant growth can be found in fertilizer experiments: the response of natural pastures to N fertilizer was greater than to P fertilizer (APRU 1977).

The above data were felt to be sufficient to fulfil the precondition posed, and the equation was subsequently used to estimate biomass. As the different stocking rates maintained in traditional and ranching systems are expected to have an effect on the biomass availability in these systems, two separate cases were considered. In Case I the exploitation intensity in both management systems was assumed to have no effect on biomass production, i.e. f was assumed to be the same (it was estimated at 0.40) in both systems, while in Case II a higher exploitation intensity in traditional systems was assumed to affect their biomass production, i.e. f was estimated at 0.55 in traditional systems and 0.40 in ranching. The f factors were estimated following De Wit and Krul (1982), and the average long-term rainfall (R) was taken to be 550 mm.

The resulting N_b values were 10.7 kg N per hectare with f = 0.55 and 16.5 kg N per hectare with f = 0.40. In a five-year experiment, just across the border in Zimbabwe, an average N_b value of 14.9 kg N per hectare was estimated (Mills 1966). Although the exploitation pressure (f) must have been somewhat higher than 0.40, because the plots were hayed every year rather than grazed, the average N_b value found in Zimbabwe is close to the N_b value calculated with the f factor (0.40) in this paper.

The N content at flowering stage is around 1 percent (Pratchett 1983), and at maturity it is assumed to be 0.8 percent. The estimated biomass at a later stage will thus be:

10.7/0.008 = 1350 kg DM ha^{-1} (f = 0.55)

or

16.5/0.008 = 2050 kg DM ha^{-1} (f = 0.40)

The amount of GE available in pastures was estimated by multiplying DM production by 18.5 MJ per kg DM (NRC 1976). The amount of CP was calculated by multiplying N_b by 6.25.

The resulting values for DM, GE *and* CP *obtained with* f = 0.40 *and* f = 0.55 are summarized in Table 3.3.

TABLE 3.3 Estimated amounts of nitrogen in de the above ground biomass (N_b), dry matter (DM), gross energy (GE) and crude protein (CP) in pastures under two different exploitation intensities.

	f = 0.40	f = 0.55
N_b (kg N ha^{-1} yr^{-1})	16.5	10.7
DM (kg ha^{-1} yr^{-1})	2 050	1 350
GE (MJ ha^{-1} yr^{-1})	37 925	24 975
CP (kg ha^{-1} yr^{-1})	103.1	66.9

3.3 Results

PRODUCTIVITY

Table 3.4 summarizes productivity per LSU and per hectare in the two livestock systems.

Compared with Table 3.1, in Table 3.4 growth and mortality not only of calves,

TABLE 3.4 Productivity in live weight equivalents per hectare and per livestock unit (LSU) in traditional systems and ranching in eastern Botswana.

	Traditional systems		*Ranching*	
Calves (Table 3.1)		6.53		5.01
Heifers	2.55		1.44	
Bullocks	3.31		2.31	
Young bulls	0.52		0.15	
	+ 6.38		+ 3.90	
Mortality (> 1 year)	- 5.65		- 0.83	
	0.73	0.73	3.07	3.07
Milk offtake (Table 3.1)		2.22		-
Draught power (Table 3.1)		0.65		-
Production per hectare ($kg\ ha^{-1}\ yr^{-1}$)		10.13		8.08
Stocking rate ($LSU\ ha^{-1}$)		0.167		0.08
Production per LSU ($kg\ LSU^{-1}\ yr^{-1}$)		60.65		101.00

but also of other classes of animals, were taken into account. The mortality of all classes of animals more than one year old was estimated at 8 percent (Bailey 1982; Carl Bro Int 1982) in traditional, and 2.5 percent in ranching systems (APRU 1980).

Table 3.4 shows that in traditional systems the productivity of all classes of stock more than one year old was almost completely offset by mortality. Despite this, productivity, expressed in live weight equivalents per hectare, was at least 20 percent higher in traditional systems than in ranching. However, productivity per LSU was about 65 percent higher in ranching than in traditional systems.

No information is available on fallen meat/emergency slaughter, but some of the animals that died in traditional systems are likely to have been consumed. If it is assumed that 20 percent of the lost animals are consumed, the productivity per hectare becomes 40 percent higher in traditional systems, while the productivity per LSU is 50 percent higher in ranching.

GE AND CP BALANCES

The calculated GE and CP balances of both systems are presented in Tables 3.5a and 3.5b. Assuming equal amounts of GE and CP to be available in pastures (Case I), the comparison shows that more GE and CP is consumed in traditional systems than in ranching and, consequently, less GE and CP are left uneaten in pastures under traditional management.

TABLE 3.5 Gross energy (GE in MJ ha^{-1} yr^{-1}) and crude protein (CP in kg ha^{-1} yr^{-1}) balances in ranching and traditional systems in eastern Botswana.

(a) RANCHING SYSTEMS

	GE	%	*CP*	%
Available in pasture	37 925	100.0	103.1	100.0
Consumption by cattle	4 580	12.1	22.8	22.1
Left in pasture	33 345	87.9	80.3	77.9
Requirements for maintenance	4 168	11.0	17.2	16.7
Requirements for production	412	1.1	5.6	5.4
Of which for growth of:				
calves	138	0.4	2.0	1.9
heifers	110	0.3	1.4	1.4
bullocks/young bulls	165	0.4	2.2	2.1
Milk offtake	-	-	-	-
Draught power	-	-	-	-

(b) TRADITIONAL SYSTEMS

	Case I [a]				*Case II* [b]			
	GE	%	*CP*	%	*GE*	%	*CP*	%
Available in pasture	37 925	100.0	103.1	100.0	24 975	100.0	66.9	100.0
Consumption	10 048	26.5	47.2	45.8	10 048	40.2	47.2	70.6
Left in pasture	27 877	73.5	55.9	54.2	14 927	59.8	19.7	29.4
Required for maintenance	9 335	24.6	37.7	36.6	9 335	37.4	37.7	56.4
Required for production	713	1.9	9.5	9.2	713	2.8	9.5	14.2
Of which for growth of:								
calves	188	0.5	2.8	2.7	188	0.8	2.8	4.2
heifers	158	0.4	2.6	2.5	158	0.6	2.6	3.9
bullocks/young bulls	209	0.6	3.1	3.0	209	0.8	3.1	4.6
Milk offtake	108	0.3	1.0	1.0	108	0.4	1.0	1.5
Draught power	50	0.1	-	-	50	0.2	-	-

[a] In Case I the availability of GE and CP in the pastures of traditional systems is assumed to be equal to that in ranch pastures.

[b] *In Case II a lower availability of GE and CP is assumed in pastures of traditional systems.*

In traditional systems relatively less of the GE and CP intake (7.1 percent and 20.1 percent respectively) is used for production than for maintenance. In ranching, on the other hand, 9.0 percent of the GE intake and 24.6 percent of the consumed CP is used for production. In absolute terms, however, traditional systems use more GE and CP for production than ranching, which is manifested in their higher productivity (Table 3.4).

BIOLOGICAL EFFICIENCY

The efficiencies of traditional systems and ranching were compared in several ways. First, the net energy (NE) in the different products was estimated using tables from NRC (1976) and ARC (1980). Losses caused by mortality were subtracted from production. The NE values per kilogram of empty body weight were taken from ARC (1980). Based on these data, three ratios were calculated (Table 3.6).

TABLE 3.6 Ratios in animal products to maintenance energy requirements of animals (MA) and to plant energy produced (PE), and of energy consumed (CE) to plant energy produced.

	Ranching systems	*Traditional systems*	
		Case I	*Case II*
	%	%	%
PE/MA	2.78	1.33	1.33
NE/PE	0.31	0.33	0.50
CE/PE	12.08	26.49	40.23

The NE/MA ratio indicates the efficiency in terms of energy produced per unit energy used for maintenance. According to this ratio, ranching appears to be 110 percent more efficient than traditional systems, as less of the energy consumed is allocated to maintenance and more to production.

The NE/PE ratio indicates the efficiency in terms of net energy produced per unit plant energy produced. In this case, traditional systems appear to be more efficient than ranching - by 6 percent and 61 percent, depending on whether equal (Case I) or lower (Case II) GE and CP availabilities in pastures of traditional systems are assumed.

The CE/PE ratio indicates the food chain efficiency, which was defined by Western (1982) as the consumption of trophic level n-1 (GE and CP consumed by cattle) divided by production of trophic level n (GE and CP available in pastures). The food chain efficiency of traditional systems appears to be more than two and three times higher (Cases I and II respectively) than in ranching.

Ratios were also calculated using the CP balance. However, in order to avoid arbitrary estimates of CP percentage in such animal products as meat and milk, CP consumed for production was used instead of the animal protein produced (Table 3.7). Ranching appears to be 30 percent more efficient than traditional systems in terms of CP consumed for production per unit CP used for maintenance, while traditional systems are 70 percent and 160 percent (Cases I and II respectively) more efficient than ranching in terms of CP consumed for production per unit plant CP produced. The food chain efficiency of traditional systems is one or two times higher than that of ranching, depending on whether equal (Case I) or lower (Case II) availability of GE and CP is assumed.

TABLE 3.7 Ratios of crude protein (CP) consumed for production to CP consumed for maintenance of animals (CPM) and to plant CP produced (CPP), and of CP consumed for maintenance and production (CCP) to plant CP produced.

	Ranching systems	*Traditional systems*	
	%	*Case I* %	*Case II* %
CP/CPM	32.56	25.20	25.20
CP/CPP	5.43	9.21	14.20
CCP/CPP	22.11	45.78	70.60

PASTURE DEGRADATION AND DROUGHT

Degradation in the species composition of pastures resulting from higher stocking rates is felt to be beyond the scope of this paper. However, degradation is considered here in terms of increased risks of erosion, which are the result of lower infiltration and higher run-off rates because of the smaller amount of biomass available to protect pastures under higher stocking rates.

First the annual DM intake per hectare was calculated using the GE and CP consumed by cattle for maintenance and production. The values obtained were about 580 kg DM per hectare for the traditional systems and 270 kg DM per hectare for ranching. The long-term average primary production was estimated at 2050 kg DM per hectare per year. After subtracting from this figure the annual DM intake per hectare, 1470 and 1780 kg DM per hectare remained uneaten to protect pastures against degradation in traditional systems and ranching respectively.

The difference between the two systems does not seem to justify the conclusion that traditional systems are subjected to a high degradation risk. However, if lower DM production is assumed in traditional systems owing to higher stocking rates, only 770 kg DM per hectare would be left to protect pastures against degradation under traditional management. Furthermore, during years with below-average rainfall the risk of pasture degradation will be much higher in traditional systems than in ranching.

Sandford (1978) defined drought as a shortage of some economic good (livestock feed) brought about by inadequate or badly distributed rainfall. It is assumed arbitrarily that mild droughts will occur when the biomass production is lower than twice the consumption level of cattle; severe droughts occur when biomass production is lower than the calculated consumption level.

Assuming equal availability of DM in both systems, the small difference in intake levels does not justify the conclusion that traditional systems will encounter feed shortages more often than ranching. However, if lower DM production is assumed in traditional systems owing to higher stocking rates, it can be expected that these systems will run into problems sooner than ranching, as rainfall only slightly below the long-term average will result in a biomass production that is lower than twice the calculated consumption level of cattle.

In 1972/73, when rainfall was 50 percent below the long-term average, traditional systems in Botswana were under severe stress, whereas ranching did not encounter any difficulties during that period. The period 1983/84 is another example of increased annual fluctuation in the productivity of traditional systems. However, this annual fluctuation in productivity is offset by higher yields per hectare over a sequence of years, as was shown by the calculations in the present analysis, which were based on data collected over ten years, including three drier years.

3.4 Conclusions

A fast growing population and its increasing demand for food and work are matters of great concern to many African governments. Ranching is often proposed for the improvement of traditional livestock production systems in order to meet the increasing demand for meat in urban areas as well as for export, and to reduce the risk of pasture degradation.

The shift from traditional animal production to ranching involves a change in product allocation, and serious losses of efficiency and productivity per hectare are likely to occur. Meat, milk and animal power previously consumed and used in rural areas are, under ranching, converted to higher quality meat for urban consumers or for export. In a country like Botswana, where land is becoming scarce (Sandford 1980), a change towards ranching would mean that many rural people will eventually be left without work or food. Increased migration to urban areas will be the result, leading to greater unemployment and increased dependence on external food sources. More foreign currency will be earned with the increased export of high quality meat, but much will be required to finance food imports and to create employment opportunities. A socio-economic analysis is badly needed to weigh the advantages and disadvantages of the development of ranching on a national scale.

The calculations in this paper suggest that the lower stocking rates observed on experimental ranches in Botswana may reduce the risk of pasture degradation. They also indicate that if the risk of degradation is to be reduced, the price to be paid is lower productivity, which is rather cynical when the demand for food is increasing. However, there are other ways of avoiding the risk of degradation. For example, qualitative and quantitative improvements in forage production could be obtained through mixed cultivation of cereals and fodder crops, especially legumes, and the use of fertilizer.

It is true that such improvements are difficult to achieve and are often considered uneconomical, but it may well be that from the socio-economic point of view they will be more profitable than further development of ranching. On the other hand, investments of this kind are probably more advantageous and more easily accepted in ranching than in traditional systems, where only the wealthier herd owners are likely to show any interest in them.

Chapter 4

Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West-African semi-arid tropics (SAT).

This chapter has appeared as:

De Ridder N and H van Keulen 1990. Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West-African semi-arid tropics (SAT). *Fertilizer Research* 26:299-310

Chapter 4

Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West African semi-arid tropics (SAT)

N. de Ridder and H. van Keulen

4.1 Introduction

Intensified land use in the West African SAT, associated with increasing population pressure, puts high demands on maintenance and improvement of soil fertility. The demands on traditional systems of shifting cultivation ("cultures itinérantes") have exceeded their limits owing to shortage of land. Hence, they must be replaced by more intensive systems (Breman et al. 1990; Van Keulen and Breman 1990).

This problem was first encountered in the 1950s, mainly in the vicinity of urban centres. It led to research concentrating on the development of semi-intensive production systems, in which the fallow period was replaced by cultivation of a forage crop, either a perennial grass or a leguminous species. Morel and Quantin (1972), summarizing experimental work in the Central African Republic covering the period 1954-1963, concluded that continuous cultivation using external inputs (mainly chemical fertilizer) was more productive than these semi-intensive systems.

Application of organic manure, on its own or in combination with chemical fertilizer, to increase the production per unit area, had been considered as early as 1946/1947 at several locations in Mali (Traoré 1974). Long-term fertilizer experiments were initiated in the early 1960s in the SAT of West Africa by the Research Institute for Tropical Agriculture (IRAT). In these experiments yields and "soil fertility" were recorded for periods of at least ten years under different rotations and with different fertilizer regimes (without fertilizer, with chemical fertilizer, with organic manure, or with combinations of chemical fertilizers and organic manure). The experiments in Saria (Burkina Faso) cover a period of 29 years (Pichot et al. 1981).

Many of the results of these experiments have been summarized by Piéri (1986, 1989). He concludes that fertilizer application is an effective means to increase yields in arable farming systems without fallows. However, he cautions against the possibility that in the long term problems may arise, especially in the drier areas. To substantiate this, he cites Pichot et al. (1981): Application of NP and NPK fertilizers results in increased yields for some years, but in the long run it leads to decreasing base saturation and acidification of the soil. These phenomena, associated with the use of N fertilizers, are characterized by increasing K-deficiency, decreasing pH and occurrence of aluminium toxicity. Application of organic materials such as green manures, crop residues, compost or animal manure can counteract the negative effects of chemical fertilizers. This led Piéri (1986) to conclude that soil fertility in intensive arable farming systems in the West African SAT can only be maintained through efficient recycling of organic material in combination with effective use of N-fixing leguminous species and chemical fertilizers. Crop residues should be composted or recycled through the animal, as direct application of material with a high C/N ratio may have negative effects owing to immobilization of N during its decomposition (Figure 4.1). However, application of animal manure or compost generally has a positive effect, also in combination with chemical fertilizer (Table 4.1).

Annual applications of at least 5 ton per hectare compost or animal manure appear necessary to maintain a constant production level after clearing fallow land. Higher applications are necessary to reach increased yields (Pichot et al. 1981). However, limited availability of crop residues is a serious constraint for the production of such quantities of compost, as straw is generally used for other purposes. Evaluation of the availability of straw for composting in different regions of Senegal, showed that only in the south a surplus existed of 1 to 2.5 ton per hectare (Allard et al. 1983). In all other regions all straw is used as animal feed, construction material and fuel. Similar analyses for Burkina Faso led to the same conclusions (Sedogo 1981). Even if all the straw would be used as animal feed, the manure production would still be insufficient, and substantial areas of natural pasture would be required to produce the necessary 5 ton of manure per hectare arable land. Quilfen and Milville (1983) observed that in the present production systems in the north of

TABLE 4.1 Effect of application of different types of organic manure (10 t ha^{-1}) with and without feritilizer N on grain yield (kg ha^{-1}) of millet. (Source: Sedogo 1981)

Treatment	*Fertilizer N (kg ha^{-1})*	
	0	60
No organic manure	1831	2796
Sorghum stover	1652	3427
Animal manure	2409	3591
Compost	2505	3688

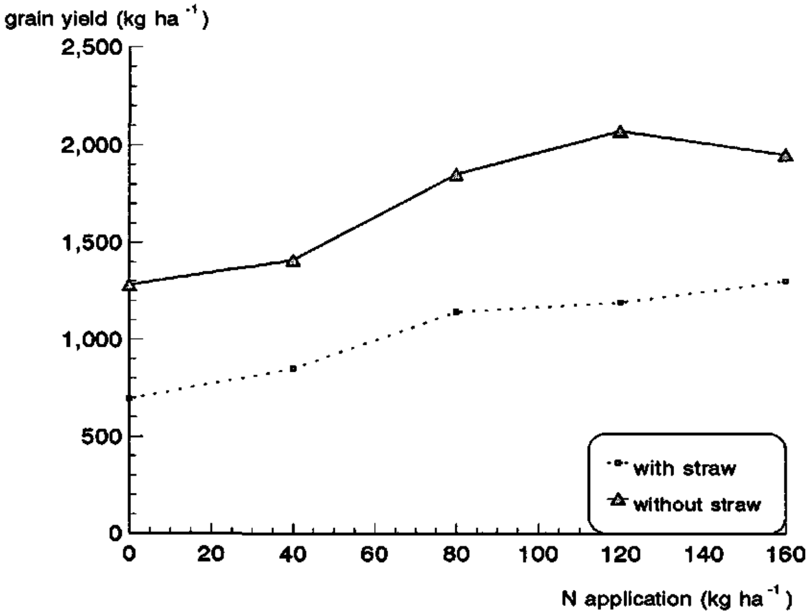

FIGURE 4.1 Grain yield of millet as a function of nitrogen fertilizer application, with (10 t ha^{-1}) and without straw application. (Source: Traoré 1974)

Burkina Faso, only 2.5 to 4 ton of animal manure per hectare of arable land is applied. Breman and Traoré (1986a, 1986b, 1987) showed that at the present animal density the feed availability from natural pastures and crop by-products is insufficient for the production of the manure required to maintain the present production levels in arable farming in Niger, Burkina Faso and Mali. This would even be so, if all feed would be used for that purpose.

Hence, if compost or animal manure are indispensable to maintain soil fertility, while insufficient organic manure is available, this would imply that sustainable arable farming systems, which are characterized by stable, high yields, cannot be developed in the semi-arid tropics of West Africa.

In this paper the role of organic manure in maintaining soil fertility is critically evaluated and possible alternatives to avoid the negative effects of chemical nitrogen fertilizers are discussed.

4.2 Effects of organic manure

Organic manure is generally applied to reach two major goals: (1) increased supply of nutrient elements to the crop and (2) increased organic matter contents in the soil, resulting in more favourable physical and chemical soil properties. These two goals are conflicting, as the release of nutrient elements requires decomposition of the organic material, which is then lost for the formation of soil organic matter. First the role of organic manure application in the supply of plant nutrients will be discussed and subsequently the effect of organic manure application on soil organic matter content will be dealt with.

4.3 Organic manure as a source of plant nutrients

In the last decades, many experiments have been carried out in West Africa to determine crop yields as affected by fertilizer application, with or without organic manure. In analyzing these experiments, generally yields are compared at a certain level of fertilizer application with and without organic manure application, as illustrated in Figure 4.2. The yield increase, in this case the grain yield of millet, is attributed to the combined positive effects of organic manure on crop growth. The observed variability in response shown in the various experiments is attributed to differences in the quality of organic manure.

In most cases, no attempts were made in the analyses to differentiate between the quantitative effects of organic manure as a source of additional nutrient elements and any possible other positive effects. Such a differentiation

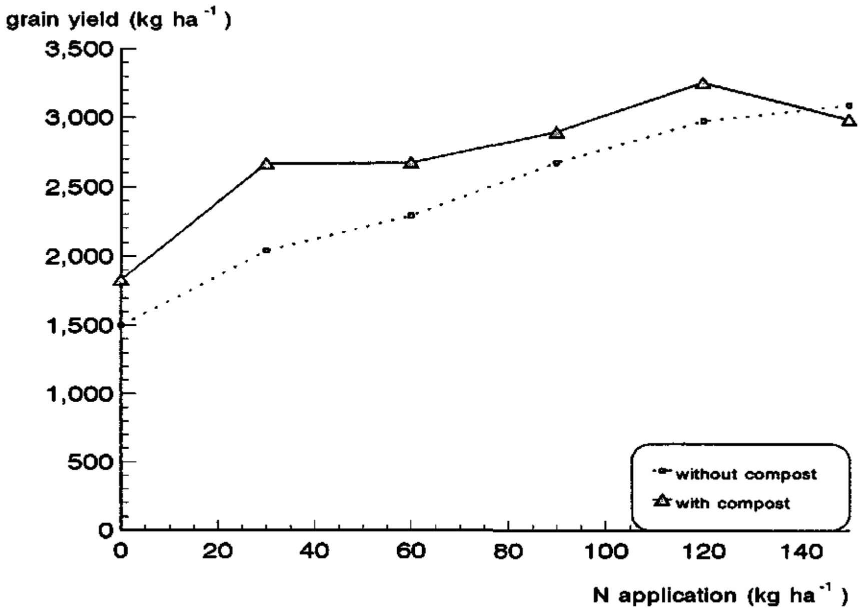

FIGURE 4.2 Grain yield of millet as a function of nitrogen fertilizer application with (11 t ha^{-1} in the first year, 15 t ha^{-1} in the second year, year of observation) and without compost application. (Source: Ganry et al. 1974)

is facilitated if, in addition to fertilizer application and crop yield, the chemical composition of organic manure and harvested products have been determined. If such data were available, analysis and comparison of application/uptake and yield/upake relations could be carried out for different combinations of organic manure and fertilizer application in so-called three quadrant figures (De Wit 1953). In such figures, the upper left hand side presents the relationship between application of a nutrient element and production and the upper right hand side the relationship between uptake of a nutrient element and production. In the lower right hand side the relationship between application rate and uptake can be found.
To illustrate the method, the results of a nitrogen fertilizer experiment in Niger (Pichot et al. 1974) are presented in Figures 4.3a-c. The data refer to an experiment with millet, carried out during three consecutive seasons on the same plots. The treatments consisted of application of 0, 45 and 90 kg N per hectare as urea, with and without application of 10 000 kg of straw per hectare, containing 35 kg of nitrogen. The annual rainfall in the three years,

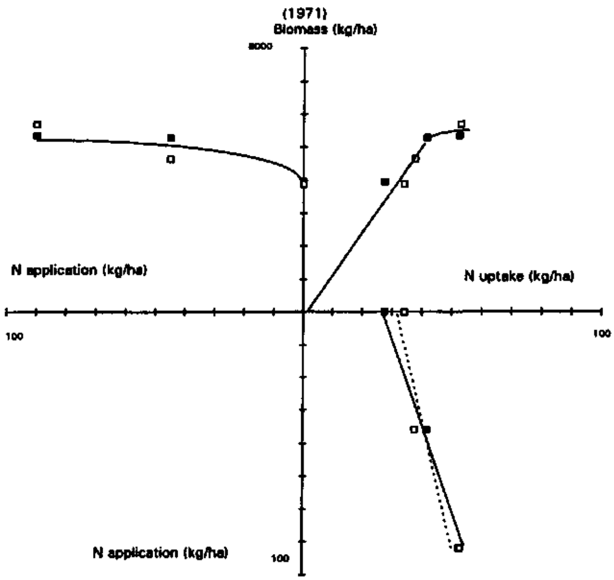

FIGURE 4.3 The relationship between (quadrant I) yield and N application, between (quadrant II) N uptake and yield, and between (quadrant III) N application and N uptake for millet in three consecutive years: 1971 (a), 1972 (b) and 1973 (c). (Source: Pichot at al. 1974). Filled rectangles: without straw. Open rectangles: with straw.

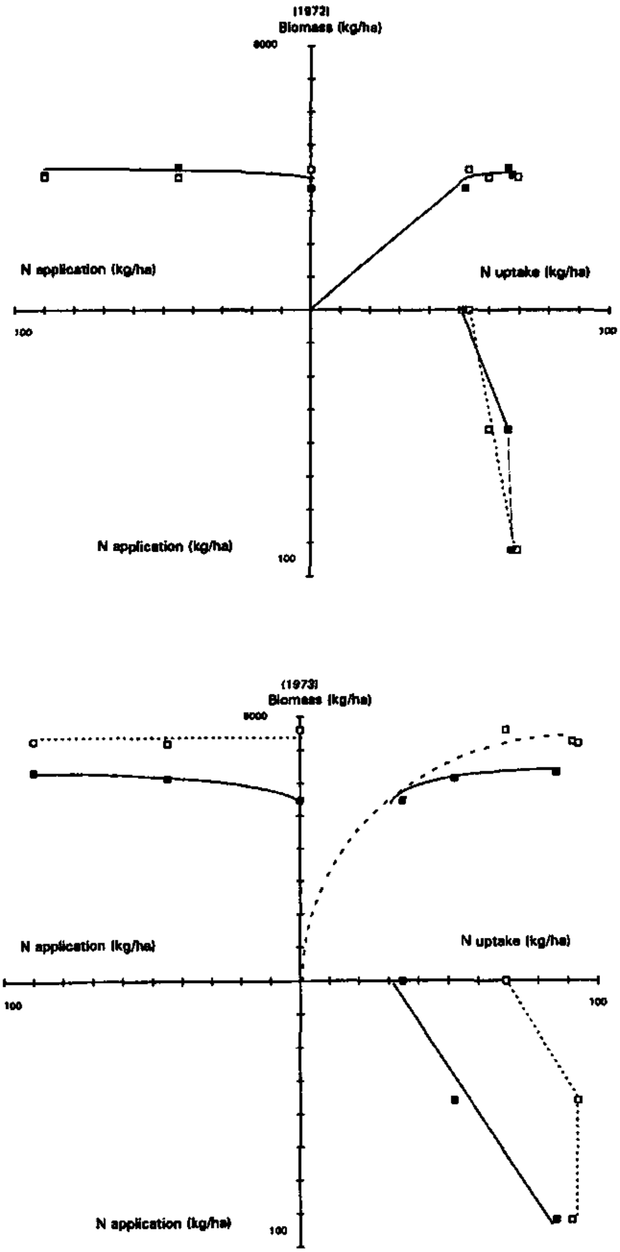

FIGURE 4.3 (continued) The relationship between (quadrant I) yield and N application, between (quadrant II) N uptake and yield, and between (quadrant III) N application and N uptake for millet in three consecutive years: 1971 (a), 1972 (b) and 1973 (c). (Source: Pichot at al. 1974)

339, 283 and 296 mm respectively, was well below the long-term average of 600 mm per year.
In the first year a linear relationship was found between nitrogen uptake and above-ground dry matter production, almost till the highest uptake level (Figure 4.3a, II). The relationship between application and uptake appeared to be linear, both with and without straw, as is often found in experiments involving nitrogenous fertilizers (Van Keulen and Heemst 1982), but the recovery of fertilizer N is slightly lower (0.21 versus 0.28) in the presence of straw. Presumably, a larger part of the fertilizer N is not available for uptake, which may be the result of immobilization by straw decomposing micro organisms.
In the second season (Figure 4.3b) production hardly responded to increased nitrogen uptake, while the maximum yield was substantially lower than in the preceding season. Apparently, nitrogen availability was not the growth-limiting factor as was also expressed in the very high concentration of N (17.2 g per kg) in the tissue at harvest at the highest application rates. The presence of straw again affects the relationship between application and uptake: uptake at zero fertilizer application is slightly higher in the presence of straw, while the recovery fraction is lower. Without straw, increased fertilizer application from 45 to 90 kg per hectare does not result in higher uptake, presumably because the crop was "saturated" with nitrogen throughout its growth cycle.
In the third year (Figure 4.3c), the highest yield was achieved, with again at the highest application rates no response to increased nitrogen uptake: another factor (nutrients other than N or water availability) appeared to be yield determining. At the highest uptake levels, production in the combined straw/fertilizer treatments seemed somewhat higher than in the treatments with fertilizer only, a phenomenon that is also frequently observed under Dutch conditions with application of organic manure to silage maize (Schröder and Dilz 1987). This suggests that the situation with respect to the production determining factor had improved. This could be the result of the higher organic matter content in the soil under the straw treatments with its associated higher water holding capacity, more favourable pH, improved availability of nutrient elements other than nitrogen, etc. This may be deduced from the results of the chemical soil analyses: higher values for organic carbon (C), total P, cation exchange capacity (CEC), and base saturation in the soils amended with straw.
The relationship between application and uptake shows that in the presence of straw, uptake without fertilizer application is higher by about 35 kg per hectare, while the recovery of fertilizer N differs only slightly (0.56 versus 0.51). Presumably, some of the nitrogen immobilized in organic material in the preceding seasons is mineralized in this season.
The N uptake at zero fertilizer application without straw is intermediate

between the first and the second year.

Other fertilizer experiments reported in literature (not only involving nitrogen, but also phosphorus) have been analysed in a similar way (Arrivets 1976; Dupont de Dinechin 1968; Ganry et al. 1974; Gigou 1984; Jenny 1974; Nabos et al. 1974; Tourte et al.1971; Traoré 1974). They are not treated in detail in this paper, but on the basis of those analyses the following conclusions can be drawn:

- higher nutrient uptake owing to fertilizer application generally leads to higher yields;
- higher yields obtained with the combined application of organic manure and fertilizer compared to fertilizer alone, can in first instance be explained by the additional supply of the limiting nutrient element. Higher yields obtained with the combined application of organic manure and fertilizer, at similar non-limiting uptake levels, may be attributed to the supply with organic manure of nutrient elements other than the one applied in the fertilizer or to more favourable soil physical or chemical properties;
- recovery of N from fertilizer in the first years is higher in the absence than in the presence of organic manure, probably because of immobilization. Part of the N may, however, be released in subsequent years;
- uptake of N from organic manures varies strongly from year to year and depends on the quality of the organic material and on environmental conditions.

4.4 Build-up of soil organic matter

Increasing the soil organic matter content of cultivated soils in the semi-arid tropical zones of West Africa is tedious, as can be illustrated, for example, by the results of the long-term experiment in Saria (Burkina Faso). After 18 years of annual applications of 60 ton per hectare of animal manure in combination with 60 kg N, 45 kg P and 25 kg K per hectare, the organic C content had increased from 2.5 to about 6.6 g per kg (or from 4.5 to 12 g organic matter per kg) (Pichot et al. 1981). Similar conclusions can be drawn from the results of an experiment in which millet and groundnut were rotated, which started in 1972 in the north of Senegal. Annually, either chemical fertilizer was applied on its own (100 kg NPK, 14-7-7 and 100 kg N as urea) or in combination with 10 ton per hectare of animal manure. In 1983 the soils in this experiment were analysed, showing that the organic carbon content in the soils that had received organic manure, was 0.3 g per kg higher in the upper 10 cm and 0.15 g per kg higher in the 10-20 cm layer. Below the latter depth the organic carbon content was identical to that of the soils that had received chemical fertilizer only (Cissé 1988). Another example refers to an experiment in which

annual applications of 11.5 ton per hectare of compost and 150 kg fertilizer N per hectare were compared with return of the millet stover produced only. After four years, the organic carbon was 2 g per kg higher in the top 20 cm of the soil under the former treatment (Feller et al. 1981a).
To put these results into perspective, in Table 4.2 an approximate calculation is presented of the amounts of organic material necessary to increase the organic carbon content in the top 20 cm of a soil with a bulk density of 1.4 g per cm^3 in one year by 1 g per kg. In the calculations, it is assumed that the relative rate of decomposition of soil organic matter is 0.06 per year (Harpaz 1975). Hence, if the original carbon content is 3 g per kg, 500 kg carbon per hectare is required to maintain the organic carbon content at that level. To increase the carbon content by 1 g per kg an additional 2800 kg per hectare of carbon is required. The rate of decomposition of organic material added to the soil depends on the quality of the material as was shown by Van Duivenbooden and Cissé (1989). They recorded losses of 0.4 and 0.6 kg carbon per kg over a 90-day period in the growing season for millet straw and animal manure, respectively. Feller et al. (1981b) followed decomposition of

TABLE 4.2 Schematic calculation of the amounts of straw, animal manure or compost necessary to increase the organic C in the top 20 cm of a soil by 1 g kg^{-1} (for details see text).

C Loss from existing organic material (kg ha^{-1} yr^{-1})			500
Required C for increasing carbon content by 1 g kg^{-1} (kg ha^{-1})			2800
Total C required (kg ha^{-1})			3300
Relative rate of decomposition of organic material (kg kg^{-1} yr^{-1}):			
- straw	0.5		
- animal manure	0.7		
- compost	0.8		
C content (kg kg^{-1}) in:			
- straw	0.45		
- animale manure	0.35		
- compost	0.30		
Organic material required (t ha^{-1}):			
- straw		14.7	
- animale manure		31.4	
- compost		55.0	

compost in a rainy season of 120 days and found a loss of 0.8 kg per kg. In the calculations of Table 4.2, relative decomposition rates of 0.5, 0.7 and 0.8 per kg during a 120-day rainy season were used for straw, animal manure and compost respectively. The amounts of these materials that were required to increase the organic carbon content by 1 g per kg are then 14.7, 31.4 and 55.0 ton per hectare, assuming carbon contents of 0.45, 0.35 (Cissé and Van Duivenbooden in prep.) and 0.3 g kg (Feller and Ganry 1982), respectively.

To maintain these higher carbon contents in subsequent years, annual applications of 3000, 6425 or 11250 kg per hectare of straw, animal manure or compost are necessary.
The large amounts of organic material necessary to increase the organic matter content of soils, are mainly due to the high rates of decomposition under tropical conditions. This argument is supported by observations on the dynamics of organic matter following the clearing of forest or savanna vegetations. These processes have been studied in West Africa: in Ghana (Nye and Greenland 1964), in Sierra Leone (Brams 1971), in Senegal (Casamance) (Fauck et al. 1969 and Siband 1972, 1974) as well as in other parts of the world (Sanchez 1981). In the Casamance, soils under forest were compared with soils that had been under cultivation for periods ranging from 3 to 90 years, with varying fallow periods. Soil organic matter was highest in the soil under forest and lowest in the soils cultivated for 90 years, the differences

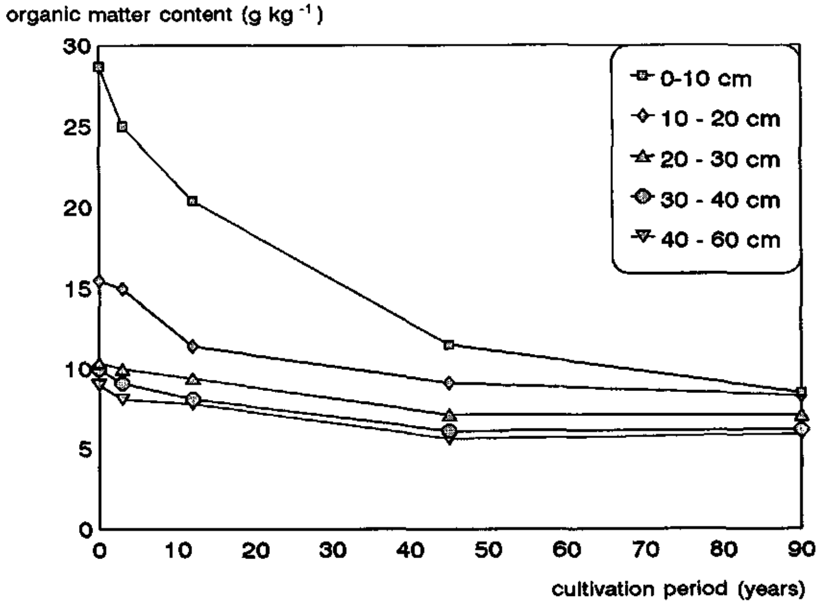

FIGURE 4.4 Organic matter content in various soil layers for clay-sandy soils after different periods of cultivation.

being most pronounced in the top 20 cm. The soil organic matter content rapidly declines in the first few years following clearing, after which the decrease proceeds more gradually (Figure 4.4).

4.5 Effect of soil organic matter content on soil physical properties

Organic matter content especially affects the stability of the aggregates formed from the clay and loam particles. The degree of aggregation affects the pore volume and pore size distribution, and hence the infiltration capacity and soil moisture retention characteristics.

Aggregate stability also influences soil structure, which affects aeration and erosion susceptibility. These effects, however important they may be, are difficult to quantify and are therefore not further discussed here.

Cissé and Vachaud (1987) studied the water balance of the soils from their experiment in northern Senegal that was referred to earlier. They concluded that the differences in organic carbon content were too small to cause significant differences in soil hydraulic properties such as infiltration capacity, soil moisture retention curve (Figure 4.5) and hydraulic conductivity curve are similar for soils differing 0.15-0.3 g per kg in organic carbon.

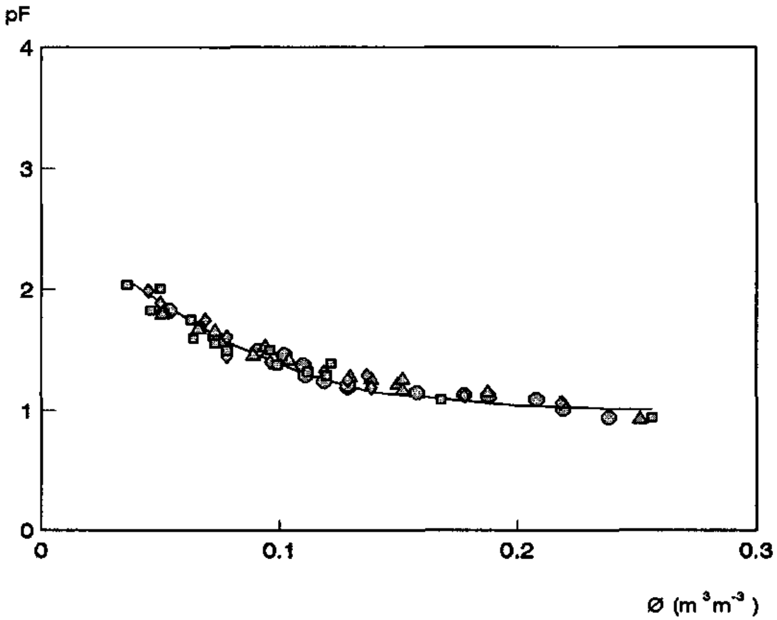

FIGURE 4.5 Soil moisture retention curve for the top soil layers of sandy soils differing 0.3 (0-0.1 m) and 0.15 (0.1-0.1 m) g kg^{-1} in organic C content.

More pronounced differences in organic carbon may not substantially affect the moisture availability to a crop. The difference in available soil moisture between the forest soils and the soils long under cultivation (Figure 4.4; Siband 1974) is only some tenths cm^3 per cm^3 (Table 4.3). The differences in total available water are probably also related to the lower clay and loam contents in the upper layer of the soils under cultivation, as a result of migration to deeper layers.

These considerations therefore lead to the conclusion, that the difference in maximum yield observed in the experiment in Niger (Figure 4.3c, II), where the difference in organic carbon content was 1 g per kg after three years, is not likely to be the result of differences in moisture availability.

TABLE 4.3 Moisture content (cm^3 cm^{-3}) at pF 2.5, pF 3.0 and pF 4.2 and available moisture (cm^3 cm^{-3}) between pF 2.5 and pF 4.2, and between pF 3.0 and pF 4.2 for forest soils and soils under cultivation for various periods. (Source: Siband 1974)

	Forest soil	*Lenght of period under cultivation (yr)*			
		3	*12*	*46*	*90*
pF 2.5:					
0-10 cm	11.4	10.4	9.7	7.5	7.2
10-20 cm	9.7	9.7	9.8	9.7	8.9
pF 3.0:					
0-10 cm	9.6	8.2	7.6	6.2	5.5
10-20 cm	8.0	7.5	8.1	9.7	7.1
pF 4.2:					
0-10 cm	7.5	5.9	6.0	4.6	3.9
10-20 cm	5.4	5.2	6.6	6.5	4.8
pF 2.5-pF 4.2					
0-10 cm	3.9	4.5	3.7	2.9	3.3
10-20 cm	4.3	4.5	3.2	3.2	4.1
pF 3.0-pF4.2					
0-10 cm	2.1	2.3	1.6	1.6	1.6
10-20 cm	2.6	2.3	1.5	3.2	2.3

4.6 Effect of organic matter content on soil chemical properties

The most important soil chemical characteristic affected by the soil organic matter content is its cation exchange capacity (CEC). The latter is also determined by clay content and mineralogical composition of the clay fraction. In his review, Pichot (1975) points out that in tropical soils, where the clay fraction is dominated by kaolinite and Fe- and Al-oxides and -hydroxides, the soil organic matter content is the major factor influencing the cation exchange capacity. This conclusion is based on results from Senegal (Siband 1972), Ivory Coast (Cabanettes and Le Buanec 1974), the Central African Republic (Pichot 1971), Burkina Faso (Arrivets 1974) and Niger (Charoy and Nabos 1974; Pichot et al. 1974), where significant positive correlations were observed between organic matter content and CEC.

To quantify the effect of changing organic carbon contents in the soil on CEC, either through organic manuring or through prolonged cultivation, the relationship between the change in carbon content and the associated change in CEC needs to be established. For construction of that relationship, the results found in the north (Cissé 1988) and south (Siband 1974) of Senegal, in Niger (Pichot et al. 1974) and Burkina Faso (Pichot et al. 1981) were used. They led to a significant correlation as is shown in Figure 4.6. A difference of 1 g per kg in organic carbon results in a difference of 4.3 mmol per kg in CEC (pH 7). This value is within the range (3.64-5.46) presented by Bolt et al. (1976). The residual variability must be ascribed to differences in origin, nature and quality of the organic material.

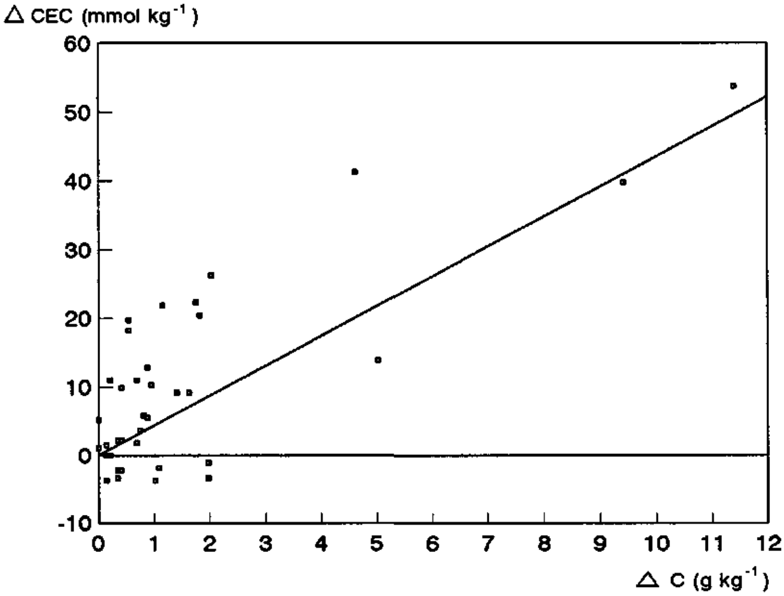

FIGURE 4.6 Change in cation exchange capacity (Δ CEC) as a function of organic C content (Δ C). (Source: Cissé 1988; Pichot et al. 1981, 1974; Siband 1974)

At higher CEC values the buffering capacity for cations such as K, Mg and Ca is higher. Exchange of cations with Al^{3+} and H^+ lowers base saturation, but also counteracts the decreasing pH. Hence, CEC serves as a buffer for pH changes.

Application of organic manures not only supplies N and P, but also other important elements like K, Mg and Ca, which contribute to maintaining base saturation at a high level. The positive relationship between pH and base saturation was illustrated by, among others, Pichot (1971; Figure 4.7).

4.7 Long-term effects of fertilizer application

In a number of the fertilizer experiments reported in this chapter the positive response to increased nutrient availability declines with time when only chemical fertilizers are applied as demonstrated in the long-term experiment in Saria, Burkina Faso (Pichot et al. 1981). In this experiment, started in 1960, sorghum was cultivated in monoculture or in rotation with groundnut and *niébé*, both legumes, under different fertilizer regimes: chemical fertilizer only (two levels), and in combination with 5, respectively 40 ton per hectare of animal manure. The amounts of N and P given annually varied over the years, while since 1969 K fertilizer was applied. Over the first 19 years these amounts were on average 25 kg N, 30 kg P and 10 kg K per hectare at the lower level and 60 kg N, 45 kg P and 25 kg K per hectare at the higher level.

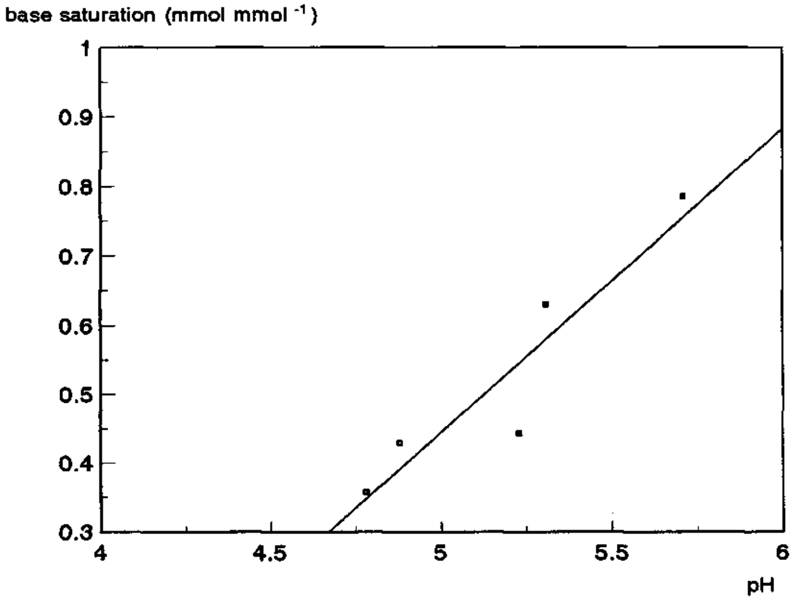

FIGURE 4.7 Relationship between pH and base saturation. (Source: Pichot 1971)

The sorghum grain yields in the control plots declined within a few years to about 150 kg per hectare. After 1970, the yields in the treated plots decreased also: first the yield under the high fertilizer only treatment, followed by that under the lower fertilizer only treatment and by the treatments with the low manure application rate. Only in the high manure/high fertilizer treatments the yields remained stable.

The results of the soil chemical analyses carried out in 1978 (some of which are given in Table 4.4) serve as the basis for the explanation of the yield decline by Pichot et al. (1981).

The organic carbon content in the fertilizer only plots is lower than that in the control, while in the plots receiving organic manure it is much higher. The CEC (pH 7) varies little among the treatments, except for the plots with the highest appliation of organic manure. Base saturation clearly differs: in the fertilizer only treatments it is significantly lower than in the control, in the manure plots higher. pH is related to base saturation and, hence, lower than the control in the fertilizer only plots and higher in the animal manure plots. The lower pH and base saturation must be attributed to the acidifying effect of the fertilizer (most probably ammonium sulphate and/or ammonium phosphate).

TABLE 4.4 Organic carbon content (g kg^{-1}), CEC (mmol kg^{-1}), base saturation (fraction), exchangeable K, Ca and Mg (mmol kg^{-1}), pH (water) for soils from experiments in Saria, Burkina Faso. (Source: Pichot et al. 1981)

	C content	*CEC*	*Base saturation*	*Exchangeable cations*			*pH*
				K	*Ca*	*Mg*	
Control	2.5	26.5	0.63	1.6	11.5	3.5	5.2
Chemical fertilizer:							
low	2.4	26.5	0.37	0.9	6.6	2.2	4.6
high	2.4	25.0	0.38	1.5	6.0	2.1	4.4
5 t ha^{-1} (chemical fertilizer low):	3.5	25.0	0.70	2.2	11.4	3.9	5.2
40 t ha^{-1} chemical fertilizer high):	6.6	39.4	1.00	5.0	23.7	10.7	5.9

Pichot et al. (1981) explained the declining yields with the low pH values. Small differences in pH in the vicinity of pH 5 can have dramatic effects: Al ions can be liberated from the clay lattice, and preferentially be adsorbed at the exchange complex. At pH values below 5.2 the concentration of Al in the soil solution increases sharply (in the plots receiving only fertilizer, up to 50 mg per liter), with toxic effects on the crop. Yield reductions of 80 percent were observed at 50 percent Al at the complex.

Alternatively, the yield reduction could be caused by K deficiency. The potassium supply with fertilizer may not have been sufficient to compensate for the export of K in grain and straw. An indication could be that the exchangeable K is lower in the fertilizer only plots than in the control. Application of organic manure provides K and other cations, thus counteracting the decline in base saturation and preventing acidification and hence aluminium toxicity. However, large amounts of organic manure are required, as in the plots receiving 5 ton per hectare of animal manure, pH still approaches critical values of around 5.

The results of the chemical analyses of the soils in the Niger experiment are comparable to those found in Saria (Table 4.5). Application of chemical fertilizer only (in this case urea) led to a decline in pH (although the critical value of 5 was not yet reached). The differences in maximum yield between the fertilizer only plots and those receiving organic manure also, could indicate that problems similar to those in Saria can be expected in the long run.

TABLE 4.5 Organic carbon content (g kg^{-1}), CEC (mmol kg^{-1}), base saturation (fraction), exchangeable K, Ca and Mg (mmol kg^{-1}) and pH for soils from experiments in Tarna, Niger. (Source: Pichot et al. 1974)

	C content	*CEC*	*Base saturation*	*Exchangeable cations*			*pH*
				K	*Ca*	*Mg*	
Control	1.6	11.8	0.9	0.4	8.5	1.7	6.1
90 kg N ha^{-1}	1.8	12.1	7.2	0.5	6.8	1.4	5.5
10 t straw ha^{-1} + 90 kg N ha^{-1}	1.8	16.7	9.3	1.8	10.7	3.1	6.2

4.8 Discussion

To achieve food self-sufficiency for a growing population in West Africa, the only solution is to increase production per unit area. Agricultural research has shown convincingly that to achieve that goal, improved nutrient availability - in addition to other agricultural measures - plays a key role (Penning de Vries and Djitèye 1982).The nutrient supply to the crop can be improved by applying either chemical fertilizer or organic manure, resulting in increased production of marketable products (grains) as well as crop residues (stover, straw). Larger amounts are required of organic manure than of chemical fertilizer, as the former's element concentration is lower than that of chemical fertilizers. Moreover, the rate of nutrient supply from organic manures is slower, as the organic material must be decomposed to release the nutrient elements. This also makes timing of the nutrient availability uncertain. On the other hand, organic manures contain various nutrient elements, while most commonly used chemical fertilizers specifically supply N and P only, and sometimes K as well. The availability of organic manures is limited, while the price of chemical fertilizers may be prohibitive to application.

Agricultural research faces the challenge of answering the question which combination of fertilizers is the most efficient for production increase. It is important to realize that intensive systems should also be sustainable. Considering the results presented earlier, two major problems appear:

- The use of chemical NP fertilizer without organic manure, or alternatively without liming and K and possibly Mg fertilizer application, may result in acidification of the soil, with the associated risk of Al toxicity and deficiencies of other nutrient elements;
- The availability of organic manures is insufficient to realize the required production increase and to prevent, in combination with chemical fertilizers, soil acidification.

In most of the fertilizer experiments cited in this paper it was common practice to remove all the biomass from the field in the fertilizer only treatments. This leads to declining organic carbon levels in the soil with the associated reduction in CEC. Together with the organic material substantial quantities of N, P and other minerals are removed, which is insufficiently compensated for if only chemical NP fertilizers are applied. This results in a decrease in base saturation and a lower pH. To assess which practices can result in sustainable production systems, quantitative assessment of the following aspects is necessary:

- Is the production increase in crop residues, associated with the use of chemical fertilizers, sufficient and necessary to stabilize the soil organic carbon content?
- Are the losses of carbon and nutrient elements incurred during the transformation of crop residues to compost or animal manure compensated by the greater availability of the remaining elements and the added value of the material as animal feed or as a source of energy (biogas)?
- Does a minimum soil organic carbon content exist for a given level of fertilizer application and production?
- Which mixture of chemical fertilizers is necessary to maintain the base saturation at a favourable level, taking into account possible supply of cations through crop residues, animal manure or compost?
- What is the optimum pH value for a given production system and to what extent is liming necessary to maintain that pH?

To provide quantitative answers to these questions, determination of more nutrient response curves can hardly be helpful. Target-oriented experiments are necessary in which production and nutrient uptake (of both grain and straw) are determined for different doses of various chemical fertilizers and organic material alone and in combination with lime application.

Evidently, in ensuring the sustainability of intensified production systems, the equivalent acidity of fertilizers is a major consideration. If ammoniacal fertilizers are used, they must be combined with liming to maintain the soil pH at a favourable level. Rock phosphates, with their inherent impurities, not only serve as a source of P, but may also help in maintaining a sufficiently high base saturation (Flach et al. 1987). In combination with nitrate fertilizers soil pH can be also maintained. Hence, judicious application of chemical fertilizer may lead to sustainable, intensified agricultural production systems in West Africa, provided that their use is not prevented by economic considerations.

Chapter 5

Estimating biomass through transfer functions based on simulation model results: a case study for the Sahel.

This chapter has appeared as:

De Ridder N and H van Keulen 1994. Estimating biomass through transfer functions based on simulation model results: a case study for the Sahel. *Agricultural water management* 28:57-71

Chapter 5

Estimating biomass through transfer functions based on simulation model results: a case study for the Sahel

N. de Ridder and H. van Keulen

5.1 Introduction

GENERAL

In land use planning in the semi-arid and sub-humid tropics it is common practice to estimate the biomass production of natural pastures as the basis for carrying capacity and livestock production (Behnke et al. 1993). In most cases one has to rely on literature data on biomass production, occasionally combined with relationships between rainfall and biomass (Le Houérou and Hoste 1977; McNaughton 1985). Such data are scarce. Alternatively, land use planners have to collect their own data in the field, sometimes in combination with satellite data (Boutton and Tieszen 1983; Tucker et al. 1985; Wagenaar and De Ridder 1986; Groten 1991; De Ridder 1991).

However, these biomass estimates have some drawbacks. Feed quality, in terms of protein and digestibility, is not taken into account. This makes it impossible to discriminate in terms of carrying capacity and livestock production between pastures with equal biomass but of different quality. Field data for one year cannot cope with the year-to-year variability in rainfall amount and its distribution pattern. Data obtained from relationships between long-term rainfall and biomass do not account for possible differences between landscape units. Water availability for plant growth is not only determined by rainfall, but depends also on run-off, which is a function of rainfall pattern and soil type, and on water storage capacity as a function of soil texture and depth. Furthermore, nutrients, often both nitrogen and phosphorus, are frequently the main plant growth determining factor. This has, for example, been shown for pastures in southern Africa (Mills 1966) and for pastures in the Sahelian countries (Breman and De Wit 1983).

Many simulation models have been developed and are widely used to estimate biomass production (Fischer and Turner 1978). These models vary in complexity and basic principles. For example, McGown (1973) developed a simple water balance model to calculate the length of the growing season and related production of Australian pastures as a function of the available soil water storage capacity. Others have tried to include nitrogen balances (e.g. Van Keulen et al. 1986). In that case, the quality of herbaceous biomass in terms of proteins is simulated as well. However, such models become very complex and are not widely used because of the expertise, numerous parameters and advanced equipment they require.

CASE STUDY: PASTURES IN SAHELIAN COUNTRIES

In their manual for evaluation of productivity of pastures in Sahelian countries, Breman and De Ridder (1991) proposed a new assessment method. This method starts from landscape characteristics such as geomorphology, relief, soil texture and depth, and climate. This combination determines the water availability for pasture growth. Climate is considered through rainfall and evapotranspiration, and landscape characteristics through the run-off and water storage capacity of the soil. Furthermore, the authors link the water balance to the nitrogen balance. For the Sahelian and the Sudan zones, 250 mm per year of the available water is the transition between water limited production(< 250 mm per year) and nitrogen limited production ($\geq$ 250 mm per year) (Penning de Vries and Djitèye 1982). For these two production situations, two different model equations have been developed to estimate the herb layer biomass and the amount of nitrogen in the above ground biomass.
For less than 250 mm per year the water availability is (De Ridder et al. 1991):

$$B = 7.25\,I - 593 \qquad (\text{for } I > 82 \text{ mm yr}^{-1}) \qquad (5.1a)$$

$$N_b = N_{content} * B \qquad (5.1b)$$

and for equal to or greater than 250 mm year (De Wit and Krul 1982):

$$N_b = 0.0083\,I\,/\,f - 0.13 \qquad (\text{for } f > 0.13) \qquad (5.2a)$$

$$B = N_b / N_{-content} \qquad (5.2b)$$

in which
I = total infiltration of water (mm yr^{-1})
B = the dry matter (DM) of the herb layer biomass (kg ha^{-1})
N_b = the amount of nitrogen in the above ground biomass (kg ha^{-1})
$N_{-content}$ = the fraction of nitrogen in the above ground biomass (kg kg^{-1})
f = yearly losses of nitrogen from the above ground biomass (kg kg^{-1})

The fraction f represents the losses of nitrogen by volatilization, grazing, bush fires and other causes, for example, insects. Nitrogen inputs accounted for are: wet

deposition through rainfall, dry deposition, and fixation by algae, free living bacteria and legumes (De Wit and Krul 1982).
As the biomass nitrogen content is reasonably well correlated with its digestibility, livestock production as a function of production goals and carrying capacity can be derived from B and N_b (Ketelaars 1991; Breman and Ketelaars 1991).
In Equations 5.1a and 5.2a the average annual infiltration (I) is used. This can simply be calculated from the average annual rainfall and an annual average run-off coefficient, which is experimentally determined (e.g. Stroosnijder and Koné 1982) or estimated (e.g. Casenave and Valentin 1989):

$$I = R * (1 - RC) \qquad (5.3)$$

where R is the average annual rainfall (mm per year) and RC the average run-off coefficient per year.
However, not all infiltrated water is available for plant growth. Depending on soil texture and total infiltration, some water may percolate below the rooting zone, with associated leaching of nitrogen. This also holds for shallow soils. Here, the water storage capacity is low, leading to percolation of water and leaching of nitrogen into the cracks of the underlying parent rocks. In Equations 5.1a and 5.2a I has then to be corrected for the percolated water in order to avoid overestimation of B and N_b.

This chapter presents a case study in which transfer functions are developed. According to Bouma and Van Lanen (1987) transfer functions are mathematical expressions relating different characteristics and properties with one another. These functions use widely recognized and easily measurable indicators such as rainfall, slope angle and length and texture as independent variables in regression equations. Examples of transfer functions are the relationship between soil bulk density and texture and organic matter content and the relationship between moisture content and texture and organic matter content. In order to construct transfer functions many data have to be obtained to carry out the regression analysis. There are two basic sources of data: actual field data and data generated with simulation models. In the latter case, the model must be fully validated.
In this chapter data for regression analysis are generated by a process-simulation model. The transfer functions presented can be used to calculate the maximum depth of soil wetting and water losses from the rooting zone or shallow soils using water content at pF 2.5 and average annual infiltration as dependent variables.

5.2 Methods

SHORT DESCRIPTION OF THE MODEL

Annual water balances for different circumstances are calculated with a model called SAHEL (Van Keulen 1975; Penning de Vries and Van Laar 1982; Van Keulen and Wolf 1986; Penning de Vries et al. 1989; De Ridder et al. 1991). This model has been extensively validated on the basis of data from Israel (Migda), Senegal (Bambey) and Mali (Niono) (e.g. Van Keulen et al. 1986; De Ridder et al. 1991). It calculates the water balance with one-day time steps, requiring daily rainfall records as input. Part of the rain is supposed to be intercepted by the vegetation. Subsequently, run-off is subtracted, using an average run-off coefficient per year. This run-off coefficient is experimentally determined and soil-type specific. For each rainfall event, the run-off coefficient is corrected for rainfall intensity and duration. The remaining water is assumed to infiltrate.

The soil profile (3 m maximum total depth) is divided into 23 compartments (10 layers of 0.05 m, 5 layers of 0.1 m and 8 layers of 0.25 m) which are assumed to be homogeneous. Each layer is characterised individually by water content at field capacity (pF 2.5: Hillel 1971; Slatyer 1968) and wilting point (pF 4.2: De Ridder et al. 1991), whereas the water content of air-dry soil is set at 1/3 of the value at wilting point (Van Keulen and Seligman 1987). The total profile depth and the thickness of each soil compartment can easily be adjusted to calculate the average annual percolation of shallow soils.

Total infiltration is partitioned over the soil layers using the "tipping bucket" principle. The soil compartments are filled up to field capacity from the top downwards until the total infiltration is dissipated or the soil profile is completely saturated to field capacity, causing excess water to percolate out of the profile.

To calculate water losses from the profile, potential evapotranspiration of the soil-plant system is introduced as a forcing function (De Wit and Goudriaan 1978). Potential soil evaporation is derived by subtracting potential transpiration of the vegetation from potential evapotranspiration. Potential transpiration is calculated on the basis of intercepted energy, which is taken as a function of soil cover (LAI = Leaf Area Index) taking into account exponential extinction in the canopy (Goudriaan 1977).

On rainy days, and depending on potential evapotranspiration rates and soil type up to three days later, soil evaporation is potential. During subsequent dry days, soil evaporation is linearly related to the square root of time with an experimentally determined slope depending on soil type (Stroosnijder and Koné 1982). Total water loss by soil evaporation is extracted from the various soil layers by using an

extinction function, mimicking redistribution of water under developing moisture gradients (Van Keulen 1975).
The transpiration rate is derived from potential transpiration, taking vertical distribution of the root system, root activity and distribution of water in the profile into account. Water is taken up from rooted soil layers with water contents above wilting point, root activity depends on water availability (defined as the water content between pF 2.5 and pF 4.2) and root density.
Simulation of vegetation growth includes germination, which starts at the first day, when the top 0.015 m of the soil has a moisture content above wilting point, and is completed at the end of an exogenously defined average germination time. If the top soil dries out to a water content below wilting point, the seedlings die and a new germination wave is initiated following the resumption of rain.
The initial biomass after germination is defined exogenously, as a function of average annual rainfall. Half of the initial biomass is allocated to the roots, the other half to above ground biomass.
The model treats development, defined as phenology, and growth, being the increase in biomass of the vegetation, independently. Development is governed by temperature and day-length.
Potential growth is defined as growth that is not limited by water and nutrient availability. It is calculated using daily global irradiance and the fraction intercepted light for photosynthesis derived from LAIs. Input Gross assimilation rates are calculated assuming a mixture of C_4 and C_3 plants and are reduced proportionally to the relative transpiration deficit (actual transpiration/potential transpiration). Maintenance respiration is subtracted: 0.015 kg CH_2O per kg dry matter for above ground biomass and 0.01 kg CH_2O per kg dry matter for roots. Growth rates in dry matter are calculated by taking growth respiration into account using a conversion factor of 0.7 kg dry matter per kg assimilates (Penning de Vries 1975). As soon as the cumulative infiltration exceeds 250 mm, being the transition point between water limited and nutrient limited growth, the growth rates are set at an upper limit of 50 kg DM per day (Stroosnijder and Koné 1982).
Dry matter increase is distributed over the different plant parts (roots, stems, leaves and grains) depending on the development stage. If the soil dries out completely and remains dry for a certain number of days, the vegetation dies.

RAINFALL DATA

From a data base covering 50 years the daily rainfall records of ten rainfall stations (CIEH 1974), 50 rainfall years are selected. The long-term average rainfall of the stations range from 64 in the north to 1196 mm per year in the south of Mali. The selection criteria are: total annual rainfall (a reasonable representation of dry, average and wet years) as well as distribution pattern (differences in total number of showers and number per size class). An illustration of the latter is given in Table 5.1. The selected rainfall data are used as input into the model.

SOIL DATA

Actual soil texture data from sites on a north/south transect in Mali were used to calculate an average texture over the entire profile (Table 5.2). Based on data of Brouwers and Keita (1976) linear equations were established (De Ridder et al. 1991) correlating water content at field capacity to sand percentage and water content at wilting point to clay percentage:

$$\theta_{pF\,2.5} = \{(0.37 - 0.0035\ \mathrm{Sp}) * \mathrm{Bd}\}/100 \quad (R^2 = 0.82) \qquad (5.4)$$
$$\theta_{pF\,4.2} = \{(0.007 + 0.0039\ \mathrm{Cp}) * \mathrm{Bd}\}/100 \quad (R^2 = 0.84) \qquad (5.5)$$

in which
$\theta_{pF\,2.5}$ = water content at field capacity ($cm^3\ cm^{-3}$)
$\theta_{pF\,4.2}$ = water content at wilting point ($cm^3\ cm^{-3}$)
Sp = sand percentage (50-2000μ)
Cp = clay percentage (< 2μ)
Bd = bulk density ($g\ cm^{-3}$)

These equations were used to calculate water contents at pF 2.5 and pF 4.2 of the soils presented in Table 5.2 assuming an average bulk density of 1.4 g per cm^3 (De Ridder et al. 1991); in practice, bulk density can vary between 0.7 to 1.9 g per cm^3. However, if they are known, actual bulk densities can be applied in these equations. The water contents of the different soil types at pF 2.5 and pF 4.2 are used as inputs into the model.

SIMULATION RUNS

The model was run with all possible combinations of input data of soil type as characterised by texture, rainfall years and soil depths of 2, 1.5, 1, 0.75, 0.50 and 0.25 m. The following model outputs were used in the subsequent regression analysis: maximum depth of wetting of the soil profile and cumulative percolation at

TABLE 5.1 Number of rainfall showers (total and per class of < 6-15 mm, 16-30 mm and > 30 mm) of some of the rainfall years used in the simulation study.

Annual rainfall (mm)	*Total number of showers*	*Number of showers per class*			
		< 6 mm	*6-15 mm*	*16-30 mm*	*> 30 mm*
213	17	8	4	3	2
213	36	24	9	2	1
216	23	12	7	2	2
431	49	22	21	5	1
433	39	18	10	8	3
444	48	27	11	6	4
546	37	10	15	8	4
549	42	15	15	8	4
556	48	18	19	8	3
851	54	12	17	22	3
853	41	10	13	9	9
865	33	1	10	10	12
1128	58	18	15	17	8
1129	40	12	12	9	7
1154	75	29	20	11	15

Table 5.2 Characteristics of the soil types used in the simulation study.

Soil texture		$\theta_{pF\,2.5}$ *(cm³ cm⁻³)*	$\theta_{pF\,4.2}$ *(cm³ cm⁻³)*	$\theta_{pF\,2.5\,-\,pF\,4.2}$ *(cm³ cm⁻³)*
Sand % (50-2000μ)	*Clay % (< 2μ)*			
90.3	2.7	0.075	0.025	0.05
49.4	39.2	0.275	0.225	0.05
64.7	16.4	0.20	0.10	0.10
13.7	43.8	0.45	0.25	0.20
54.5	16.4	0.25	0.10	0.15
13.7	53.0	0.45	0.30	0.15
44.3	16.4	0.30	0.10	0.20
13.7	43.8	0.45	0.25	0.20
34.1	16.4	0.35	0.10	0.25
13.7	34.7	0.45	0.20	0.25
23.9	16.4	0.40	0.10	0.30
13.7	25.5	0.45	0.15	0.30

the various soil depths.

REGRESSION ANALYSIS

For each of the combinations of soil type and rainfall year, the average annual infiltration was calculated, according to Equation 5.3 using average run-off coefficients. The run-off coefficients are determined experimentally and soil-typespecific. First, these values for I are correlated to the maximum depth of soil wetting (dw_{max} in cm) for the various soil types, characterised by their water content at field capacity. Subsequently, infiltration was correlated to cumulative percolation (P_e in mm per year) for a defined soil depth of 2 m and for each of the shallower soil depths. The enter method was used for regression analysis.

5.3 Results

The relationships between I calculated with Equation 5.3 and the maximum depth of the wetting front for soil types varying in water content at field capacity, can be presented by straight lines (R^2 for all lines vary between 0.96 and 0.98). The relationships for three different soil types are presented as an illustration in Figure 5.1. For a given I, the depth of wetting seems to be mainly determined by the water content at field capacity. Figure 5.2 shows that the depth of wetting differs only slightly for soils with similar field capacity but varies widely in wilting point. Thus, in further analysis only field capacity is considered.

On the basis of the results of all simulation runs, Figure 5.3a could be constructed. The lines in this figure can be presented by:

$$dw_{max} = \alpha \ (I - 69)/1.15 \qquad (5.6)$$

in which dw_{max} is the maximum depth of soil wetting (cm) and α a coefficient depending on water content at field capacity (see Figure 5.3b).

At a soil depth of 2 m, water losses out of the profile occur to a varying degree, depending on water contents at field capacity. In light soils, having a water content at pF 2.5 of 0.05 cm^3 per cm^3, this happens already at 300 mm infiltration, while in

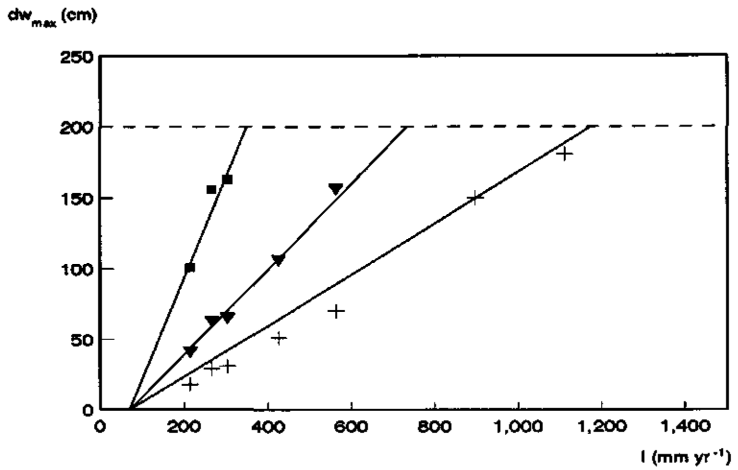

FIGURE 5.1 Maximum depth of wetting (dw_{max}) in relation to annual infiltration (I) for three soil types with variable water contents ($cm^3\ cm^{-3}$) at field capacity ($\theta_{pF\ 2.5}$) and wilting point ($\theta_{pF\ 4.2}$):
filled rectangles: $\theta_{pF\ 2.5}$ = 0.075 $cm^3\ cm^{-3}$ and $\theta_{pF\ 4.2}$ = 0.025 $cm^3\ cm^{-3}$; filled triangles: $\theta_{pF\ 2.5}$ = 0.20 $cm^3\ cm^{-3}$ and $\theta_{pF\ 4.2}$ = 0.10 $cm^3\ cm^{-3}$ and crosses: $\theta_{pF\ 2.5}$ = 0.45 $cm^3\ cm^{-3}$ and $\theta_{pF\ 4.2}$ = 0.20 $cm^3\ cm^{-3}$.

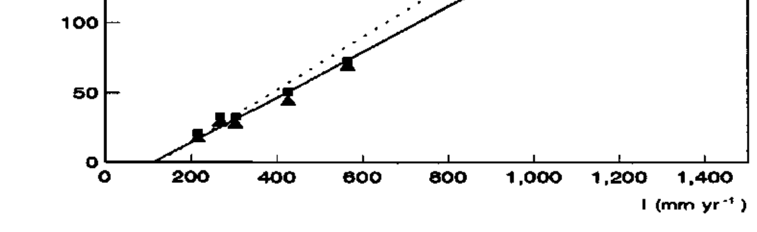

FIGURE 5.2 Maximum depth of wetting (dw_{max}) in relation to annual infiltration (I) for two soil types with variable water availabilities ($\theta_{pF\ 2.5}$ - $\theta_{pF\ 4.2}$: 0.15 rectangles, and 0.30 $cm^3\ cm^{-3}$: triangles), but with equal water contents at field capacity.

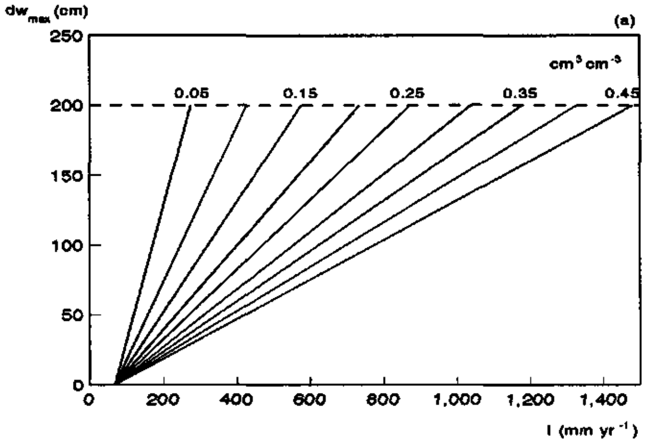

FIGURE 5.3a Relationship between maximum depth of wetting (dw_{max}) and annual infiltration (I) for soil types with variable water contents ($cm^3\ cm^{-3}$) at field capacity ($\theta_{pF\ 2.5}$). The relationship is described by $dw_{max} = \alpha^* (I - 69)/1.15$.

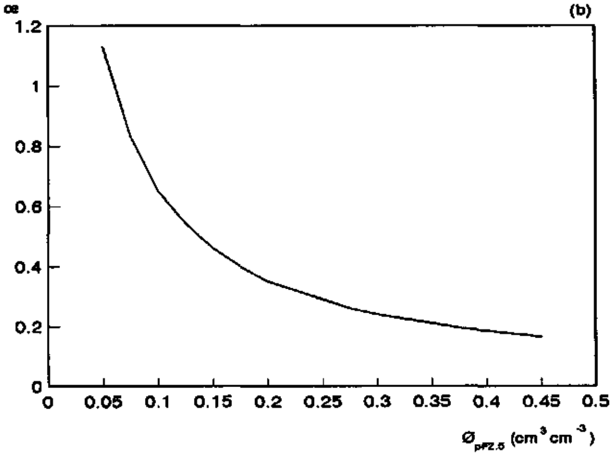

FIGURE 5.3b Relationship between the coefficient α and the water content at field capacity.

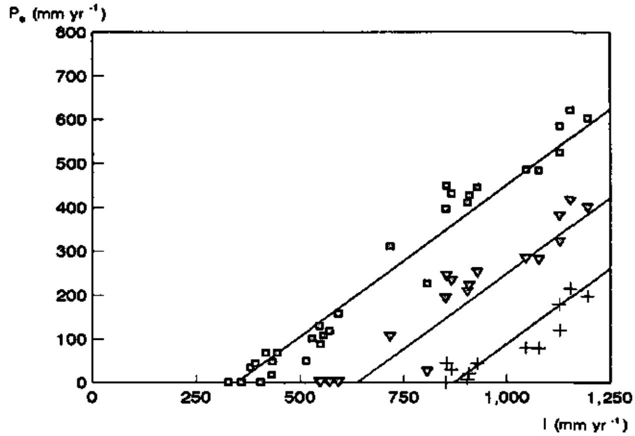

FIGURE 5.4 Percolation (P_e) from a 2 m soil profile as a function of annual infiltration (I) for three soils types with variable water contents ($cm^3\ cm^{-3}$) at field capacity ($\theta_{pF\ 2.5}$) and wilting point ($\theta_{pF\ 4.2}$):
filled rectangles: $\theta_{pF\ 2.5} = 0.075\ cm^3\ cm^{-3}$ and $\theta_{pF\ 4.2} = 0.025\ cm^3\ cm^{-3}$
filled triangles: $\theta_{pF\ 2.5} = 0.20\ cm^3\ cm^{-3}$ and $\theta_{pF\ 4.2} = 0.10\ cm^3\ cm^{-3}$
crosses: $\theta_{pF\ 2.5} = 0.30\ cm^3\ cm^{-3}$ and $\theta_{pF\ 4.2} = 0.20\ cm^3\ cm^{-3}$.

heavy soils, with a water content at pF 2.5 of 0.45 cm^3 per cm^3, percolation only starts at infiltration exceeding 1500 mm (Figure 5.3a).

The relationships between infiltration calculated with Equation 5.3 and percolation at 2 m soil depth calculated with the model for all soil types varying in water content at field capacity, can also be represented by straight lines (R^2 for all lines varies between 0.84 and 0.96). As an illustration, Figure 5.4 presents the relationships for three different soil types. The distance between the lines is proportional to the water content at field capacity. The straight lines can be represented by a combined equation:

$$P_e = 0.69\ I - 1605\ \theta_{pF\ 2.5} - 118 \qquad (5.7)$$

where P_e represents percolation losses (mm per year), beyond a soil of 2 m (Figure 5.5).

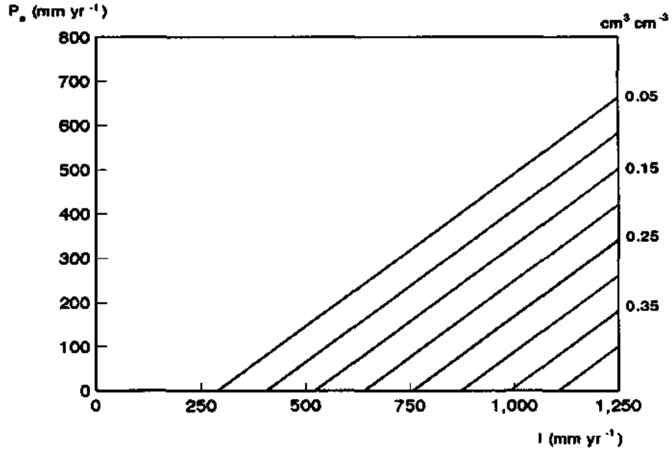

FIGURE 5.5 Relationship between percolation (P_e) and annual infiltration (I) for soil types with variable water contents (cm^3 cm^{-3}) at field capacity ($\theta_{pF\ 2.5}$). The relationship is described by $P_e = 0.69\,I - 1605\ \theta_{pF\ 2.5} - 118$.

The same analysis has been repeated for the other soil depths. The series of equations obtained are presented three-dimensionally in Figure 5.6. Thus, the general equation representing percolation in relation to total infiltration, soil depth and water content at field capacity is:

$$P_e = 0.69\,I - 45\ \theta_{pF\ 2.5} - 0.22\,sd - 7.8\ (\theta_{pF\ 2.5} * sd) - 74 \qquad (5.8)$$

where *sd* is the soil depth (cm).
Equations 5.7 and 5.8 are used as transfer functions, and can be applied to estimate yearly percolation losses from a soil 2 m in depth or from shallower soils.

5.4 Discussion

In addition to soil characteristics and total infiltration, evapotranspiration rates determine the occurrence of percolation from the soil profile. Evapotransipiration rates depend on growth rates of the canopy, which in turn are determined by nutrient availability. In the Sahelian countries, application of nitrogen fertilizers can speed up growth rates from about 35-50 to more than 200 kg per ha per day, resulting in substantially higher cumulative seasonal evapotranspiration. The measured peak evapotranspiration rates are 2.7 mm per day for bare soils, 2.8 mm per day for sandy soils with unfertilized natural pastures, 4.2 mm per day for sandy soils with fertilized pastures and 5.1 mm per day for clay soils with fertilized pastures. Over a complete growing season this can end up in a difference of 150

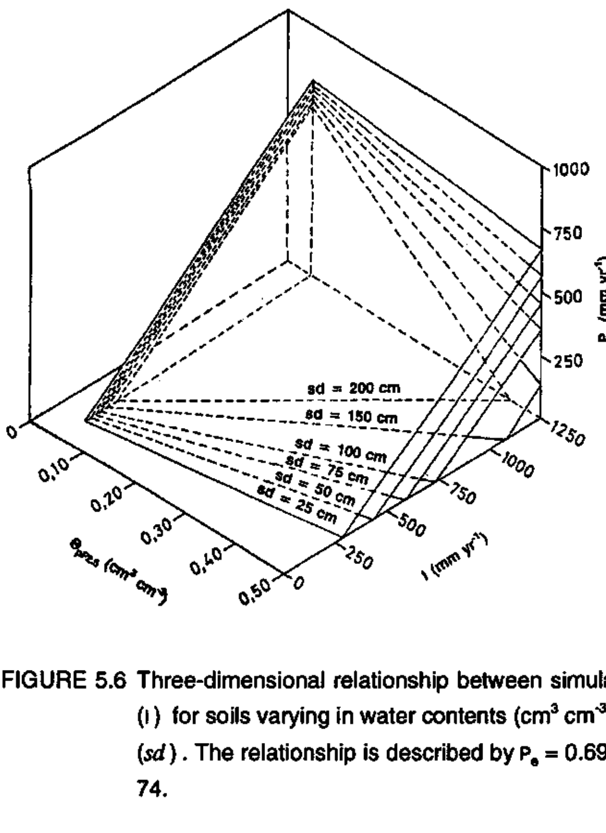

FIGURE 5.6 Three-dimensional relationship between simulated percolation (P_e), annual infiltration (I) for soils varying in water contents (cm^3 cm^{-3}) at field capacity ($\theta_{pF\,2.5}$) and soil depth (*sd*). The relationship is described by $P_e = 0.69\,I - 45\,\theta_{pF\,2.5} - 0.22\,sd - 7.8\,(\theta_{pF\,2.5} * sd) - 74$.

mm in evapotranspiration (Stroosnijder and Koné 1982). In the model used to generate the transfer functions, a maximum growth rate of 50 kg per ha per day, related to the current average soil fertility, is used. Evidently, these transfer functions cannot be used in situations with much higher nutrient availabilities, as percolation will be lower and less frequent. The variability in natural soil fertility in the Sahel, although important to explain the actual variability in total biomass production, is relatively small and will affect seasonal cumulative evapotranspiration only to a limited extent: the difference between evapotranspiration rates of bare soils and soils covered with natural pastures is only 0.1 mm per day. The effects on maximum depth of wetting and percolation will thus be relatively small.

The total infiltration calculated according to Equation 5.3, does not take into account the effect of rainfall distribution on run-off and infiltration, while in the model run-off is corrected for intensity and duration of the rainfall showers. However, the differences observed between seasonal infiltration calculated with Equation 5.3 and those derived from the model are plus or minus 70 mm per year at the most. The effect of a difference of 70 mm infiltration on maximum depth of wetting of the soil profile in relation to the water content at pF 2.5 is 80 cm on lighter soils, but much less on heavier soils. Hence, the maximum depth of wetting (dw_{max}) and percolation (P_e) calculated with the transfer functions will be less accurate for lighter soils, but only in rainfall years with extreme distribution of rainfall, rainfall intensities and size of the showers.

The variation in the relationship between annual infiltration calculated with Equation 5.3 on the one hand and the maximum depth of wetting of the soil profile (Figure 5.1) and percolation at a soil depth of 2 m on the other (Figure 5.4) can partly be explained in the same way: the model takes distribution of rainfall, and intensity and duration of the rainfall showers into account and thus calculates the maximum depth of wetting and percolation using a slightly different amount of infiltrated water than that calculated with Equation 5.3.

The transfer functions to calculate the maximum depth of wetting and percolation are based on a wide range of rainfall years, each with its particular distribution pattern, including extreme rainfall years. They are used to calculate biomass and nitrogen in the above ground biomass according to Equations 5.1a, 5.1b, 5.2a and 5.b. In the case of landscape units with shallow soils, percolation losses are deducted from annual infiltration (I). The results are shown in Figure 5.7. Le Houérou and Hoste (1977) collected biomass data for West Africa on which they

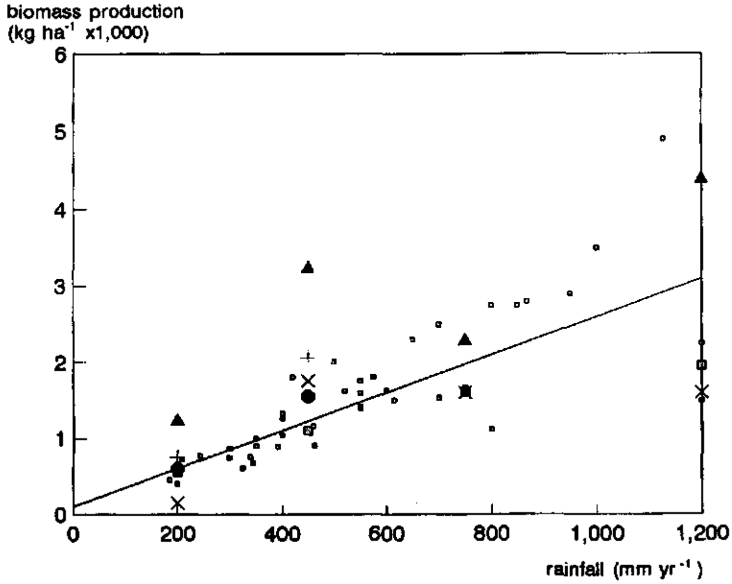

FIGURE 5.7 Relationship between rainfall and biomass (solid line) and biomass data (open rectangles) after Le Houérou and Hoste (1977) and biomass calculated using the transfer functions for four rainfall zones and five major landscape units in West Africa (De Ridder, 1991): undulating sand dunes (Os: pluses), sandy plains with little relief (Ps: dots), plains with loamy-sandy soils (Pl: crosses), lowlands and depressions with clay-loamy soils (La: triangles) and shallow soils (Sq: filled rectangles).

established a general relationship between rainfall and biomass. The differences between the observed data and the established relationship can partly be explained by differences in landscape

and related differences in water balance, and are neglected by using the simple relationship. Figure 5.7 also shows that this differentiation is taken into account when the biomass production is calculated for the five major landscape units in West Africa, using the transfer functions. The calculated values fall within the range of the collected biomass data. However, the calculated biomass data for the landscape unit La (lowlands) tend to be higher than the maximum values presented by Le Houérou and Hoste (1977). This is caused by the fact that these authors excluded data from depressions.

When using the transfer functions in an extreme rainfall year, or for sites with, for example, a very irregular distribution of texture in the soil profile or very high soil fertility, corrections have to be made, using site and year specific information. Infiltration, calculated with Equation 5.3, has to be corrected taking into account the distribution of the rainfall, and the intensity and size of the rain showers for that particular year (De Ridder et al. 1991).
Straightforward application of the transfer functions, valid for pastures in Sahelian countries only, to other arid and semi-arid regions of the world is not possible. With the same method, for each region new transfer functions may be developed, taking climate and natural soil fertility into account.

5.5 Conclusions

This case study for the Sahel shows that transfer functions can be developed using a process simulation model. The application of the transfer functions to estimate biomass production at a less detailed scale, indicates that, in comparison to simple rainfall/biomass relationships, more detail can be obtained taking into account the water balance per landscape unit.
The approach followed here may also be relevant for agroecological zoning methods, where the length of growth periods is extensively used as a classification criterium (FAO 1978; Henricksen and Durkin 1985; Jätzold 1991; Andriesse and Fresco 1991; Windmeijer and Andriesse 1993). The length of the growing periods is only based on climatic data and an arbitrary determined soil water storage capacity. With transfer functions, as developed in this case study, the length of growing periods could be established with more accuracy for each landscape unit.

Chapter 6

Computed evapotranspiration of annual and perennial crops at different temporal and spatial scales using published parameter values.

This chapter has appeared as:

Radersma S and N de Ridder 1995. Computed evapotranspiration of annual and perennial crops at different temporal and spatial scales using published parameter values. *Agricultural water management* 31:17-34

Chapter 6

Computed evapotranspiration of annual and perennial crops at different temporal and spatial scales using published parameter values.

S. Radersma and N. de Ridder

6.1 Introduction

Land use changes may affect local and global environment in general, and water balances in particular (McNaughton and Jarvis 1983). Higher evapotranspiration rates may lower groundwater tables since replenishment is reduced. Changes in water balances on one particular land unit may affect surface and subsurface flows to adjacent land units. Land use change from perennial to annual crops or vice versa is one of the possible land use changes affecting the water balance through differences in evapotranspiration rates (Stewart 1984). Breman and Kessler (1995) evaluated the effects of tree species in West African natural vegetation on water (and nutrient) balances. However, such an evaluation is not available for perennial and annual crops.
Evapotranspiration may be lower from land occupied with annual crops than with perennial crops. This may in part be caused by a lower aerodynamic resistance of trees compared with annual species. McNaughton and Jarvis (1983) call this a difference in omega-factor, indicating a higher degree of coupling with the atmosphere for tall crops in comparison to short crops. Annual crops are only present during part of the year, and bare soil evaporation is generally lower than evapotranspiration of a vegetated area (Peschke et al. 1991). Furthermore, evapotranspiration may be higher from land occupied with perennial crops because of their higher interception of precipitation. Evaporation of intercepted water is potential, since no resistance exists (McNaughton and Jarvis 1983). Finally, differences in evapotranspiration may result from differences in transpiration characteristics between plant species e.g. differences in stomatal behaviour in relation to light intensity, CO_2 concentration and temperature, vapour pressure deficit of the air, and leaf water potential.
Direct comparison of evapotranspiration of perennial and annual crops reported in literature is hardly possible, since differences in soils and climate make data incomparable. Moreover, reference levels (pan evaporation or potential evaporation) and time scales are often different. No data sets have been found where a perennial and an annual crop are grown under identical environmental (climatic and soil) conditions. Yet these data are essential for any quantitative

assessment of past or future land use changes at one location. It is virtually impossible to obtain data sets on perennial and annual crops under identical conditions (this would require cutting the perennial crop to replace it by the annual). Furthermore, before any field measurements of this nature are undertaken, it has to be considered which variables are critical at different scales. This chapter reviews relevant literature and presents literature data on crop parameters and environmental conditions that determine transpiration for four crops (oil palm, cocoa, maize and rice) and evaporation. Transpiration at leaf scale and soil evaporation as well as evaporation of intercepted rain are calculated using these data and have been scaled-up to canopy scale. The objective is to quantify evapotranspiration of the crops under identical environmental conditions at two temporal scales: daily and annual evapotranspiration.

6.2 Theoretical background

Evapotranspiration of crop canopies (ET in kg m^{-2} s^{-1}) can be approximated with the Penman-Monteith equation (e.g. FAO, 1992):

$$ET_a = \frac{\Delta\ (R_n - G\ ) + \rho_a c_p\ \delta_e / r_a}{\lambda\ [\ \Delta + \gamma\ (1 + r_s / r_a)]} \qquad (6.1)$$

in which

Δ = slope of saturated vapour pressure - temperature curve (Pa °C^{-1})
R_n = net radiation (J m^{-2} s^{-1})
G = sensible heat flux into the ground and vegetation (J m^{-2} s^{-1})
ρ_a = air density (kg m^{-3});
c_p = specific heat of air (J kg^{-1} °C^{-1})
δ_e = vapour pressure deficit (δ_{sat} - δ_{act}) (Pa)
r_a = aerodynamic resistance (s m^{-1})
r_s = surface resistance of canopies [s m^{-1}]
λ = latent heat of vaporization (2.454 MJ kg^{-1} at 20 °C)
γ = psychrometric constant (Pa °C^{-1})

This equation has proven to be useful for the analysis of the interrelationships between evapotranspiration, canopy properties and meteorological conditions (McNaughton and Jarvis 1983). At identical temperature and air pressure, the evapotranspiration of plant canopies depends on net radiation (R_n), sensible heat storage in the canopy and in the ground (G), the aerodynamic resistance (r_a) of the boundary layer above the crop, vapour pressure deficit (δ_e), and the surface resistance of crops (r_s). The most important relations and variables will be discussed below.

NET RADIATION

The net radiation may vary among canopies, because of differences in the reflection of total irradiance. The reflection coefficients are in the range of 0.10-0.15 for coniferous forests, 0.15-0.20 for broad leaved forests and 0.20-0.30 for herbaceous vegetation and crops (Rutter 1970), 0.15-0.40 for bare soils and 0.05-0.10 for water (Hillel 1971). This means that more radiation is absorbed by forests than by crops/herbaceous vegetation. However, Rutter (1970) showed that the influence of different reflection coefficients is small compared to that of differences in surface resistances of crops when the aerodynamic resistance (r_a) is below ≈ 20 second per cm. At higher values of r_a, typical for annual crops, differences in reflection coefficients are more important.

HEAT STORAGE IN CANOPY AND SOIL

Part of the net radiation is converted to heating of the soil and is thus not available for the evaporation process. The radiation used to heat the soil may depend on soil cover. The storage of heat in a short vegetation is negligible compared to storage in the soil. Heat storage in the soil is 5-15 percent of R_n, depending on the season (Hillel 1971).

AERODYNAMIC RESISTANCE

Assuming prevailing turbulent transport in the boundary layer of crops, the aerodynamic resistance may be calculated by (Jones 1986):

$$r_a = \frac{\{ \ln[(z - d) / z_0] \}^2}{k^2 u_z} \tag{6.2}$$

in which:
z = reference height (m)
u_z = wind speed at reference height z [m s^{-1}]
d = zero plane displacement (≈ 0.65 * crop height) (m)
z_0 = vegetation roughness parameter (≈ 0.13 x crop height) (m)
k = Von Karman constant (= 0.41) (-)

The aerodynamic resistance decreases with increasing crop height, zero plane displacement (d) and canopy roughness (z_0). Thus, forests tend to have lower aerodynamic resistances than field crops. Since r_s and r_a are coupled in series, r_a is relatively important in annual crops in determining the total resistance, while in perennial tree crops r_s may be of greater importance. Jones (1986) states that evapotranspiration from annual crops, with their high aerodynamic resistance, is relatively insensitive to surface resistance which needs to increase to about 100 second per m before significant reductions in actual evapotranspiration occur.

VAPOUR PRESSURE DEFICIT

Evapotranspiration of a forest is generally much more sensitive to vapour pressure deficit than to net radiation while the reverse is true for grasslands (Jones 1986). Potential evapotranspiration is generally higher for taller crops, such as perennial tree crops, than for shorter crops like cereals.

SURFACE RESISTANCE

For canopies, surface resistance is a combination of resistance to (1) transpiration by the vegetation, (2) evaporation of soil water and of zero-resistance to evaporation of (3) water intercepted by the vegetation and (4) soil surface storage water. These resistances are coupled in parallel.

Transpiration resistance to water transport in the gaseous phase depends on leaf resistance, which consists of stomatal resistance and cuticular resistance (Jones 1986). Jones states that these resistances are coupled in parallel. Cuticular resistance is generally much higher (2000 to >10 000 second per m for single leaves) than stomatal resistance (minimum for mesophytes 80-250 second per m; for succulents, xerophytes and conifers 200-1000 second per m for single leaves), caused by low water permeability (liquid and gaseous) of the cuticle and overlaying wax layer (most strongly developed in plants in arid regions). Hence, stomatal resistance may nearly always be the determining leaf resistance.

Factors influencing stomatal opening are light, soil moisture (Θ), vapour pressure deficit of the air (δ_e), leaf water potential, CO_2 concentration and temperature. The importance of each factor differs per plant species.

Stomatal opening is primarily governed by light. In both C_3 and C_4 species the stomata close in the dark and open with increasing light intensity to maximum opening at about a quarter of full sunlight (200 W per m^2 shortwave radiation; Jones 1986). This causes a diurnal pattern of stomatal opening and closure.

Soil moisture deficiency may lead to stomatal closure. Upon drying of the soil several plant species seem to monitor a certain level of dryness around their roots (Passioura 1982). They produce abscisic acid (ABA) in the roots, which is transported through the xylem towards the leaves, upon which the stomata start to close (Zhang and Davies 1989, 1990; Tardieu et al. 1991, 1992, 1993).

High saturation deficits (δ_e) may also cause stomatal closure as a direct response. Although an increase in saturation deficit tends to increase transpiration, stomatal closure may counteract this, setting a ceiling to the transpiration rate.
These feed-forward mechanisms prevent high transpiration rates and delay the development of water stress in leaves. Such mechanisms vary considerably among species even within closely related groups. They depend also on the history in development of the plant (McNaughton and Jarvis 1983).
Stomata tend to open as the CO_2 concentration in the intercellular space decreases and as temperature increases, although the magnitude of the temperature response depends on the vapour pressure deficit (Jones 1986).

SOIL EVAPORATION

Soil evaporation losses, influenced by radiation and wind, may be considerable during periods of tillage, planting, germination and early seedling growth of crops, when the soil is largely bare. The actual evaporation rate is determined by either atmospheric demand ($r_a \approx 0$) or by the rate of transport of water to the soil surface, whichever is the lowest.
After soil wetting and under constant conditions in the subsequent period, Hillel (1971) distinguishes two fairly distinct phases in the drying process of the soil: (1) a *constant rate stage* during which the evaporation rate is determined by external and soil surface conditions, and (2) a *falling rate stage* during which evaporation proceeds at a rate determined by the ability of the soil profile to transport moisture towards the evaporation zone.
During the first stage, the surface resistance is zero, and the evaporation rate can remain constant as long as the increasing potential gradient in the surface soil at each point can compensate for the decreasing hydraulic conductivity. The soil can supply the water fast enough to keep the surface wetness above the value at which the transfer of water to the atmosphere is significantly reduced. For a wet soil surface, soil evaporation is less than 5 percent of total evapotranspiration (ET_a) when LAI ≥ 4 and may be higher than 50 percent when LAI ≤ 2 (Jones 1986) (LAI is the leaf area per unit ground area).
During the falling rate stage, with a dry layer at the surface, the evaporation rate is reduced because water movement is mainly by vapour diffusion. When the soil surface approaches equilibrium with the overlying atmosphere (air dry), the potential gradients towards the surface cannot increase anymore to compensate for the decrease in soil conductivity upon drying.
Water stored at the soil surface as puddles, whenever the rainfall intensity exceeds the infiltration capacity of the soil, evaporates with zero resistance.

INTERCEPTION

Water intercepted by the vegetation evaporates also with zero surface resistance. Evaporation of wet surfaces is close to potential and thus higher than actual evapotranspiration of the vegetation. Hence, the length of the period during which this process takes place, is important. It depends on atmospheric demand, on the amount stored as interception by the vegetation and stored at the soil surface. The soil surface storage capacity depends on the micro relief. Interception as fraction of total rainfall depends on crop canopy structure, leaf area, rain intensity and total rainfall (Noij et al.1993).
Jones (1986) and McNaughton and Jarvis (1983) note that evaporation of intercepted water can exceed the total transpiration of forests in humid temperate areas and may lead to the total forest evapotranspiration being twice that of grass. Balek (1977) stresses that interception as a function of rainfall established in temperate conditions does not hold for tropical conditions, because of a very different time and space distribution, intensity and amount of rainfall. He estimated that about 70-80 percent of the precipitation reaches the soil surface below the rain forest, about 80 percent below savanna grassland and 80-85 percent below dense tropical crops.

6.3 Evapotranspiration of oil palm, cocoa, maize and rice

Evapotranspiration of the four crops has been calculated according to Equations 6.1 and 6.2, considering two theoretical cases (two time scales, day and year). First, the daily evapotranspiration of the four crops, fully grown with LAI > 3.5, was calculated for abundant availability of water (Situation 1) and for sub-optimal water supply (Situation 2). In the second case, the annual evapotranspiration of the four crops was compared for a theoretical set of environmental conditions.

DAILY EVAPOTRANSPIRATION

The weather conditions for both situations and the optimal and sub-optimal water supply are supposed to be identical. The temperature and air pressure are fixed at 30 °C and 100 kPa, respectively. For these conditions other parameters of Equation 6.2 can be derived (FAO 1992): $\Delta = 0.2434$, $\rho_a = 1.1391$, $c_p = 1.013$, $\lambda = 2.43$ and $\gamma = 0.067$. The net radiation (R_n) is set at 0.25 kJ per m per second, representative of conditions in La Mé, Ivory Coast during the wet season. The vapour pressure deficit (δ_e) is set at 0.5 kPa. The influence of light on the diurnal pattern and possible differences among species in diurnal patterns of stomatal opening are neglected. At a net radiation of 0.25 kJ m^2 per second optimal light conditions are supposed for maximum opening of the stomata. Identical nutrient conditions are assumed to avoid differential effects of plant nutrient status on transpiration. Flooded rice is not considered, since the other crops are not grown under these conditions.

According to Equation 6.1, evapotranspiration of different crops growing under similar conditions depends on the sensible heat loss to the ground (G), their aerodynamic resistance (r_a), albedo and resistance on the surface (r_s). Temporary water stress influences evapotranspiration through the surface resistance.

The value of G for crops fully covering the soil (LAI > 3.5) is set at 0. Table 6.1 summarizes the values for r_a, albedo and r_{leaf} that were used to calculate the transpiration of the four crops under study.

TABLE 6.1 Values for height of the crop (h), aerodynamic resistance (r_a), albedo and leaf resistance (r_{leaf}) used to calculate transpiration of oil palm, cocoa, maize and rice.

	Oil palm	*Cocoa*	*Maize*	*Rice*
h (m)	12	7	2	1
r_a (s m^{-1})	22	38	80	108
albedo (-)	0.18	0.19	0.23	0.23
r_{leaf} optimal water supply (s m^{-1})	70	60	50	20
r_{leaf} sub-optimal water supply (s m^{-1})	675	1350	600	390

TABLE 6.2 Literature data on leaf resistance (r_{leaf}) for oil palm (PFD = photon flux density).

r_{leaf} (s m^{-1})	*r_{leaf} affecting variables*	*Location*	*Agronomy and conditions*	*Reference*
175-1050*	δ_e, drought	field, Colombia	27°C *PFD* > 500 μmol m^{-2} s^{-1}	Smith 1989
56-100	leaf temperature	field, Ivory Coast		IRHO 1989
125>	drought	field, Ivory Coast		IRHO 1989
170-245	leaf age	field, Ivory Coast (La Mé)	fertilized, 26.3 °C	Dufrêne et al. 1992
125-670	drought	field, Ivory Coast		Dufrêne 1989
110>	δ_e	field, Ivory Coast		Reis de Carvalho 1991

* derived from conductance (g_s) for CO_2 in mmol m^{-2} s^{-1} by $r_s = [(1/g_s)/42.2]*0.63$

The aerodynamic resistance is determined by crop height (Table 6.1) and wind speed (Equation 6.2). The average wind speed in La Mé, Ivory Coast is 1.5 m per second according to Dufrêne (1989), which value is used to calculate the aerodynamic resistance. Dufrêne et al. (1992) found for oil palm an aerodynamic resistance between 9 and 90 second per m, with an average of 17 to 19 second per m. Volpe and Brunini (1990) estimated the aerodynamic resistance of a maize crop (2.8 m high) in Brazil (Campinas) at wind speeds from 0.2 to 3.5 m per second at 19 second per m.

TABLE 6.3 Literature data on *leaf resistance* (r_{leaf}) for cocoa (PFD = photon flux density; RH = relative humidity).

r_{leaf} ($s\ m^{-1}$)	r_{leaf} *affecting variables*	*Location*	*Agronomy and conditions*	*Reference*
60> 100>	water, plant nutrition, light	Ghana, pots and field, seedlings and mature trees	wide range of conditions	Hutcheon 1977
1500-7000	leaf temperature, δ_e, low light intensity	glass house, 5-months seedlings in pots	light 50 μmol m^{-2} s^{-1}	Raja Harun and Hardwick 1988
380-1200	light	glass house, seedlings in pots	av. leaf temp. 21.4 °C, δ_e 6.16 KPa (76% RH)	Raja Harun and Hardwick 1986
250-750	δ_e	growth chamber, seedlings in pots	regularly irrigated to excess; temp. day 25 °C, night 22 °C; FDP 350 μmol m^{-2} s^{-1}; RH 80% (max)	Sena Gomes et al. 1987
1400-3000	leaf age water stress	greenhouse, 9-months seedlings in pots	regularly fertilized; well watered or periodical droughts; temp. day 27 °C, night 23 °C	Joly and Hahn 1989
300-900	water stress	Malaysia, 5-6 months seedlings in pots	fertilized; rain shelter (and shade); irrigation up to field capacity	Mohd Razi et al. 1992
150-2000	δ_e	Colombia, seedlings in pots, outdoors	fertilized; well watered; under Eucalyptus trees; mean annual temp. 24 °C; PFD 300-500 μmol m^{-2} s^{-1}	Hernandez et al. 1989
70-1400	diurnal seasonal	Southern India, field, 20 year old trees	fertilized; irrigation every 10 days in dry months	Balasimha et al. 1991

Only few data are found for the value of the albedo of the four crops. Jacobs and Van Pul (1990) present a value of 0.23 for maize at low latitudes. Ling and Robertson (1982) present values for oil palm (0.18) and for cocoa (0.19) in

Malaysia. No data are found for rice, hence the maize values are used. Net radiation (R_n) is calculated taking albedo per species into account.
To quantify the surface resistance, the soil surface resistance to evaporation can be neglected at an LAI > 3.5. Thus, surface resistance is determined by transpiration resistance.
Under optimum water supply, transpiration resistance is mainly determined by leaf resistance. Under water stress the soil-root resistance and the changes in stomatal resistance have to be considered as well. Tables 6.2, 6.3, 6.4, and 6.5 summarize the information on leaf resistance for the four crops. The observed variation may be attributed to differences in growth conditions (temperature, radiation, humidity and agronomic treatments), measurement method and growth stage of the plant.

TABLE 6.4 Selected literature data on leaf resistance (r_{leaf}) for maize.

r_{leaf} (s m^{-1})	r_{leaf} affecting variables	Location	Agronomy and conditions	Reference
50-600	drought	field, USA (Florida)	fertilized; irrigation around 40-60 d.a.e.*	Lorens et al. 1987
370-3300		China		Jing and Ma 1990
360-1000	diurnal course of r_s (light response)	field, India	fertilized; one post sowing irrigation; PAR max 1600? at h	Singh et al. 1987
53-844**	leaf water potential	greenhouse and pots, Venezuela	fertilized; half of plants no irrigation after 30 d.a.s.; PAR > 1800 µE m^{-2} s^{-1}; temp. 29-32 °C	Sobrado 1990
360-2500	irrigation and drought	greenhouse and pots	compost; PAR > 100 µmol m^{-2} s^{-1}; temp. 23-28 °C	Zhang and Davies 1989
330-670	irrigation and drought	greenhouse and pots	compost; PAR > 100 µmol m^{-2} s^{-1}; temp. 17-28 °C	Zhang and Davies 1990
130-330	irrigation, drought	field, France	fertilized; soil structure	Tardieu 1987
170-422**	drought	field, France	soil structure	Tardieu et al. 1991
211-1690**	drought	field, France	soil compaction; ABA-sign	Tardieu et al. 1992
140-1690**	δ_e	field, France	ABA-sign	Tardieu et al. 1993

* d.a.e.= days after emergence; d.a.s. = days after seeding.
** values were given as g_s in mol m^{-2} s^{-1} and converted to r_s in s m^{-1} by $r_s = 1/(g_s/42.2)$ (Goudriaan and Van Laar 1994)

For Situation 1, one may assume that leaf resistance approaches its minimum value. There is no stress (drought, extreme temperature, vapour pressure deficit) and light does not limit stomatal opening. Hence, the minimum values in literature can be considered as representative for Situation 1. However, the minimum resistance for oil palm (56 second per m, Table 6.2) is measured at a temperature of 38 °C. Assuming a linear relationship between stomatal resistance and temperature (Raja Harun and Hardwick 1988) this value has been adjusted to 70 second per m. The lowest leaf resistance found for rice is 10 to 20 second per m depending on varieties (Table 6.5); 20 second per m is chosen arbitrarily.

TABLE 6.5 Selected literature data on leaf resistance (r_{leaf}) for rice.

r_{leaf} ($s\ m^{-1}$)	r_{leaf} *affecting variables*	*Location*	*Agronomy and conditions*	*Reference*
35-80**	δ_e		Japan	Ishihara and Kuroda 1986
48-56	water stress	field, India	fertilized	Mohandass et al. 1988
107-270**	nitrogen supply and water stress	pot	fertilized; 22-25 °C	Otoo et al. 1989
35-70	no water stress	field, Philippines	upland; fertilized; irrigated close to field capacity	Dingkuhn et al. 1989a
->500	with water stress	field, Philippines	less irrigation after 42 d.a.s.*	Dingkuhn et al. 1989a
10-20	different varieties	field, Philippines	upland (dry season); fertilized, irrigation (mild water stress)	Dingkuhn et al. 1989b

* d.a.s = days after seeding
** derived from conductance for CO_2 by $r_{H_2O} = 1/g_{H_2O}$ and $g_{H_2O} = g_{CO_2}/0.63$.

For Situation 2, values for transpiration resistance for the four crops under comparable water stress conditions should be considered. However, the data presented in Tables 6.2, 6.3, 6.4, and 6.5, indicate that they are not easy to compare. Furthermore, indications on the relationship between stomatal resistance and the degree of water stress are only given for oil palm. Appropriate values have been selected from the tables and an average is calculated per crop whenever more than one value was available.
For oil palm, transpiration resistance under water stress is considered to be 675

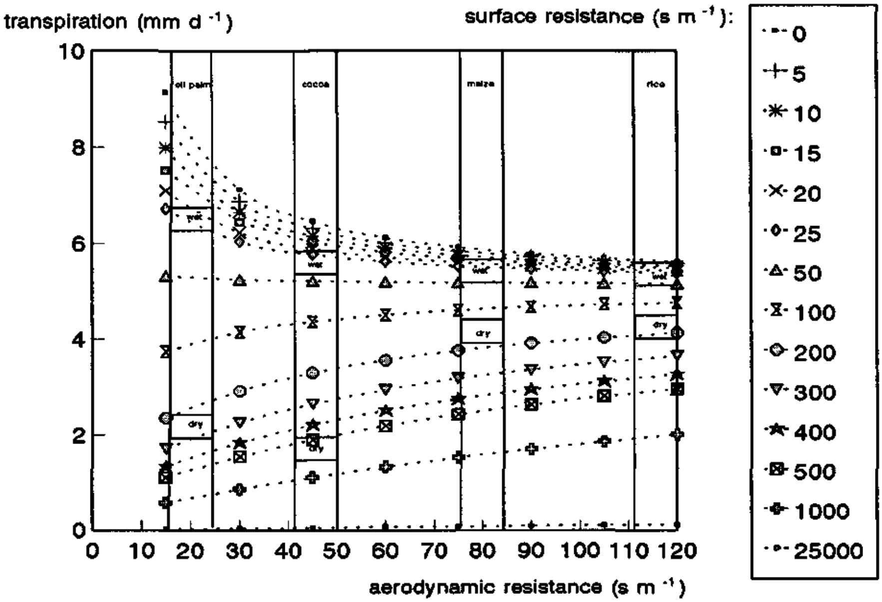

FIGURE 6.1 Transpiration (mm day^{-1}) in relation to aerodynamic resistance (r_a in s m^{-1}) for a range of values for surface resistance (r_s in s m^{-1}) calculated with Eq. (6.1). Parameter values used: temperature = 30 °C; air pressure = 100 kPa; Δ = 0.2434; ρ_a = 1.1391; c_p = 1.013; λ = 2.34; γ = 0.067; R_n = 0.5 kJ m^{-2} s^{-1}; δ_e = 1 kPa; G = 0 (*LAI* > 3.5). Surface resistances (transpiration resistance at *LAI* > 3.5) for the four crops under optimal water supply and under water stress are indicated.

second per m. This value relates to a water stress described as 65 percent of the available water taken up by the crop (Dufrêne et al. 1989; Dufrêne et al. 1992). For cocoa a value of 1350 second per m has been assumed, close to the value measured by Balasimha et al. (1991). This is the only value found for fully grown trees; all the other values cited in Table 6.3 refer to seedlings growing in pots. Since transpiration resistance is affected by the age of leafs and trees, these values are not considered as representative for trees. For maize a value of 600 second per m has been selected, which corresponds to the average from the highest values reported under drought and field conditions as presented in Table 6.4. The values presented by Tardieu (1987) and Tardieu et al. (1991, 1992) have to be divided by two, since they refer to one side of the leaf only, whereas maize leaves have stomata at both sides. For rice a value of 390 second per m has been selected, an average of the values reported under water stress by Otoo et al. (1989) and Dingkuhn et al. (1989a). To estimate transpiration resistance at canopy scale, a conversion is used according to Kelliher et al. (1995): leaf resistance at leaf scale is divided by three to obtain transpiration resistance at canopy scale. Figure 6.1 presents the general relationship between aerodynamic resistance (r_a) and daily transpiration of the four crops for a range of surface resistances (r_s). The supposed aerodynamic resistance (r_a) and surface resistance (r_s) for the four crops under optimal and sub-optimal water supply are indicated as well.

The figures for evapotranspiration of the four crops (mm per day) under optimal and sub-optimal water supply are presented in Table 6.6, including those for the effect of doubling the radiation term (R_n) and vapour pressure deficit (δ_e) on evapotranspiration.

TABLE 6.6 Daily transpiration rates (mm) of four crops (LAI > 3.5) under optimal and sub-optimal water supply and the effect of doubling radiation term (R_n in kJ m^{-2} s^{-1}) and δ_e (kPa).

	Optimal water supply				*Sub-optimal water supply*	
	R_n = 0.25 δ_e = 0.5	R_n = 0.5 δ_e = 0.5	R_n = 0.25 δ_e = 1.0	R_n = 0.5 δ_e = 1.0	R_n = 0.25 δ_e = 0.5	R_n = 0.50 δ_e = 1.0
oil palm	3.3	5.4	4.4	6.5	1.3	2.5
cocoa	3.0	5.4	3.8	6.1	1.0	1.9
maize	2.7	5.0	3.1	5.4	2.0	4.0
rice	2.7	5.1	3.0	5.4	2.2	4.4

Parameter values used: temperature = 30 °C; air vapour pressure = 100 kPa; Δ = 0.2434; ρ_a = 1.1391; c_p = 1.013; λ = 2.43; γ = 0.067; and G = 0 (LAI > 3.5). R_n is corrected for albedo: 0.18 for oil palm, 0.19 for cocoa and 0.23 for maize and rice.

ANNUAL EVAPOTRANSPIRATION

To calculate the annual evapotranspiration, a rainy season of six months is assumed. Annual crops are grown during this season with a crop cycle of 150 days. Land preparation (bare soil) is set to one month. LAI is supposed to be one on average for the first two months and > 3.5 on average for the last three months. Perennial crops have an LAI > 3.5 in both seasons.

For both seasons temperature and air pressure are set at 30 °C and 100 kPa respectively, resulting in parameter values (with the exception of net radiation and vapour pressure deficit) for Equation 6.1 equal to those specified for daily evapotranspiration. This does not reflect reality, since temperature and air pressure are bound to be different during the dry season. However, effects of temperature and air pressure on these parameters are minor and constant conditions are preferred for comparison of the crops. Net radiation (R_n) in the dry season is set at 0.5 kJ per m per second, derived from data of La Mé, Ivory Coast during the dry season. The vapour pressure deficit (δ_e) during the dry season is set at 1 kPa.

Daily evapotranspiration rates of intercepted rain water under wet season conditions are calculated using zero surface resistance. The number of days with this evapotranspiration is calculated by dividing the fraction intercepted multiplied with total rainfall (1500 mm) by the daily evapotranspiration rate. This fraction is 0.13 for oil palm (Dufrêne 1989), 0.24 for cocoa (Opakunle 1989) and 0.018 for maize (Acevedo and Sarmiento 1993; Girardin 1992; Warner and Young, 1991). No data were found for rice, thus 0.018, as for maize, has been selected. This resulted in 49, 106, 9,5 and 9,9 days with daily evapotranspiration rates of 4.0, 3.4, 2.8 and 2.7 mm for oil palm, cocoa, maize and rice, respectively.

During land preparation for annual crops, the soil is considered to be wet for 20 days; the upper layer is assumed to be dry for 10 days. Evaporation of bare soil is calculated assuming an aerodynamic resistance of 400 second per m and a surface resistance of 0 (wet soils) or 25 000 second per m (soils with dry upper soil layer). The water stress during the growing season is assumed to occur for 50 days, spread evenly over the five-month period. As LAI = 1, evapotranspiration is supposed to consist of 50 percent transpiration and 50 percent evaporation.

TABLE 6.7 Evapotranspiration per season and per year (mm) for oil palm, cocoa, maize and rice. A = leaf resistance for crops growing under sub-optimal water supply according to literature data; and B = for all crops equal to 200 s m^{-1}. See text for further explanation.

	Dry season		Wet season		Annual total	
	A	B	A	B	A	B
oil palm	395	428	623	623	1018	1051
cocoa	294	490	584	584	878	1074
maize	46	46	367	361	413	407
rice	46	46	372	364	418	410

The aerodynamic resistance is than set to 120 second per m for maize and 150 second per m for rice. The surface resistance at LAI = 1 for both crops is set to three times the surface resistance at LAI > 3.5: thus 50 (maize) and 20 (rice) second per m for wet soils and 450 (maize) and 390 (rice) second per m for soils with a dry upper layer.

It is supposed that perennial crops only suffer from water stress during the dry season and not during the wet season because of their deeper rooting system. The figures for annual and seasonal evapotranspiration for the four crops are presented in Table 6.7. The table also contains the results based on the assumption of equal surface resistance under water stress (200 second per m) for the four crops.

6.4 Discussion and conclusions

Tables 6.2, 6.3, 6.4, and 6.5 show a large variation in measured leaf resistance at leaf scale for the four crops, which may be the result of the wide range in environmental conditions, e.g. climate, soil fertility and water stress. Crop specific characteristics (e.g. the diurnal course of stomatal opening, feed-back and feed-forward mechanisms in regulating stomatal closure, rooting characteristics, etc.) add to this variation, but are difficult to separate from the environmental factors. At canopy scale the variation is smaller. Transpiration resistance is strongly reduced owing to higher leaf area and the associated increase in parallel resistances (Jones 1986). Although this increase is not linear, since part of the leaf area within the crop canopy is exposed to a lower potential gradient (lower ET_p) as driving force for transpiration, owing to a lower net radiation and saturation deficit. Thus, transpiration resistance at canopy scale is determined by LAI and canopy structure, which influence radiation profiles and vapour transport within the canopy.

Also, transpiration resistance varies with position inside a canopy, mainly because of variations in *stomatal* resistance, under the influence of differences in vapour pressure deficit, radiation, temperature or CO_2 concentrations.

Moreover, aerodynamic resistance varies with the position inside a canopy. It is higher deeper inside the canopy as the wind speed is lower there.

Several authors have proposed ways to estimate transpiration resistance at canopy scale from leaf resistance at leaf scale. Perrier (1988) divides the canopy in a surface layer and a total inside layer to quantify total transpiration resistance, as the largest difference in transpiration resistance and aerodynamic resistance occurs between the surface of the canopy and its interior. The question remains at what depth to define the limit between surface and inside layers.

Dufrêne (1989) calculates the total transpiration resistance of a canopy (r_a in second per m) as:

$$r_a = 1 \,/\, \left(\sum_{i=1}^{i=n} \mathrm{LAI}_i / r_{si} \right) \qquad \text{(Equation 6.3)}$$

in which

LAI = leaf area index in layer i (-)

r_{si} = average stomatal resistance r_s in leaf layer i (s m^{-1}).

However, in this approach differences in aerodynamic resistance among different canopy layers are not taken into account. Moreover, average leaf resistance in the defined layers must be known.
Allen (FAO 1992) calculates crop canopy resistance as:

$$r_c = r_l / (0.5 * \text{LAI}) \qquad \text{(Equation 6.4)}$$

in which
r_c = transpiration resistance at canopy scale (s m^{-1})
r_l = transpiration resistance at leaf scale (s m^{-1})
LAI = leaf area index (-)

According to this equation, transpiration resistance at leaf scale has to be divided by 1.75 to obtain transpiration resistance at canopy scale at LAI = 3.5. However, this equation may be not valid at such high LAI values, with steep gradients in light intensity causing the stomata of leaves within the canopy to close.
For this study it was decided to use the simple approach of Kelliher et al. (1995), since data were lacking to follow one of the approaches cited above. Kelliher et al. compared maximum conductances at leaf scale and canopy scale for non-stressed, mainly temperate crops and vegetation at LAI > 3.5 - 4. They found that canopy conductance is about three times higher than leaf conductance for forests, herbaceous vegetation and crops. In this analysis it appears that the canopy conductance of natural vegetation (trees or herbaceous) is about 0.6 cm per second and of agricultural crops about twice as high i.e. 1.2 cm per second. The authors suppose that this difference is caused by the use of fertilizer on crops. Comparison of crop transpiration (LAI > 3.5) under constant and equal climatic conditions (R_n = 0.5, G = 0 and δ_e = 1) in relation to transpiration resistance at canopy scale (r_s) and aerodynamic resistance (r_a), as illustrated in Figure 6.1, shows that differences among crops are small at low transpiration resistance (r_s = 20-25). At zero resistance (wet leaf surface), transpiration of perennial tree crops, such as oil palm, is higher than that of shorter crops. Differences in transpiration resistance under optimal water supply, used for further calculations, are not reflected in differences in transpiration, as an increasing aerodynamic resistance counteracts this effect.
Penman (1952) compared perennial crops (tall trees and short fodder crops) and short annual crops under irrigated conditions. He concluded that transpiration is dominantly a weather-controlled phenomenon in which plant characteristics such as plant height play a minor role. Under increasing moisture stress, causing stomata to close, transpiration decreases, but at equal transpiration resistance a somewhat stronger reaction occurs in tall crops, such as oil palm and cocoa, than in short crops, like rice and maize. In practice, this difference will be levelled out,

since tall crops with their deeper rooting systems, and thus exploiting larger soil volumes, will react later to water stress in drying soils. Transpiration resistances, as used for calculations of daily transpiration rates of the four crops under water stress, are lower for the short crops and may accentuate the differences among short and tall crops. However, this difference may have been the result of differences in the degree of moisture stress. Although the occurrence of drought was mentioned in the relevant publications, no indication was given of the severity of water stress, with only one exception for oil palm (Dufrêne 1989). For comparison among species it would be worthwhile to measure the leaf resistance of crops under comparable water stress conditions.

Differences in daily transpiration rates as a result of differences in irradiance (R_n) and vapour pressure deficit (δ_e) are much greater than those caused by differences in crop characteristics (Table 6.6). Albedo and sensible heat flux into the ground and the vegetation (G) affect the net irradiance and are thus also important factors in explaining the differences in daily transpiration rates. Attention for data collection on albedo and G for tropical crops should increase. In the West African climate irradiance is high, resulting in high values for the first term in the denominator of Equation 6.1, whereas wind speed is low, resulting in high values for r_a and subsequently low values for the second term of the equation. In particular the first term of the equation, and thus the factors influencing net radiation, are important for both short and tall crops (Table 6.6). McNaughton and Jarvis (1983) use a factor (Ω) to evaluate the change in evapotranspiration when the land use changes from forest to grassland in a temperate climate. Ω is coupled with the type of vegetation and is large for short grassland and small for tall forest. However, under these climatic conditions both terms of the denominator of the equation are of equal importance (Webb 1984). This is in contrast to the West African climate where the first term of the equation is larger than the second term. This means that differences in Ω become small so that this factor is less appropriate to evaluate changes in evapotranspiration with land use changes.

Scaling-up to annual time scale and to land units, may cause large differences between land units occupied by perennial crops or by annual crops (Table 6.7). Supposing equal transpiration resistance for all crops under sub-optimal water supply does not change the order of magnitude in differences. Measured annual evapotranspiration rates for the four crops are in the same order of magnitude: e.g. between 700 and 1340 mm per year for oil palm (Dufrêne 1989) and between 341 and 565 mm per year for two successive maize crops with a four-months cycle each (Poss et al. 1988).

The differences between perennial and annual crops are partly built up during the wet season, but mainly during the dry season. The difference in the wet season is caused by the shorter time period in which the soil is covered with annual crops. During land preparation and at low crop cover (LAI = 1) evapotranspiration is completely (one month) or partly (two months) determined by soil evaporation rates. These rates are smaller than the transpiration rates of the crops, in particular in dry soils. Differences in interception of rain water by the crops or water stored at the surface of soils do not contribute much to differences in evapotranspiration between crops. Evapotranspiration rates of water at the surface of leaf or soil are close to transpiration rates of crops at optimal water supply and of wet soils. Differences in annual evapotranspiration between perennial and annual crops are mainly caused by the fact that perennial crops transpire during the dry season, albeit at low rates, but still considerably higher than evaporation rates of bare and dry soils. Apparently, the degree of soil cover with vegetation in space and in time is of major importance to evaluate differences in annual evapotranspiration caused by changes in land use from tree to annual crops and vice versa.

Chapter 7

"Mimicking" scale-dependency of run-off coefficients: a multi-scale water balance model with reference to West Africa.

Sections of this chapter are submitted as:

De Ridder N, TJ Stomph and LO Fresco (submitted). "Mimicking" scale-dependency of run-off coefficients: a multi-scale water balance model with reference to West Africa. *Catena*

Chapter 7

"Mimicking" scale-dependency of run-off coefficients: a multi-scale water balance model with reference to West Africa

N. de Ridder, T.J. Stomph and L.O. Fresco

7.1 Introduction

LAND USE DYNAMICS AND SCALE-RELATED PROPERTIES

Land use changes have profound effects on landscape evolution, for example through induced changes in soil characteristics, run-off and erosive processes. The expanding world population during the last century has induced major changes in land use (Turner et al. 1993). Land covered with natural vegetation has been turned into cropped land and pastures, while urbanization and related expansion of infrastructure has led to changes from natural vegetation or agricultural land into roads and cities (Waggoner 1994).

Man induced changes relate to units and processes that have scale related properties (e.g. Turner et al. 1995). This holds for the effects of land cover conversions, for example deforestation, which affect the soil properties and nutrient flows at the deforested plot as well as lower lying areas in a watershed (Lowrance and Groffman 1987). It may even affect the meso-climate on a longer time scale (Holling 1992). Similar scale related properties are found in the factors driving changes in land use generally situated at a higher level, such as markets or migration (Veldkamp and Fresco 1996). In both types of cases, the step from effects or drivers at plot level to a higher level is not just cumulative: at higher levels different processes occur. Hence, the level of the analysis determines the nature of explanatory variables.

In classical agronomy much attention is given to effects of cultivation practices on water and nutrient balances at the detailed level of a plot. Changes in available water for crop growth caused by e.g. land preparation, contour plowing, row planting, use of bunds etc, are well studied, as well as nutrient flows such as leaching of nutrients and losses of nutrients by erosion in relation to these cultivation practices. However, a loss at one level (field), may be part of recycling at a higher level (watershed), since losses of nutrients and water at the uplands and the slopes can be used at the lower parts of a watershed, the bottomlands (Jensen 1992). So far, scale dependency of variables related to the water and nutrient balance have been ignored. Yet, the understanding of this scale dependency is essential if agronomy wants to contribute to studies which relate changes in land use to biophysical variables and their effect on landscape evolution.

SCALE DEPENDENCY OF VARIABLES RELATED TO THE WATER BALANCE

In neighbouring disciplines such as erosion studies and hydrology, awareness of scale dependency is more common. For example, the validity of extrapolating predictions based on the USLE (Uniform Soil Loss Equation), even when it is corrected for sediment delivery, has been questioned before (Rogowski et al. 1985). The basis for this failure lies in the fact that erosion pin data (i.e. most detailed scale) overestimate the values obtained at plot level and higher levels, owing to phenomena such as turbulence in run-off. If application of results to smaller (i.e. coarser) spatial scales takes place, 'due reservations concerning other processes that may emerge at a larger (sic) scale' are necessary (Rose 1985).
Extinction of the run-off coefficient with increasing size of catchments (Shanan et al. 1969; Yair and Lavee 1985) or watersheds (for West Africa: Rodier and Auvray 1965; for the USA: Dunne 1978) is commonly known. The run-off coefficient is an example of a scale dependent variable.
At the most detailed spatial scale (pin data) the infiltration process is determined by rainfall characteristics (intensity and duration) and physical soil characteristics (antecedent soil humidity, soil conductivity etc). In the first step of scaling-up this process to plots of 1 m^2, the unit of measurement of run-off is most commonly used, soil surface storage capacity and interception by vegetation have to be included in the infiltration/run-off equation. In further scaling-up, the increasing variety in land units (e.g. uplands, slopes and bottomlands) with different infiltration capacities (caused by land form, soil types, soil surface roughness, antecedent soil humidity conditions) and their spatial configuration in larger entities (watersheds) have to be included to understand the infiltration/run-off processes in these larger entities.
Yair (1983) shows for the Negev Desert in Israel that the infiltration/run-off process of combined geographical units is not a simple mathematical average of the processes of its components. A slope with a total planimetric area of 900 m^2 was divided into three subplots (Table 7.1). The run-off per unit area (liter per m^2) of the entire slope is almost equal to the run-off per unit area of the colluvial, lower part of the slope, whereas the run-off per unit area of the upper part of the slope (rocky slope) is much higher. The mathematical average for the entire slope clearly leads to an overestimation of run-off of the two land units: (13.3 + 33.2)/2 = 23.25 liter per m^2, whereas 11.7 liter per m^2 is measured (Table 7.1). The author explains this by

discontinuity in flow at the contact line between the rocky and the colluvial slope sections.

TABLE 7.1 Effect of plot size on run-off owing to differences in infiltration characteristics for slope parts (after Yair 1983).

Subplot	*Planimetric area (m^2)*	*Total run-off yield (liters)*	*Run-off per unit area ($l\ m^{-2}$)*
Whole slope	439	5149	11.7
Colluvial slope	307	4084	13.3
Rocky slope	161	5348	33.2

In scaling-up from run-off plots to larger geographical units, temporal dimensions become important as well. The travelling time of run-off water increases with growing likelihood of this water to infiltrate. Using a deterministic simulation model to simulate overland flow generation, Yair and Lavee (1985) show the effect of the length of the slope on the run-off. Assuming equal infiltration capacities along a slope, the generated run-off increases in absolute terms with increasing slope length, but the run-off per unit area decreases, owing to the likelihood of run-off water to infiltrate with increasing travelling time.

THE CASE: WEST AFRICA AND ITS INLAND VALLEYS

West Africa provides an excellent example of temporal and spatial land use dynamics. Large differences in cropping and livestock systems exist between the agroecological zones (AEZ), with the importance of grazing decreasing with increasing rainfall in a southerly direction. Albergel (1988) compared land use and run-off at the outlets of two watersheds in West Africa over a period of 20 years in which the use of land changed remarkably (fallow has turned into permanently cropped land and natural vegetation into annual crops). Rainfall has decreased drastically whereas the run-off coefficients stayed the same during that period. Thus, changes in land use have increased the run-off to the extent that decreases in run-off, expected to be the result of decreasing rainfall, are compensated.

Inland valleys are defined as small watersheds of about one to several square kilometers (Andriesse et al. 1994; Windmeijer and Andriesse 1993). As such, they represent an intermediate level between individual fields and slope on the one hand and large river systems on the other. They occupy between 22-52 million hectare of land in West Africa. Depending on climate and geology/lithology, inland valleys vary widely in geomorphology, hydrology, soil types and vegetation (Windmeijer and Andriesse 1993). In this chapter "watershed" and "inland valley" are used interchangeably.

At a more detailed scale, the West African landscape displays the basic land units

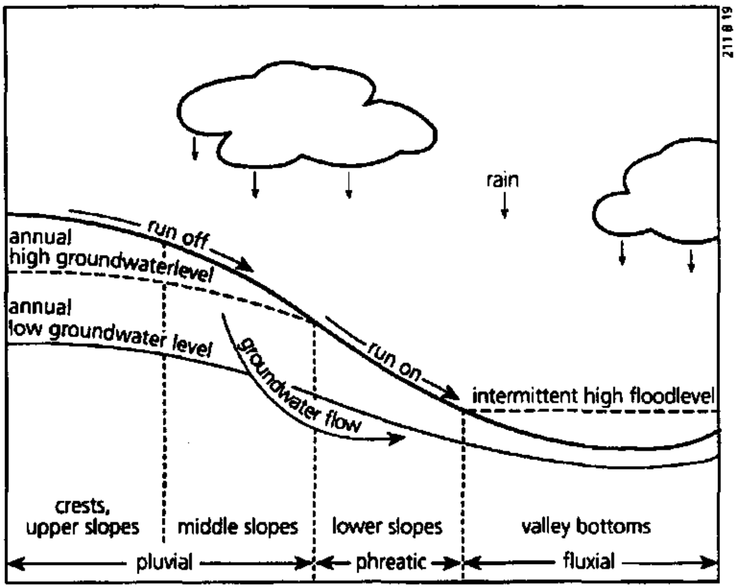

FIGURE 7.1 Landscape elements and physio-hydrography along a toposequence of an inland valley (Andriesse and Fresco 1991).

of uplands, slopes and valley bottoms (Figure 7.1). The use of inland valleys - with their successive land units - depends on AEZs. In particular, the extent to which valley bottoms are used for crop production depends on the rainfall and the labour demands for clearing and the presence of water-borne diseases. Furthermore, land use changes because of new cropping techniques. Introduction of animal and machine power changes the land use pattern from small fields scattered in the landscape to large contingent fields (Becker and Diallo 1992).

OBJECTIVES OF THIS CHAPTER

The water balance at different spatial scales, in particular run-off, forms a good way to approach scale-dependency of land use dynamics. Based on West African inland valleys we have developed a water balance model. The water balance itself is rather simply modelled by using transfer functions, but spatial aspects of run-off are explicitly included, to show scale dependency of run-off coefficients.

7.2 Model and methods

SYSTEM BOUNDARIES OF THE MODEL

The system is spatially contained by the water divide of a watershed. The watershed is divided into n three-dimensional columns: these are of equal length and width of which the magnitude depends on the scale, and can be adjusted accordingly. The height of each column is determined by its average altitude derived from topographical data using contour lines. Long-term averages for climatic (rainfall) and hydrological data (groundwater tables) are used as inputs. It is assumed that each year, after the rainy season, the groundwater table returns to the same lowest average level. The bottom boundary of the system is defined using maximum rooting depth, soil depth and groundwater table as criteria. If the groundwater table is situated deeper in the profile than the maximum rooting depth and no impermeable layer exists creating shallower soils than the maximum rooting depth, maximum rooting depth is used to define the system boundary. If not, the groundwater table or depth of an impermeable layer are used to define the system boundary.
All columns are characterised by texture (sand percentage). A weighted average for the entire profile is calculated using data from representative soil profile descriptions. Furthermore, an average run-off coefficient per year per column is estimated, based on the assumption that the run-off coefficient for an average rainfall year (average in total amount, distribution and shower intensities) can be related to soil physical parameters (e.g. Withers et al. 1978 in Tauer and Humborg 1992; Stroosnijder and Koné 1982). Percentage of sand is taken as an approximation for soil physical parameters: the run-off coefficient is assumed to increase linearly from 0.12 at a sand percentage of 95 to 0.58 at a sand percentage of 5.

DESCRIPTION OF THE MODEL

Average rainfall per year is applied to each column. The model first sorts the columns from high to low surface altitude. For each column the average water balance per year is calculated, starting with the highest column (n = 1). The water loss by run-off (R_{off} in mm) from a column is calculated by multiplying the rainfall (R in mm) with one minus the run-off coefficient (RC). The latter is defined as the ratio between run-off water and rainfall, both expressed in mm. The remaining water infiltrates (I in mm):

$$I = R * (1 - RC) \quad (7.1)$$

Depending on the storage capacity of the soil column and evapotranspiration, surplus water percolates out of the system. The total percolation of the watershed is calculated by adding the percolation of all columns. To calculate the percolation (P_e in mm) in a column, the transfer function for percolation is used (Chapter 6):

$$P_e = 0.69\, I - 45\, \theta_{pF2.5} - 0.22\, sd - 7.8\, (\theta_{pF2.5} * sd) - 74 \quad (7.2)$$

in which
I = the infiltrated water (mm)
sd = the defined depth of the soil profile (cm)
$\theta_{pF2.5}$ = the water content of the soil ($cm^3\ cm^{-3}$) at pF 2.5

This transfer function is developed using a deterministic model called SAHEL (Van Keulen 1975; Penning de Vries and Van Laar 1982; Van Keulen and Wolf 1986; Penning de Vries et al. 1989; De Ridder et al. 1991). The SAHEL model calculates plant growth and water balances and has been extensively validated on the basis of data from Israel (Migda), Senegal (Bambey) and Mali (Niono) (e.g. Van Keulen et al. 1986; De Ridder et al. 1991). In general, the SAHEL model simulates plant growth and water balances in arid and semi-arid zones quite correctly. An example of the simulated and measured water content in a soil profile near Bambey (Senegal) is presented in Figure 7.2.
The water content of the soil (cm^3 per cm^3) at pF 2.5 is calculated using a second transfer function (Chapter 6):

$$\theta_{pF2.5} = 0.014\, (37 - 0.35\, sp) \quad (7.3)$$

in which *sp* is the average percentage of sand in the soil profile.
The run-off water of a column is distributed to adjacent columns with a lower altitude, proportionally to the differences in altitude of the column at issue and these adjacent columns. In this way the slope and its direction are mimicked. Whenever in previous computing steps the run-on water (R_{on} in mm) is passed to the n^{th} column, it is

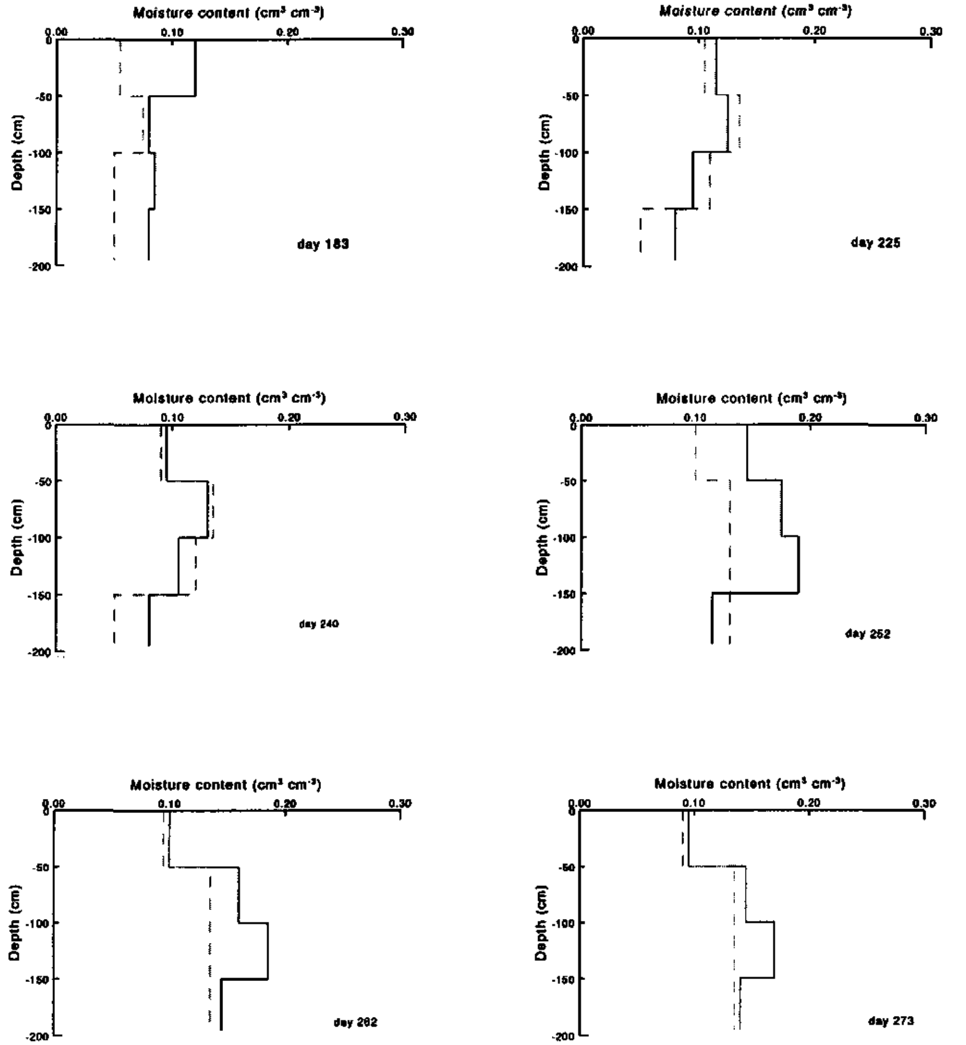

FIGURE 7.2 Simulated (dotted line) and measured (drawn line) water content of a soil profile at six dates within one rainy season at Bambey, Senegal (De Ridder et al 1991).

considered as additional water input to the water balance of this column. However, not all run-on water will have the opportunity to infiltrate and thus cannot be simply regarded as rainfall. The rate of the surface flow will change depending on the slope and the roughness of the surface. At high rates less water of the surface flow will infiltrate than at low rates. Furthermore, the surface flow may concentrate into small channels. The magnitude of concentration in small channels will depend on micro relief and vegetation.

To mimic this spatial process of infiltration and run-on water, a reduction factor (REDF) is introduced, which may vary between 0 (all run-on water to a column is considered to leave this column as run-off) and 1 (all run-on water is considered potentially to infiltrate and is added to the rainfall of this column). Thus, infiltration in the n^{th} column is:

$$I = \{R + (REDF * R_{on})\} \cdot (1 - RC) \tag{7.4}$$

The run-on water to the n^{th} column that does not infiltrate, is added to the run-off of the n^{th} column and becomes run-on for the neighboring columns. It can potentially infiltrate into the neighbouring columns, depending on the characteristics of these columns. Run-off of the lowest column, the last column in the computing procedure, is considered as the discharge of the entire watershed. The run-off coefficient of the watershed (WRC) is the discharge divided by rainfall.

MODEL RUNS

Based on a previous inventory of West African inland valleys (Hakkeling et al. 1989), a representative watershed was designed. This watershed has the following composition: uplands (24 %), slopes (56 %), bottomlands (13 %) and a stream (7 %). It is divided into 362 columns (Figure 7.3). The boundary at the bottom of the system is set at 40 cm in the bottomlands (being the average groundwater table at the lowest point in a year), gradually increasing along the slopes to 200 cm in the uplands (assumed to be the maximum rooting depth). The land units have the following characteristics: upland soils have a sand percentage of 65 and a related run-off coefficient of 0.27; soils on the slopes have a sand percentage of 50 with a run-off coefficient of 0.35; and soils in the bottomlands have a sand percentage of 35 with a run-off coefficient of 0.42 (Luiten and Hakkeling 1990). It is assumed that the REDF on the uplands, slopes and in the bottomlands equals 0.8. Water flowing through the stream is supposed not to infiltrate, thus the REDF for these columns is in all cases kept at zero. The model behaviour is tested by changing the different characteristics of this standard watershed.

In first instance, it was tested how the run-off coefficient of the watershed (WRC) relates to the size of the watershed. The standard watershed of 362 columns is enlarged to 816, 1448, 3258 and 5792 columns respectively as demonstrated in Figure 7.4. In this figure the columns with equal shading have the same properties.

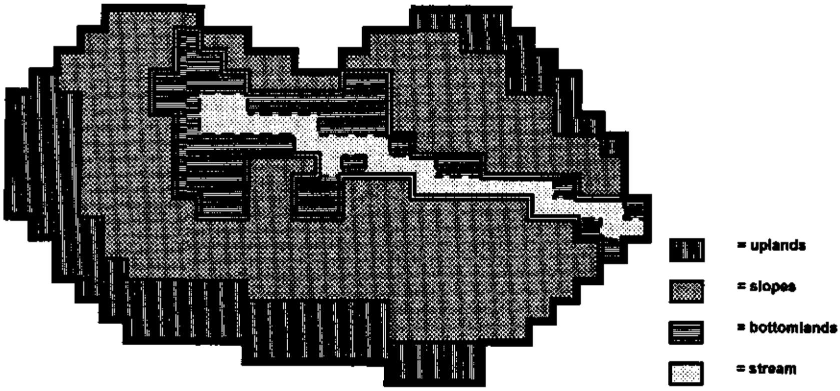

FIGURE 7.3 Uplands, slopes, bottomlands and stream in the representative watershed used in the model runs.

Altitude and depth of the added columns are changed (other shading) and are obtained by extrapolation between the values of the original columns.
Rainfall is set at 1250 mm per year. The model is run with REDF values of 0.4 and 0.8, equal for the uplands, slopes and bottomlands.
Subsequently, it was tested how WRC is related to the most important parameters (using the standard watershed size of 362 columns): reduction factor (REDF), sand percentage of the soil profile (and linked to that the run-off coefficient), and depth of the columns. First, the model is run with values for REDF, equal for all columns, from 0 to 1 with increments of 0.1. Soils are supposed not to vary and have an average sand percentage (50 percent), with a related RC of 0.35. Next, the model is run with the standard watershed, but with varying sand percentages and related run-off coefficients. The sand percentages are equal for all columns of the watershed and decrease from 95 to 5 with increments of 15. Furthermore, the soil depth is varied at rainfall values of 250, 500, 750, 1000, 1250 and 1500 mm per year. Using the standard watershed, but with a REDF of 0.5, sand percentage of 50 and a related run-off coefficient of 0.35 for all columns in the entire watershed, the model is run with a soil depth as defined in the base set and with a deeper and a shallower soil. In the alternative with shallower soils, soil depth is defined at 40 cm in the bottomlands and at 50 cm in the slopes and uplands. Deeper soils are defined at

100 cm in the bottomlands, gradually increasing along the slopes to 300 cm in the uplands.

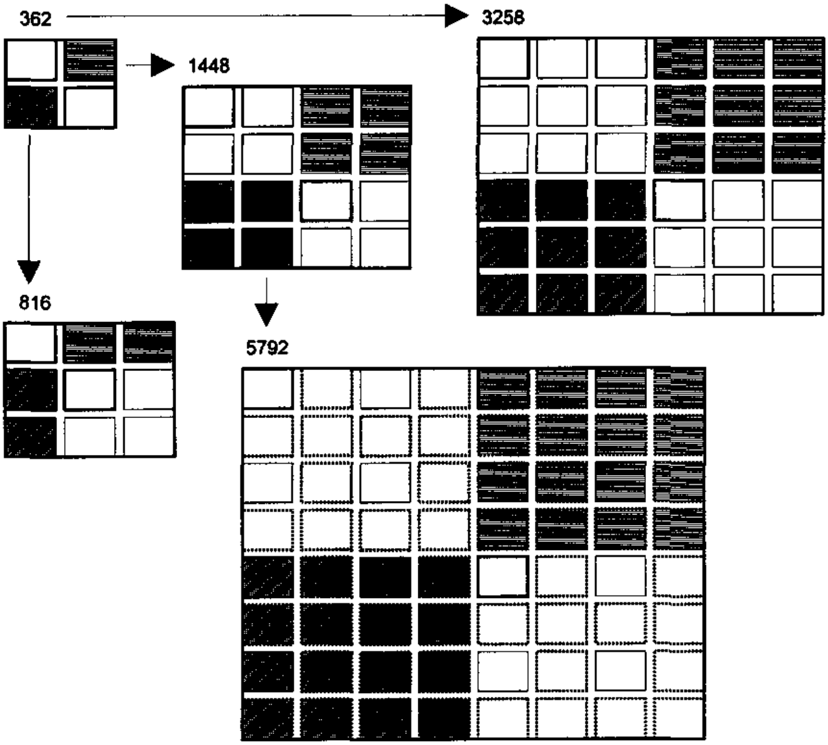

FIGURE 7.4 Procedure followed to enlarge the representative watershed of 362 columns.

Finally, the effect of different land uses is tested. The following simplified vegetation types are distinguished: a natural vegetation comprising trees, shrubs and perennial grasses, an annual crop and sparse vegetation on degraded land. It is assumed that the rate of surface flow water and channeling is highest on degraded land, intermediate on annually cropped land and lowest on land with natural vegetation. Consequently, the REDF is supposed to be highest on land with natural vegetation (0.8), intermediate on cropped land (0.4) and lowest on degraded land (0.2). The different combinations of land use tested with the model are summarized in Table

7.2. The model is run with the standard watershed, but with the REDF values as indicated in this table.

TABLE 7.2 Different land use combinations, as represented by differences in reduction factor (REDF).

Land use combination	*Uplands*	*Slopes*	*Bottomlands*
1	0.8	0.8	0.8
2	0.4	0.4	0.4
3	0.2	0.2	0.2
4	0.8	0.4	0.8
5	0.4	0.4	0.8
6	0.4	50 %=0.4; 50 %=0.2	0.4
7	50 %=0.8; 50 %=0.4	50 %=0.8; 50 %=0.4	0.8

7.3 Results

The run-off coefficient of the watershed (WRC) in relation to its size is presented in Figure 7.5. The straight line represents WRC in relation to its size, when run-off is not explicitly spatially modelled (REDF = 0). Then, WRC is the average of the individual RC values of all columns and independent of watershed size.

In Figure 7.6, WRC in relation to REDF is presented. With increasing REDF run-off of the watershed decreases from 0.34 with REDF = 0 to 0.07 with REDF = 1. The slight curving in the line is due to the stream, in all cases kept at REDF = 0.

In Figure 7.7, WRC is plotted against varying sand percentages. In the model RC is related to the sand percentage of the soil, thus run-off coefficients of the watershed decrease with increasing sand percentage from 0.43 with a sand percentage of 5 to 0.07 with a sand percentage of 95.

In Figures 7.8a and 7.8b, percolation and evapotranspiration of the entire watershed for three defined soil depths in relation to rainfall are presented. WRC does not change (not presented), because in the model soil depth does not affect run-off. Percolation increases with diminishing soil depth, even to the extent that at lower rainfall percolation becomes important. At shallower soils evapotranspiration decreases with increasing percolation.

Figure 7.9 shows WRC with varying land use combinations. Changing land use from natural vegetation (land use combination 1) to degraded land (land use combination 3) doubles WRC from 0.15 to 0.30. The WRC values for the other land use combinations are within these ranges.

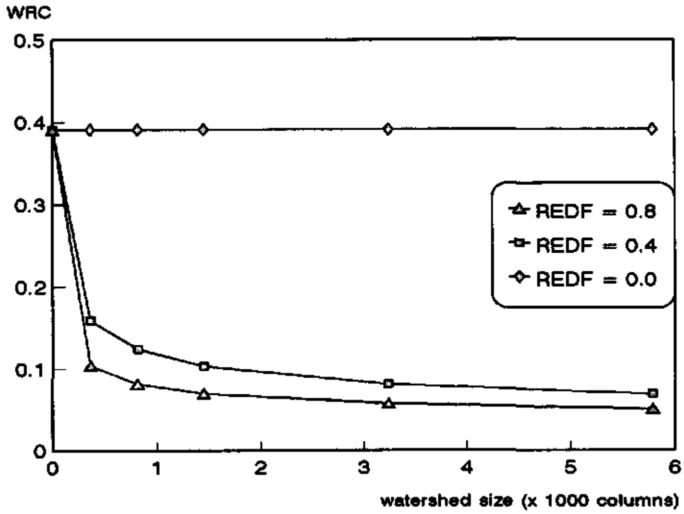

FIGURE 7.5 Computed run-off coefficient of the watershed (WRC) in relation to its size (in number of columns) for three reduction factors (REDF).

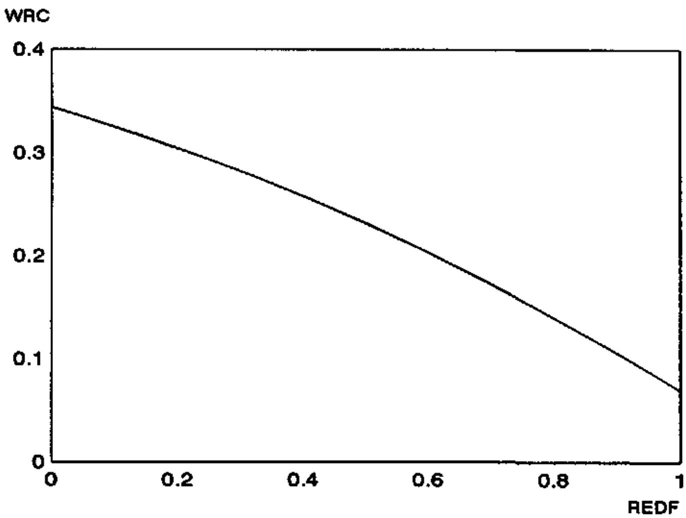

FIGURE 7.6 Computed run-off coefficient of the watershed (WRC) in relation to the reduction factor (REDF).

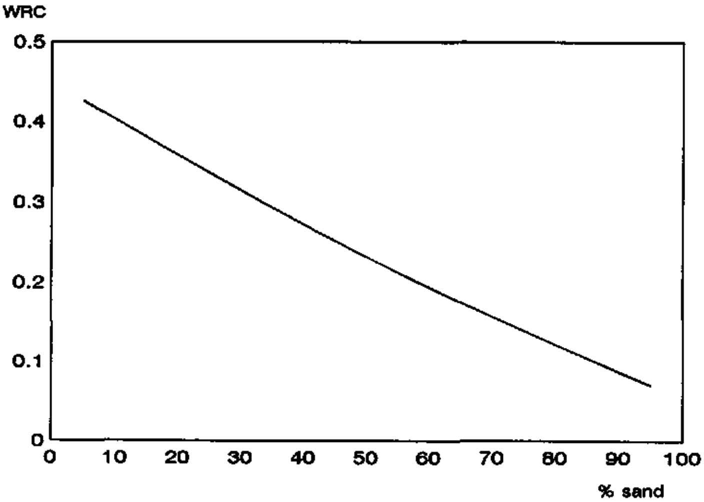

FIGURE 7.7 Computed run-off coefficient of the watershed (WRC) in relation to the sand percentage.

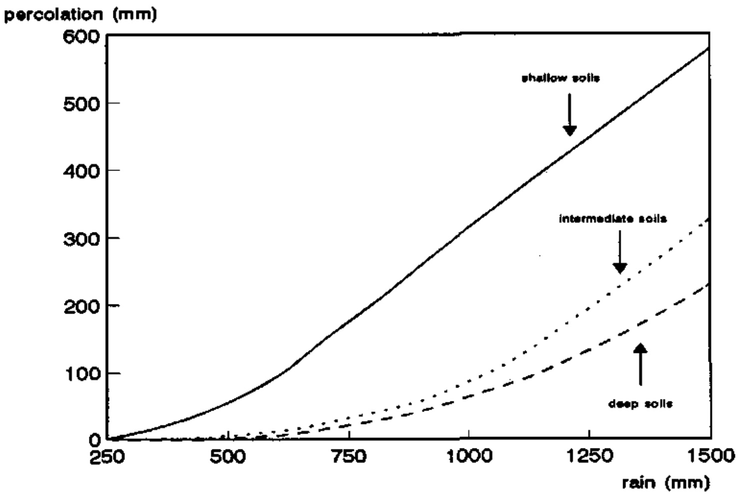

FIGURE 7.8.a Model results for percolation of the standard watershed in relation to rainfall for three soil depths.

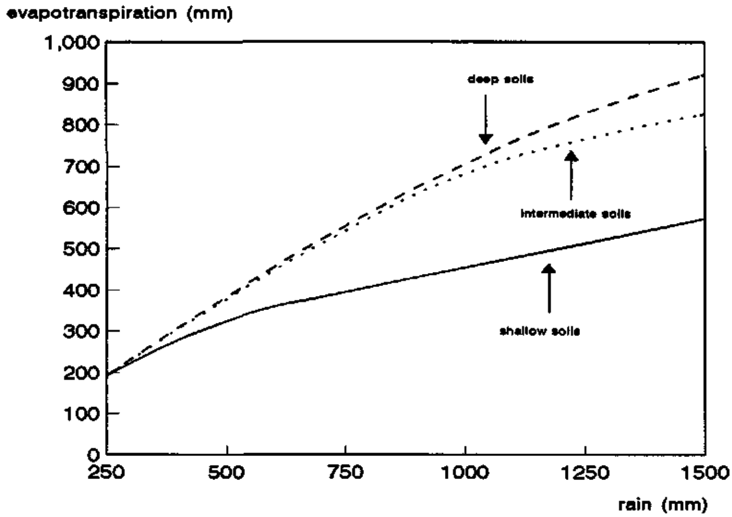

FIGURE 7.8.b Model results for evapotranspiration of the standard watershed in relation to rainfall for three soil depths.

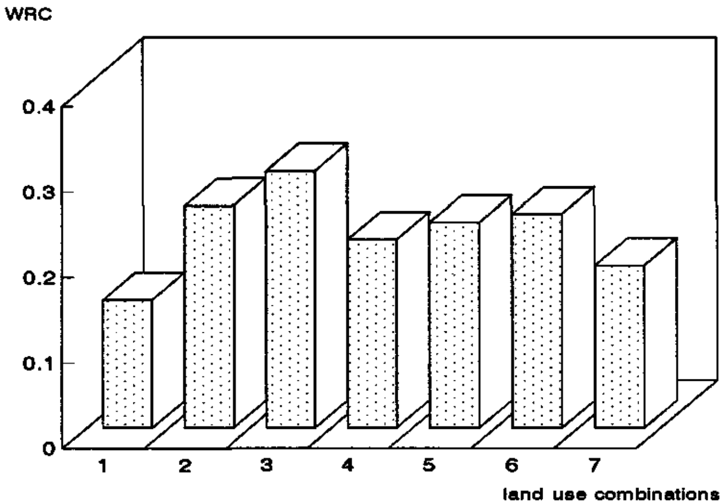

FIGURE 7.9 Computed run-off coefficient of the watershed (WRC) in relation to land use combinations (see Table 7.2).

7.4 Discussion

The purpose of this model i.e. to approach the scale dependency of land use dynamics through the scale dependency of the water balance (in particular that of run-off), is conceptual rather than predictive. By explicitly taking into account the possibility of run-off water to re-infiltrate down-slope (introduction of REDF in the model), extinction of the run-off coefficient with increasing watershed size can be mimicked (Figure 7.5): at REDF = 0 a straight line is obtained, indicating no scale-dependency; at REDF = 0.8 a curve is obtained indicating strong scale dependency.
A complete validation of the presented model is hardly possible, since the model concerns a hypothetical watershed and no data sets exist for "real" watersheds which include data of run-off at the outlet, as well as spatial distribution of run-off, infiltration, evapotranspiration and percolation, soil types and depth.
Notwithstanding the inherent impossibility of validation, this model provides an addition to our current understanding. Many distributed hydrological models exist (e.g. Kite and Kouwen 1992; Vertessy et al. 1990; Vertessy et al. 1991; Albergel 1988), but the authors are not aware of distributed models which take into account the scale-dependency of run-off.
The advantage of this model approach is that properties of the watershed can be kept constant, whereas the size can be varied. In reality, properties (soil types, slopes, land use), composition (ratios of uplands to slopes and bottom valleys) and form of the watershed will always vary between watersheds, making systematic validation nearly impossible. French researchers have accumulated a large volume of lymnographic data of watersheds in West Africa, varying in size, properties, form and composition (e.g. Puech and Chabi-Gonni 1984; Rodier and Auvray 1965). With their classification of watersheds using criteria such as rainfall zones (reflecting the magnitude of vegetative cover), permeability and magnitude of slopes, they brought some order into the data. Some data for Burkina Faso are presented in Figure 7.10. Here, run-off of the watersheds is expressed in peak discharge per surface unit. Total volumes of run-off are missing, making quantitative comparison with Figure 7.5 impossible. However, the curve in Figure 7.10 shows the same trend as that in Figure 7.5, indicating the same kind of scale-dependency and, as such, serves as a partial validation of our model.
The variation of points around the line in Figure 7.10 can be explained by variation in properties of the watersheds. The results of the model runs with the standard watershed size (362 columns) and varying properties show that the run-off coefficients of the watershed can vary greatly, depending on land use type (represented by REDF, Figure 7.6), soil type (represented by sand percentage; Figure

7.7), and soil depth (Figures 7.8a and 7.8b). However, combinations of soil types (and related run-off coefficients), covers (related to reduction factors) and soil depth level out the extremes (Figure 7.9).

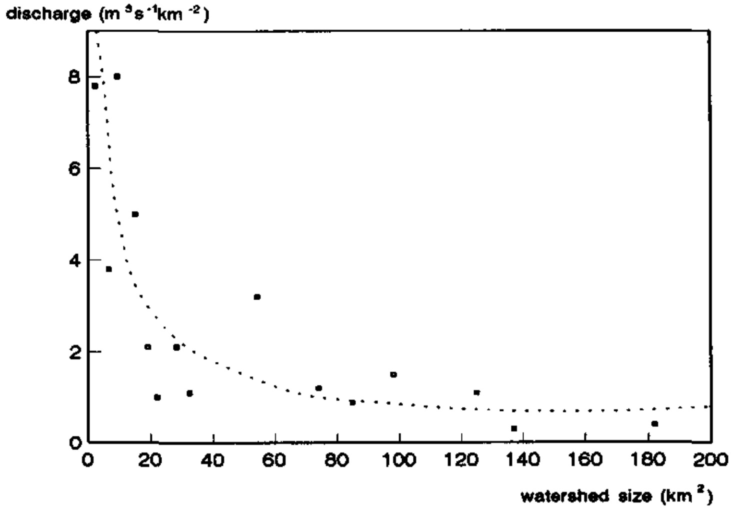

FIGURE 7.10 Discharge of watersheds in Burkina Faso (m^3 s^{-1} km^{-2}) in relation to watershed size (km^2).

Albergel (1988) developed a model to estimate the discharge of West African watersheds. In his model he applied the so-called "état de surface" concept of Casenave and Valentin (1989). This concept is based on a classification system for different soil-vegetation complexes. For each of these classes they obtained functions to calculate run-off in relation to rainfall, which are established with numerous rainfall simulator experiments. These relationships obtained at 1 m^2 plots are applied in the model to entire land units with similar soil/vegetation combinations. Run-off of a land unit is obtained by multiplying the run-off per m^2 by the total surface of a land unit. The estimated discharge of the watershed is the summation of the run-off of all land units in a watershed. This estimated discharge of the watershed has to be calibrated with at least one year field data. For eight valleys in Burkina Faso, Albergel (1988) obtained eight different regression lines. His model overestimates the discharge in six cases, whereas in two cases the model underestimates the discharge. According to the author, underestimation is the result of the possible existence of subterranean tributaries, contributing to the discharge from outside the watershed under consideration. Overestimation is most likely related

to the scale-dependency of run-off, which is not taken into account when run-off/rainfall relationships obtained at 1 m^2 plots are directly applied to larger units.
It would be worthwhile to investigate the possibilities of incorporating a scale-dependent variable (REDF) in the "état de surface" concept (Casenave and Valentin 1989). Then, relationships between run-off and rainfall need to be established on different scales: in addition to the 1 m^2 plots also measurements on larger plots have to be included. It is believed that the scale-dependent variable can be obtained with two or three different plot sizes. In addition, the concept has to be extended from different soil type/vegetation type combinations to different agricultural practices such as crop types, sowing pattern and density, contour ploughing, bunding, etc.
The model presented here is kept simple: its only purpose is to elucidate the scale-dependency of run-off and show the importance of the spatial distribution of land use. As the relationship between scale and run-off can be clarified from field experiments, it becomes valuable to upgrade the model. Then, the dynamics of the water balance within years can be included, through replacement of the transfer functions, based on yearly averages, with daily calculated water balances driven by daily rainfall. Subsequently, the effects of cultivation practices on the water and nutrient balances, such as land preparation, contour ploughing, row planting, use of bunds, etc, can be studied at levels above that of the plot (e.g. slopes and inland valleys). The model now uses a simple algorithm for the routing of the surface flows. Other algorithms exist to route run-off flows (e.g. Scoging 1992; Holmgren 1994), which could be used to replace the simple routing algorithm in the model.

7.5 Conclusions

Scale dependency of run-off can be mimicked by the introduction of a scale-dependent variable (REDF) in a simple water balance model. This scale-dependent variable has to be established in field experiments, where the run-off for different soil type and vegetation combinations is measured not only from traditionally used 1 m^2 plots but from larger plots as well i.e. measure the run-off on two or three scales in relation to agricultural practices. Then, it would be worthwhile to develop the model further so that it becomes a powerful tool to explore the effects of land use changes on landscape evolution.

Chapter 8

Effects of land use changes on water and nitrogen flows at the scale of West African inland valleys: a conceptual model.

This chapter has appeared as extended paper:

De Ridder N, TJ Stomph and LO Fresco 1996. Effects of land use changes on water and nitrogen flows at the scale of West African inland valleys: a conceptual model. In: PS Teng, MJ Kropff, HFM ten Berge, JB Dent, FP Lansigan and HH van Laar (eds), *Application of systems approaches at the farm and regional levels*. Kluwer Academic Publishers, Dordrecht: 367-381

Chapter 8

Effects of land use changes on water and nitrogen flows at the scale of West African inland valleys: a conceptual model

N. de Ridder, T.J. Stomph and L.O. Fresco

8.1 Introduction

The expanding world population during the last century has induced major changes in land use (Turner et al. 1993). The natural vegetation is increasingly replaced by crops and pastures (Waggoner 1994). These conversions of land covers are particularly important in West Africa (Alexandratos 1988; Becker and Diallo 1992).

Because of its agroecological diversity, West Africa is a suitable area to study the effects of land use conversion. A characteristic feature of West African landscape are the inland valleys. These are defined as the upper reaches of river systems, inland in respect of main rivers and tributaries, in which alluvial sedimentation processes are absent or of minor importance. Inland valleys have a minor floodplain and levee system (Andriesse et al. 1994; Windmeijer and Andriesse 1993). These inland valleys have a size of about one to several square kilometers and occupy between 22-52 million ha of land in West Africa (Windmeijer and Andriesse 1993). Within inland valleys several contiguous agro-ecosystems can be distinguished, primarily based on hydrology: (1) the upland system (crest and slopes), which depends entirely on in situ rainfall, (2) the hydromorphic system, a band at the base of the slopes, which is characterized by the presence of the groundwater table within the rooting zone and (3) the temporally flooded lowland system (Andriesse and Fresco 1991). These systems are not distinctly separated units, since their boundaries overlap both in space and in time.

Water is the major driving force for interaction between adjacent sections of the toposequence as it moves in various ways along the gradient of the slope from the upper to the lowermost part of the landscape. Rain falling on the upland portion of the landscape may partly leave this agroecosystem as run-off water, moving down-slope as surface flows. The rest infiltrates and may either be used by the vegetation, be lost as evaporation or may percolate into deeper layers down to the groundwater table. Percolated water may partly move as subsurface flow to the lowlands and, as seepage, join the run-off flow in a small stream to leave the inland valley.

The water flows not only contribute to differences in the water regimes between the agro-ecosystems, but also influence the flows of soluble nutrients e.g.

nitrates, by transporting them down-slope via run-off and through leaching by percolation.

In humid West Africa annual crops are originally grown on uplands and upper slopes, but increasing pressure on land leads to a shift of cropping down-slope to the lowlands. Changing the land use from perennial woody vegetation to crops affects the ratios of run-off to infiltration and of evaporation to transpiration and thereby the nitrogen flows. The latter will not only be changed at plot level but also at higher levels e.g. entire slopes and inland valleys.

For land use management purposes, it would be worthwhile to quantify these effects at higher levels, given the profound influences these changes may have on productivity (Jensen 1992). However, experiments at the level of entire inland valleys would be difficult and expensive, if not impossible. The variation in geomorphology, soil types and land use of inland valleys is enormous and the complexity of the systems is high. Therefore, in this study a modelling approach has been chosen.

Simulation models can be divided into verifiable, explanatory models of recurring systems and speculative or exploratory models of unique systems (De Wit 1993). By their very nature, models of inland valley behaviour are closer to the latter type. Nevertheless, the explorative nature of such models can be reduced by using verifiable "building blocks" relating to subsystems. also varying inputs and assumptions, Exploratory models can be used to obtain indications of system behaviour by varying inputs and assumptions and by studying relationships between model input and model output.

Such an analysis also provides an indication of the priority of the assumptions at which future research should be directed in order to improve understanding of the complex system.

The model presented here is of exploratory nature with the objectives (1) to conceptualize quantitatively our present understanding of the most important relationships between land use and water and nitrogen flows above plot level, (2) to study quantitatively the effect of changes in land use on changes in the flows given our present understanding, and (3) to target further research in the field of water and nitrogen flows along slopes as a function of agricultural land use.

8.2 Material and methods

MODEL

The conceptual model has three main characteristics (Figure 8.1):

1. an approach to describe the three-dimensional redistribution of water at inland valley level;
2. transfer functions to calculate the one dimensional water balance;
3. an equation for the nitrogen balance.

The model is fully described in Chapter 7.
To simulate the nitrogen flows, a simple nitrogen balance equation is included in the model. The nitrogen per column, which is fixed in the above ground biomass (N_b in kg per ha), is calculated with an equation according to De Wit and Krul (1982):

$$N_b = 0.0083\ [R + (REDF * R_{on})] - R_{off} - P_e/f - 0.13 \qquad (8.1)$$

where f represents the yearly losses of nitrogen from the above ground biomass (kg per kg). The fraction f represents the losses of nitrogen by volatilization, harvest of products, grazing, bush fires and other losses e.g. through insects. The

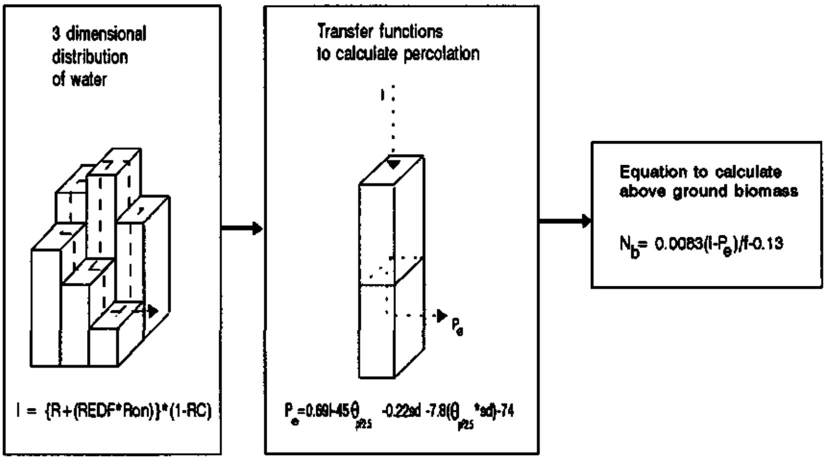

FIGURE 8.1 The three main characteristics of the conceptual model.

nitrogen inputs accounted for are wet deposition through rainfall, dry deposition, and fixation by algae, free living bacteria and legumes.
The equation has been validated for West African circumstances (e.g. Van Keulen et al. 1986; Breman et al. 1991). The correspondence between calculated and measured N_b values is acceptable, although a large spread in individual observations exists. This is mainly due to differences in rainfall distribution within years. The averages over years of calculated and measured N_b values correspond well. For the present model this average trend is of prime importance. Whenever the surface of a column is (mainly) occupied by perennial woody vegetation, we assume that the permanent root system will avoid nitrogen losses through percolation and P_e in Equation 8.1 is set to zero accordingly.

PARAMETERISATION

Using data from Hakkeling et al. (1989), a representative inland valley in West Africa has been defined with the following landscape elements and composition: uplands (24 %), slopes (56 %), bottomlands (13 %) and a stream (7 %). This inland valley is divided into 362 columns (Figure 8.2a), of which 27 columns are stream and the remaining 335 are divided into 87 columns of uplands, 202 of slopes, and 46 of bottomlands.

The boundary at the bottom of the system is set at 40 cm in the bottomlands (being the average groundwater table at the lowest point in a year), and gradually increases along the slopes to 200 cm in the uplands (assumed to be the maximum rooting depth).

The sand percentage is taken as an approximation for soil characteristics and is estimated for the different landscape elements (Luiten and Hakkeling 1990). The run-off coefficient is assumed to increase linearly from 0.12 at a sand percentage of 95 to 0.58 at a sand percentage of 5 (Withers et al. 1978 in: Tauer and Humborg 1992; Stroosnijder and Koné 1982). Hence, the landscape elements have the following characteristics: upland soils have 65 percent sand and a run-off coefficient of 0.27; soils on the slopes have 50 percent sand with a run-off coefficient of 0.35; and soils in the bottomlands have 35 percent sand with a run-off coefficient of 0.42. The annual rainfall is set at 1250 mm.

Two types of vegetation have been distinguished, a perennial woody vegetation and an annual vegetation (crops). These vegetation types differ in their values for f and REDF. Nitrogen losses, mainly caused by grain harvests with high nitrogen contents, are supposed to be much larger in crops ($f = 0.65$) than in perennial woody vegetation ($f = 0.30$) (Breman and De Ridder 1991).

Furthermore, it is assumed that a perennial woody vegetation, by the nature of its structure, is more capable of capturing run-on water (REDF = 0.9) than crops (REDF = 0.2). Finally, it is assumed that vegetation types affect the run-off coefficient differently (e.g. Barnes and Franklin 1979; Du Plessis and Mostert 1965; Haylett 1960). As a first estimate it is assumed that the run-off coefficient of a column is divided by two whenever a column is occupied by a perennial woody vegetation, but is not changed when a column is occupied by crops.

Water flowing through the stream is assumed to contribute little to infiltration, so that the REDF is kept at zero for these columns.

MODEL RUNS

Many land use combinations are possible within the assumed inland valley: for example, the surface of one column (= grid) can be occupied by crops, the rest by a perennial woody vegetation (334 grids). This single-cropped grid can be

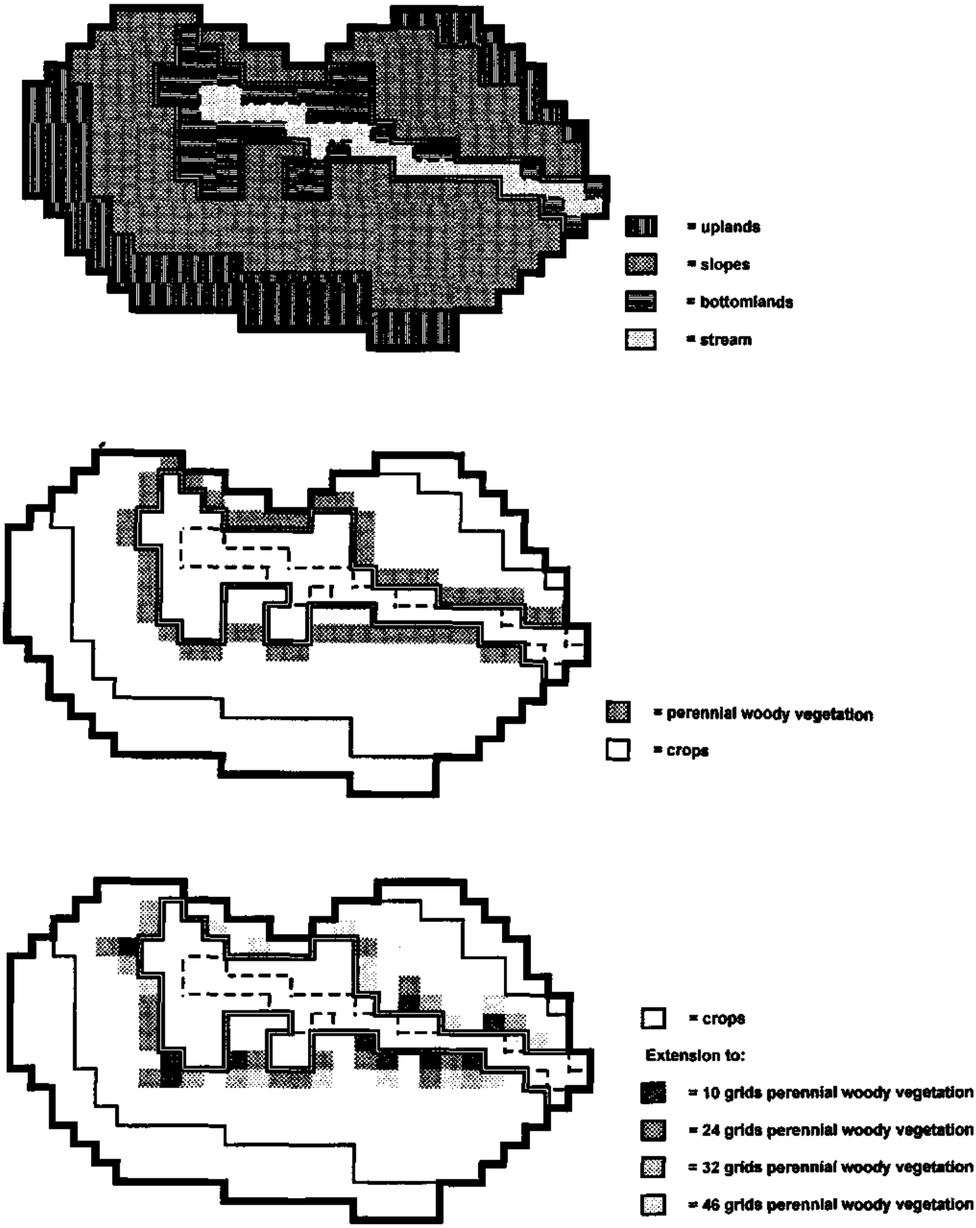

FIGURE 8.2 The inland valley with upland, slopes, bottomlands and stream as used in the model runs (a); location of the band with perennial woody vegetation around the bottomlands (b); and location of the perennial woody vegetation on slope grids which contribute most to reduction of run-on to the bottomlands (c).

chosen at 335 different locations within the inland valley, each showing a different result in water and nutrient balance. To cover a wide range of combinations and to study the effect of the location of crops in the inland valley, the following runs were chosen.

In the first runs, the entire inland valley is occupied by either a perennial woody vegetation (WWW) or by crops (CCC), representing two extremes: exploitation is negligible, as it was in the past, and all land is exploited, as may be expected in future.

Subsequently, the model is run with crops only in the bottomlands (WWC-46), only on the slopes (WCW-202) and only on the uplands (CWW-87). The place in the three-character combinations of the characters W (perennial woody vegetation) and C (crops), indicates upland (first character), slopes (second character) and bottomlands (last character) respectively. The number indicates the total number of grids occupied by crops.

Further combinations investigated are crops on both uplands and slopes (CCW-289), on uplands and in bottomlands (CWC-133) and on slopes and in bottomlands (WCC-248).

In the more humid areas of West Africa, the bottomlands are traditionally the last part of an inland valley to be reclaimed (e.g. Becker and Diallo 1992). With improved health measures, though, reclamation of bottomlands has become of greater interest, particularly for lowland rice cultivation. With this land use option one may expect the lowest N_b and the highest run-off. It might be of interest to investigate the effects on N_b and run-off when the perennial woody vegetation, which is replaced by crops in the bottomlands (46 grids), is strategically relocated on the slopes. To this end, two strategies have been followed. In the first strategy, a band of 46 grids with perennial woody vegetation is placed around the bottomlands (Figure 8.2b), with the aim of capturing run-off water from the slopes and filtering nitrogen out of percolating water (CC_bC-289). In the second strategy, perennial woody vegetation are positioned on the slopes. The model is then run with an increasing number of grids occupied with perennial woody vegetation to a maximum of 46 grids (Figure 8.2c), each time taking those grids on the slopes through which run-on to the bottomlands was reduced most.

8.3 Results

According to the logic of the model, the highest run-off is created when the entire inland valley is occupied with crops (CCC). In Figure 8.3, the relationship between run-off and number of grids under crop is presented. Run-off is expressed as a fraction of the maximum value for run-off obtained when the entire inland valley is occupied with crops. The dotted line represents the relationship between the number of grids under crop and run-off, when the spatial effects of water

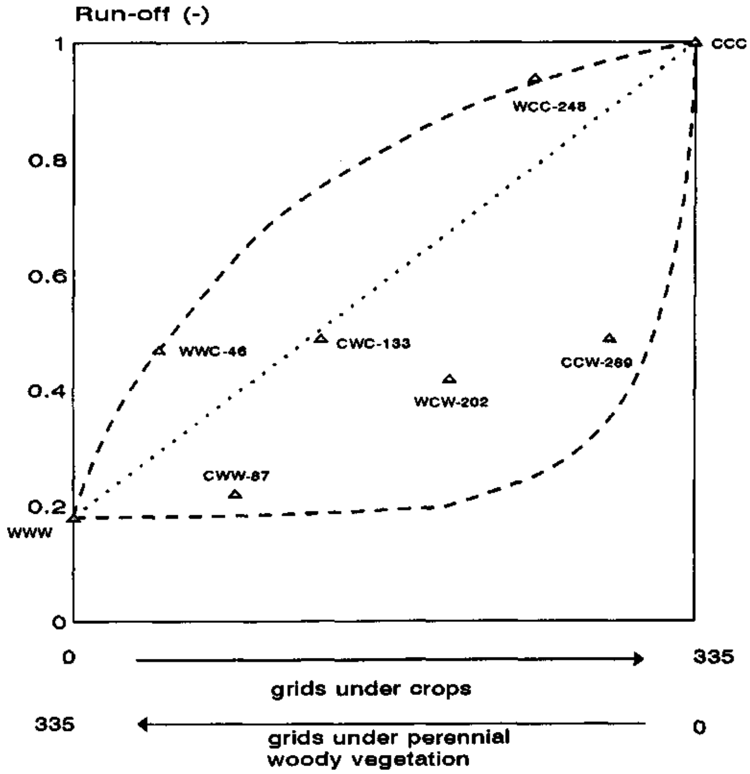

FIGURE 8.3 The solution domain of run-off values of the inland valley in relation to the number of grids covered with crops. The run-off is expressed as fraction of the maximum run-off obtained when the inland valley is fully covered with crops.

redistribution is not explicitly modelled. The points indicate the calculated run-off of the different model runs i.e. when spatial effects of water redistribution is explicitly taken into account. The points suggest a solution domain rather than a single line. A step-by-step decrease in the number of grids occupied with perennial woody vegetation through replacement with crops resulted in the dashed lines. These lines represent the limits of the domain of possible run-off values, which can be obtained with explicitly modelling the spatial effects of water redistribution. The values within the domain depend on the location of the grids under crops within the inland valley. With subsequent expansion of crops from first uplands to slopes and bottomlands (www → cww-87 → ccw-289 → ccc), the bottom line of the domain will be followed. When expansion of crops starts from the bottomlands towards the slopes and the uplands (www → wwc-46 → wcc-248 → ccc), the upper line of the domain will be followed. The distance between the two lines at any number of grids under crops shows the possible options for changing run-off through reallocation of the cropped land: with the same number of grids under crop a range of run-off values can be obtained. Thus, it is possible to increase the area of cropped land and at the same time decrease run-off, for example by replacing crops on the uplands and in the bottomlands by perennial woody vegetation and perennial woody vegetation on the slopes by crops (cwc-133 → wcw-202). Figure 8.4 Presents the relationship between N_b and the number of grids under crops. Here, according to the logic of the model, the highest N_b value is obtained when the entire inland valley is occupied with perennial woody vegetation. N_b values of the other combinations are expressed as fraction of this highest value. A comparable picture arises as for run-off: a domain of N_b values is created by explicitly modelling the spatial effects of water distribution. Relatively high run-off results in lower N_b values, following the bottom line of the domain, when expansion of crops goes from bottomlands to slopes and uplands (www → wwc-46 → wcc-248 → ccc). Relatively low run-off results in higher N_b values,

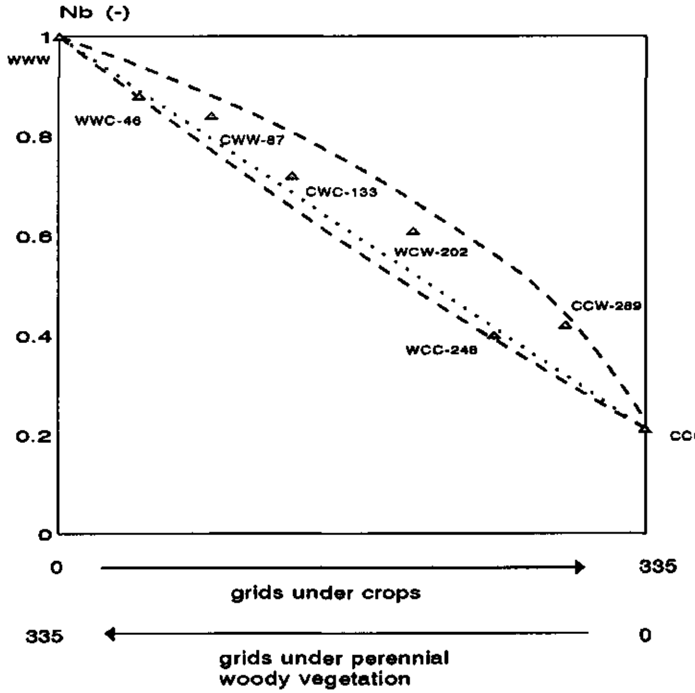

FIGURE 8.4 The solution domain of N_b-values of the inland valley in relation to the number of grids covered with crops. N_b is expressed as fraction of the maximum N_b-value obtained when the inland valley is fully covered with perennial woody vegetation.

following the upper line of the domain, when expansion of crops goes from uplands to slopes and bottomlands (www → cww-87 → ccw-289 → ccc). Similar to Figure 8.3, the distance between the two lines at any number of grids under crops shows the possible options for changing N_b through reallocation of cropped land: with the same number of grids under crops a range of run-off values and thus N_b values can be obtained. Thus, it is also possible to increase N_b by replacing crops on the uplands, and in the bottomlands for example by perennial woody vegetation and perennial woody vegetation on the slopes by crops (cwc-133 → wcw-202). Then, the harvestable N_b (part of N in cropped land) of an inland valley is increased without increasing the run-off. Figure 8.5 shows the relationship between N_b and the number of grids under crops, when the perennial woody vegetation, which in the bottomlands is replaced by crops (46 grids), is strategically relocated on the slopes. The dotted line represents the relationship when spatial effects of water redistribution are not explicitly modelled. The line

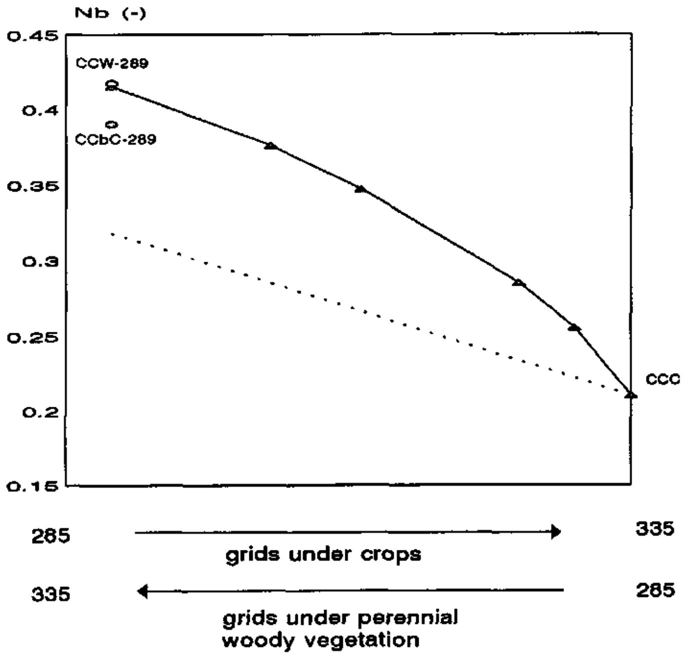

FIGURE 8.5 The relation between N_b values of the inland valley and the number of grids covered with crops, when perennial woody vegetation is strategically located on slope grids which otherwise would contribute most to run-on to the bottomlands.

with triangles represents the N_b values when grids with perennial woody vegetation are strategically placed at those places on the slopes, that contribute most to the run-on to the bottomlands. Equal run-off and N_b values for the situation where perennial woody vegetation occupies the bottomlands (ccw-289) can be obtained when perennial woody vegetation is relocated at strategic places on the slopes (left point of the line). A lower N_b value is obtained when perennial woody vegetation is placed as a band around the bottomlands (cc_bc-289). Identical values for run-off and N_b result in the case of less perennial woody vegetation, if the perennial woody vegetation is placed strategically on the slopes.

8.4 Discussion and conclusions

The model at issue demonstrates the importance of spatial patterns of land use and their effects on water and nitrogen flows at inland valley level. When surface water flows are spatially conceptualized, it appears that relationships between land use scenarios (different combinations of perennial woody vegetation and crops) and run-off and N_b values of an inland valley cannot be described by single lines: a domain of values exists, with each value in this domain representing a specific combination of land use (Figures 8.3, 8.4 and 8.5). The size and shape of the domain will alter with vegetation types, slopes, soil types and size of uplands, slopes and bottomlands (in itself as well as in relation to each other). This mutual dependency confirms the assumption that optimal combinations can hardly be found through experimental work.

The purpose of the present model is by no means to simulate the discharge of an inland valley accurately, nor the daily water balance at any location within an inland valley or erosion and sedimentation rates. To avoid any suggestion in that direction no absolute values are given here. The purpose of the model is to illustrate the dependency of water and nitrogen balances of inland valleys on the spatial distribution of surface run-off water as affected by land use. Therefore, the model is also kept simple, avoiding detailed relations such as rainfall intensity and the infiltration/run-off ratio. Rather, transfer functions needing only yearly average input values are used. Nevertheless, inclusion of more detailed relationships may change the shape and size of the solution domain.

The model represents a concept based on the present understanding of water and nitrogen flows. However, while running the model it became clear that some important issues are not included in it.

Evapotranspiration is not explicitly modelled, but probably differs considerably between perennial woody vegetation and crops on a annual basis (Chapter 5). Hence, percolation may well be considerably lower under perennial woody vegetation than under crops (Stewart 1984). This will not affect the calculated nitrogen balance, since it was assumed that the nitrogen in the percolation water will be captured by the permanent root system of perennial woody vegetation.

Furthermore, the model equation for N_b (Equation 8.1) does not take into account the losses caused by denitrification. This model equation was originally developed for the arid and semi-arid Sahelian region in West Africa, where denitrification plays only a minor role (De Wit and Krul 1982). This means that the benefits of

higher levels of N_b calculated as a result of higher infiltration at the foot of the slopes and in the bottomlands and through capturing water by introducing perennial woody vegetation, may partly diminish through denitrification.
Finally, nitrogen losses through leaching (i.e. in cropped land) are assumed to leave the system through percolation water. Nevertheless, the percolating water from uplands and upper slopes can return to the surface at the foot of the slopes as seepage, in case a semipermeable or impermeable layer exists. The leached nitrogen in the percolation water could than contribute to the N_b levels in the lower parts of inland valleys. Possible seepage has to be included in the model, because this could affect the run-off of the inland valley as well.
The model results indicate some important research issues to be tackled. The possibility of run-off water to infiltrate at lower parts of the slopes, in the model simply introduced by a run-on reduction factor (REDF), appears to be important in the relationship between water and N flows and land use: a domain of solutions instead of single line relations. Experiments are under way to investigate this factor in relation to e.g. vegetation type, micro relief, and agricultural practices.
In the model, water and nitrogen flows and relationships between the flows are simplified in transfer functions and a model equation. Although they are useful for a *first analysis because of their simplicity, these "building blocks" are not* verifiable. In future models, a time dimension will be included to explain the dynamics of water and nitrogen flows. The processes described in "building blocks" should be validated in field experiments. However, the degree of detail in a "building block" will depend on its impact on model behaviour.
Decision makers have to consider the possible effects of land use change on water and nitrogen balances not just at plot or field level, but increasingly at the level of landscape units such as inland valleys. Models as presented here, provided that the above mentioned issues are included, can show trends of water and nitrogen flows in relation to combinations of land use. As such, it can become a tool to design land use patterns and land use combinations, aiming at efficient use of water and nitrogen.

Chapter 9

General Discussion

Chapter 9

General discussion

9.1 Introduction

The previous chapters (Chapter 2 to 8) were presented as cases of agro-ecosystem analysis at different hierarchical levels. The hierarchical levels in these chapters vary from plant to watershed. Water and nitrogen run through the chapters like a continuous thread, indicating a Process-Functional approach (O'Neill et al. 1986). In addition, several issues of agro-ecosystems analysis emerged from these chapters. These issues are: (1) the definition of an agro-ecosystem i.e. system boundaries, (2) sustainability in relation to hierarchical levels, (3) up-scaling. The latter is treated in relation to: (i) a method to develop transfer functions to transfer information to higher hierarchical levels; (ii) emerging properties; (iii) spatial up-scaling of the water balance; and (iv) integrated up-scaling of soil and crop processes. In this last chapter, these issues are discussed here explicitly in the general context of agro-ecosystem analysis.

9.2 The interdependence of objectives and agro-ecosystem boundaries

In agro-ecosystem analysis we mentally isolate parts of nature. These parts are regarded as systems and have to be defined properly. According to systems theory, a system comprises five elements: components, interactions between components, boundaries of the system, inputs and outputs (Odum 1983). Each choice of elements (components, relationships between components, inputs and outputs) to be included in agro-ecosystem system analysis, i.e. the definition of the system, leads to simplification. This definition provides the boundaries of the system. Two other aspects related to the boundaries of a system are involved, the temporal and spatial scales.

The boundaries of a specific system are always artificial and defined in accordance with the objectives of the analysis. Several examples of the interdependence between objectives and boundaries of a specific agro-ecosystem analysis were touched upon in Chapters 2, 3 and 4 and will be discussed below.

In Chapter 2, the reproductive efforts of annual pasture species were compared. Mono- as well as dicotyledons were included in the study. Although quite different, they have in common that the reproductive structure is the only sink for nutrients. Other species with multiple sinks for nutrients, such as e.g. bulb or tuber forming species, and perennial species that transfer nutrients to permanent stems and root systems, are excluded from this study.

The reproductive effort is defined as the reproductive ratio (proportion of biomass invested in the reproductive organs in relation to the total biomass produced) and as harvest index (proportion of harvestable seed in relation to the total biomass produced). These definitions reflect two separate objectives of study, implying that two systems are studied each with different components and boundaries. The reproductive ratio represents a biological point of view i.e. a measure for survival of annual species. This ratio for wild annual pasture plants may reach a value of 0.50 or more and is similar to that of cultivated species. However, comparison of the highest reproductive ratio of a species on the one hand with its harvest index on the other, reveals large differences between species. Some species invest more in seed (in number and weight), others more in dispersal structures, reflecting different biological strategies for survival. The harvest index originates from agronomy, the objective being to express the efficiency of a crop to produce harvestable products such as grain or tubers. In agronomy, species and varieties are usually selected that follow the strategy to invest in seed rather than in dispersal structures. Both approaches are legitimate and have their value, although each separate approach has its limits in understanding the functioning of annual species.

The variation within a species of both ratios is great. If understanding this variation is the objective of study, this will lead to a shift in objectives. We could limit ourselves to a simple comparison of species and the reproductive ratios or harvest indices found. This implies that genetic variation is considered as the main determinant to explain the variation between species. More likely, environmental conditions will also be important determinants and have to be considered as well. Consequently, this leads to another system definition (more components and other boundaries). In Chapter 2, a model was introduced which describes the possible nitrogen allocation to the reproductive organs. The model clarifies the relationship between environmental conditions and the reproductive effort. The nitrogen concentration in the plant at flowering can be regarded as a measure for the environmental conditions (e.g. nutrient and water availability) during the preceding vegetative growth. The nitrogen concentration in the reproductive organs at maturity and the magnitude of its dilution between flowering and maturity represents the effects of the environmental conditions during the phase of seed development and maturation. Of course, the availability of other nutrients and carbohydrates at flowering stage and the allocation during seed development and maturation phase play a role as well. However, this simple model already explains to a large extent the possible variation in reproductive ratios and harvest indices, which are observed within one species.

A comparable example of the interdependence between objectives of system analysis and system boundaries was presented in the comparison of the advantages and disadvantages of ranching and traditional livestock systems (Chapter 3). One way is to compare meat production in both systems, expressed as annual weight gain of weaner calves in relation to weaning rates of calves. In this case, only one output (meat) and two components (cows and weaner calves) of the livestock systems are considered. Ranching systems with low stocking rates then appear to be more productive than traditional systems with higher stocking rates. The objective of this comparison is to judge the value of these systems in terms of meat production for export, which then seems justified. However, if one wants to compare the full value of the systems, more outputs have to be included in the system analysis. Next to meat production, also milk production and draught power have to be considered. In this case, productivity has to be expressed in terms of energy and/or protein balances. Furthermore, all animal classes within a herd are considered as components. If the objective shifts to a judgement of the value of the systems for local consumption, it is concluded that traditional livestock systems are more productive than was assumed when only one output and two components are considered.

The system analysis can be further expanded by including land availability. In that case, the objective changes to a comparison of the use efficiencies of a scarce resource (land) in both systems. Such a comparison was presented in Chapter 3, where traditional livestock systems and ranching are compared in this respect as well. In this chapter, livestock productivity is expressed per animal and per hectare. Production per animal is an appropriate measure for productivity if land is abundantly available, whereas production per hectare is more appropriate when land is scarce. In Botswana, rangelands appeared to be fully in use by traditional livestock owners. Therefore, it seems justified to compare livestock systems on a per hectare basis. The conclusion about the productivity of the two systems, i.e. land use efficiency, now alters in favour of the traditional livestock systems. This effect of system boundary on the assessment of resource use efficiency was also treated by Fresco et al. (1994) in a comparison of N flows in rice-based systems in Asia, which showed that the value of nitrogen use efficiency depends on the way the system is conceptually defined.

Another comparable example of expanding system analysis is presented in Chapter 4. Here, the viability of an arable farming system in West Africa, based on manure to sustain soil fertility, is tested. This farming system seems to be viable if it is looked at in isolation. However, the conclusion about viability alters, if potential manure production is considered, i.e. the livestock and rangelands needed to produce the manure needed on cultivated land. Given the available rangelands and livestock numbers grazing them, manure production cannot satisfy the demand of the specific arable farming systems, making them less viable than assumed. In other words, a new or an additional objective forces us to widen the system boundaries.

Another aspect related to the boundaries of a system, is the extent to which the environment is taken as an external or internal parameter or part of the system, the Population-Community or the Process-Functional approach respectively (O'Neill et al. 1986). The organism is the fundamental unit in the first approach while abiotic components (e.g. soils) tend to be regarded as external influences. In the second approach, abiotic components and the physical-chemical-biological relationships between these components are included.

Both approaches were followed in Chapter 2. By simple comparison of species and their reproductive ratios, implies considering the genetic variation between organisms (species) (Population-Community approach). Including relationships between reproductive ratios and environmental conditions changes the focus to a more Process-Functional approach.

The two approaches are both valuable as can be illustrated by the development in breeding. Breeding usually considers the harvest index as one of the properties for selection. In search for high yielding varieties environmental conditions are kept at predetermined equal and supposed optimal levels. The main focus is on genetic variation, whereas variation in environmental conditions is secondary. Although this approach is successful when environmental conditions are similar to experimental conditions, it appears that these high yielding varieties fail in cases where there are less favourable environmental conditions. Recent research in breeding also follows the Process-Functional approach. This implies that rice varieties are screened for their performance at different positions on a toposequence and under different management strategies. The positions on the toposequence as well as the different management strategies, create varying sets of environmental conditions. For each combination of management strategy and environmental conditions the appropriate variety is developed (WARDA 1994). Furthermore, crop growth simulation models are now used to design and evaluate ideo-types for specific environments (Kropff et al. 1995).

These examples show that system delimitation changes with the objectives of a study and that the objectives of the study determine the approach to follow, either a Process-Functional or Population-Community approach. Each way of delimitating agro-ecosystems is legitimate if it is in accordance with the objectives of the study. However, an additional insight is gained by looking at agro-ecosystems from different points of view.

9.3 Sustainability and a multiple hierarchical level approach

Many definitions of sustainability in agriculture have been put forward in the last decade (e.g. WCED 1987; De Wit 1989; TAC/CGIAR 1989; FAO 1992). They all state that present agriculture must exploit natural resources without undermining the natural resource base to meet future needs. Ecological sustainability, related to the natural resource base, cannot be defined without regarding multiple hierarchical levels, each with their own temporal and spatial scales (Fresco and Kroonenberg 1992). Furthermore, sustainability is not limited to the ecological dimension: future needs[1] refer to social and economic dimensions as well. In any case, sustainability has to be considered through agro-ecosystem analysis at multiple hierarchical levels. Several examples of these aspects of sustainability were touched upon in Chapters 4, 7 and 8. They are discussed below.

Chapter 4 illustrated that, to assess the ecological sustainability of an agro-ecosystem, the embedding of this system in the organizational structure at higher hierarchical levels must be considered. This chapter elucidates the necessity of organic matter for sustainable arable farming in West Africa. Based on an extensive review of agronomic research over the last decades in West Africa, Piéri (1989) concludes that arable farming systems in semi-arid and sub-humid zones in this part of the world can only produce more in a sustainable way (i.e. high production levels over prolonged periods), if large quantities of organic material (manure, compost and crop residues) are used as inputs in combination with chemical fertilizers. He argues that use of chemical fertilizers with little or no inputs of organic material will lead to declining yields in these systems. This argument is disputable (as discussed in Chapter 4), but, in addition, the conclusion does not hold when higher hierarchical levels are considered. To a large extent, supply of organic material has to come in the form of manure. Animals that have to produce this manure, have to rely on the natural rangelands. By including animal production in the system analysis, we move up in the hierarchy and change the spatial scale of the system under study (Fresco et al. 1994). Feed availability from rangelands and their area in relation to the cultivated area are now considered as well. Other studies have shown that, on average, the area of rangelands needed to keep up the fertility of the existing arable land successfully is exceeding the actual available rangelands in West Africa (Breman and Traoré 1986a, 1986b and 1987). Further overgrazing of the rangelands will

[1] Future needs will be different from to-day's needs. The world population still expands and diets may become more luxurious and include more animal proteins. It is difficult to foresee what future needs will be, because this will depend on the desires of future generations.

be the result if one tries to keep up a sustainable arable production system, that relies mainly on large quantities of organic material, i.e. manure.

A comparable example of the interdependence between ecological sustainability and hierarchical levels was shown in Chapters 7 and 8, but on a completely different subject. In Chapter 7, a conceptual water balance model for small watersheds was presented, in which the spatial distribution of run-off water is explicitly accounted for by introducing the opportunity for run-off water to re-infiltrate down-slope. In Chapter 8 a nitrogen balance was included in this model. The results of the model runs in Chapter 7 show that run-off per unit area at a low hierarchical level (plots of 1 m^2) is higher than that at higher hierarchical levels (slopes and entire watersheds). If we consider run-off as the driving force for erosion and, inherently, as a loss of nitrogen to the system, erosion at a lower hierarchical level appear be more severe than at a higher hierarchical level. Thus, what may seem not or less sustainable at a detailed level is more sustainable at a higher hierarchical level.

The conclusions on ecological sustainability of arable farming systems in West Africa in Chapter 4 are based on the *average* availability of land for grazing and the areas cultivated. However, this average availability is a poor measure for ecological sustainability. There are zones in West Africa, where the absolute and relative proportion of grazing land and arable land is such that ecologically sustainable arable farming systems, in terms of sufficient manure production, are locally possible. Furthermore, the *spatial pattern*, in this case of rangeland and arable land, is also important in judging the sustainability of agro-ecosystems. The effects of spatial patterns on conclusions about ecological sustainability, although on a completely different subject, were illustrated in Chapter 8. In this chapter the water and nitrogen balances are calculated for a watershed with different land use options. Two land use types are considered, i.e. woody perennial vegetation and annual crops. These land use types differ in their water and nitrogen balances. It appears that losses of water and nitrogen at the watershed level are not simply related to the ratio of the areas occupied by the two land uses: a solution domain exists, with a range of possible values for run-off and nitrogen in the above ground biomass (N_b) for each particular ratio of land uses. The actual value for run-off and N_b of a particular land use combination, which can be considered as a measurement of ecological sustainability at the hierarchical level of a watershed, depends on the spatial pattern of the two land uses in the watershed.

The examples in this paragraph illustrate that assessment of the sustainability of agro-ecosystems is not possible without considering multiple hierarchical levels. We constantly have to move between agro-ecosystems at different hierarchical levels. At the same time, we explicitly have to take into account the spatial scale and spatial patterns.

9.4 Up-scaling

TRANSFER FUNCTIONS

Constantly moving between hierarchical levels involves transfer of information from lower to higher levels in the hierarchy (up-scaling) or from higher to lower levels (down-scaling). Down-scaling will not be further discussed here, as this issue was not touched upon in the Chapters 2 to 8, the cases selected in this thesis.

In the transfer of information, the question arises which information in what detail has to be transferred to arrive at a reasonable description of system behaviour at higher hierarchical levels. With rapidly increasing computing capacities as a result of booming information industries, we tend to include too much information at too high a resolution in the transfer process.

In Chapter 5, a methodology was presented to develop transfer functions with simulation models. The simulation model used, describes in detail growth of vegetation in relation to the water balance. This information is summarized in transfer functions, which are subsequently used at higher hierarchical levels, in this case physiographic units. This method has some shortcomings as was discussed in Chapter 5. These shortcomings are partly related to the incompleteness of the simulation model used. For example, by-pass flows of infiltrated water in the soil are not described, implying that the transfer functions cannot be used for soils where this phenomenon is dominant. Furthermore, the plant growth rates used in the model are related to site specific soil fertility parameters i.e. West Africa, limiting the applicability of the transfer functions to this particular region. These growth rates intervene in the distribution of water used for evapotranspiration and water that percolates from the rooting zone.

Despite these shortcomings, the transfer functions provide a better description of the relationship between water availability and biomass production of pastures than simple relationships between measured biomass and rainfall data, generally used so far. An example of the latter is the relationship developed by Le Houérou and Hoste (1977) for West Africa. Furthermore, to apply the transfer functions little information and limited computer facilities are needed in contrast to the original simulation models used to develop the transfer functions. As such, the methodology of using simulation models to develop transfer functions in order to summarize detailed information, proves to be valuable.

EMERGING PROPERTIES

Attempts to transfer information of high resolution, i.e. obtained at lower hierarchical levels, to higher hierarchical levels are not always correct. At higher levels other properties may emerge than the ones dominating at lower levels.

In Chapter 6, evapotranspiration for two annual (maize and rice) and two perennial (oil palm and cocoa) crops was computed for different temporal and spatial scales. Temporal up-scaling goes from day to year and spatial up-scaling from leaf to canopy. With regard to spatial scales, the physical theory of resistances coupled in series or parallel, is used to determine which information is important in the transfer of information from lower to higher hierarchical levels. This is, for example, done to judge whether both stomatal and cuticular resistance have to be considered to obtain leaf resistance. For the calculation of transpiration at canopy level the Penman-Monteith equation has been proven to be useful (McNaughton and Jarvis 1983). At this hierarchical level, environmental factors (such as radiation, vapour pressure deficit and air density) become determinant factors, as well as the aerodynamic resistance and the canopy resistance. The aerodynamic resistance depends on crop height and vegetation roughness. The canopy resistance is obtained by using the leaf area index (LAI) and leaf resistance, indicating the importance of the vegetation structure at the hierarchical level of canopies. Thus, in spatial up-scaling of transpiration, detailed information on stomatal behaviour, although important to explain transpiration at the lower hierarchical level of leaves, is of little relevance at the higher hierarchical level of canopies. At this hierarchical level, vegetation structure and environmental factors become the important properties of the system. Furthermore, large differences between species in transpiration at the hierarchical level of leaves almost disappear at canopy scale, because leaf resistance becomes less determinant at canopy level. By increasing the time scale from day to year, evapotranspiration of canopies is mainly determined by the period within a year that the soil is covered by (any) vegetation and by the magnitude of this cover, expressed in LAI.

The process of spatial and temporal up-scaling as described in Chapter 6, showed that other properties become determining at higher hierarchical levels. Thus, to analyse an agro-ecosystem at higher hierarchical levels involves the search for those properties that emerge at these higher levels.

SPATIAL UP-SCALING OF WATER BALANCES

With spatial up-scaling the heterogeneity in system characteristics that determine the rates of processes, increases. Increased heterogeneity can be approached by a proper strategy of summation, averaging and aggregation of variables to obtain values for larger spatial entities (Jarvis 1995). Two examples of such strategies were given in the first chapter: scaling up crop production (Penning de Vries et al 1994) and nutrient balances (Smaling 1993) from plot to regional level. Both studies have in common that spatial aspects of the water balance (e.g. Yair and Lavee 1985) are not taken into account. In Chapter 7 a conceptual model was described, that explicitly takes the spatial dependency of run-off into account. Results of the runs with this model show two important features of up-scaling. Within an aggregated unit such as slopes, the water balance at each location varies, even if characteristics are supposed to be similar for the entire slope. In addition, the water balances of similar aggregates within a watershed vary, depending on the location of these aggregates in the watershed. Summation of the simulated water-limited crop production of all distinguished aggregates, without taking into account the interdependency of the aggregates and within the aggregates, would thus lead to an underestimation since the water availability in the separate aggregates and in the entire watershed is underestimated.

The degree of underestimation depends on the reduction factor, which is introduced into the model. This factor is supposed to be related to factors such as micro relief and vegetation. If little run-off water has the opportunity to re-infiltrate down slope (reduction factor close to zero), an up-scaling procedure of summation of aggregates will be close to reality. However, if large quantities of run-off have the opportunity to re-infiltrate down slope (reduction factor close to one), than this procedure will largely underestimate the water availability. Apparently, water losses through run-off at a higher hierarchical level (watershed) can be less important than might be expected from measurements at more detailed levels i.e. plots. Similarly, this type of feedback mechanism can occur with regard to the nutrient balance. The highest losses in budget counting of the nutrient balance are losses through erosion and leaching (Smaling 1993). However, these losses are calculated at plot level, without taking into account the possible recovery of nutrients at higher hierarchical levels. Thus, the aggregated balance might well be less negative if spatial aspects in up-scaling are explicitly considered.

This example shows that applying a summation, averaging and aggregation strategy with increasing spatial scale can lead to inaccurate conclusions at higher hierarchical levels owing to non-linearity in variables and processes. Of course, the model presented in Chapter 7 is conceptual. In further experimental research, the exact value of the reduction factor will have to be established in relation to land and vegetation properties. Land and vegetation properties are, for example, slope, micro relief, crop density and plant pattern which to a large extent can be manipulated by agronomic practices. If the value of this reduction factor can be successfully determined, spatial up-scaling of the run-off process can be improved.

INTEGRATED UP-SCALING OF SOIL AND CROP PROCESSES

In Chapter 1, several examples from literature were given of spatial up-scaling of crop and soil processes in relation to growth factors. It was concluded that either crop processes are considered in detail, while soil processes are seen as a black box or soil processes are considered in detail and crop processes are seen as black box (Figure 1.2). This phenomenon is partly due to the feeling that one's skill base is inadequate to integrate all disciplines involved. Combination of all detailed information on crop and soil processes will lead to a monstrous process of up-scaling. In Chapter 8 a conceptual model was presented that combines plant growth with the water balance in simple transfer functions and the water balance with the nitrogen balance in one equation. With this model the effects of changes in land use are studied to show the spatial dependence of run-off and nitrogen flows at a higher hierarchical level, i.e. the watershed. The run-off of the watershed is calculated for situations in which, step by step, the area occupied by one type of land use is replaced by another. These replacement series show a domain of values, in which each value represents a specific spatial combination of land use types. These combinations of land use are characterized by the area occupied by each of the land use types and by the location in the watershed.

From this chapter conclusions can be drawn. For agro-ecosystem analysis, it is not necessary to transfer all details of both plant and processes obtained at lower hierarchical levels, to study higher hierarchical levels. Transfer functions and/or equations can be used to integrate the processes in a simple form, which can be applied at higher hierarchical levels. However, if the objective of the study would have been to calculate the precise water balance at each location, more details are probably necessary.

9.5 Some concluding remarks

Sound management of agro-ecosystems is not solely a matter of the individual farmer, nor of only field and farm level. Consequently, the object of the science of agronomy is changing drastically. Local, national and international policy levels demand guidance from the agricultural research community to manage natural resources in a sustainable way. This implies that agronomic research has to widen its scope from developing knowledge and insight at plot level to that at higher hierarchical levels such as toposequences, watersheds, river systems, continents and the entire globe. Effects of agronomic practices such as planting and seeding patterns, soil tillage, weeding, fertilizer and biocide use, have to be considered at multiple hierarchical levels. The knowledge and methodologies for this are still in their infancy.

This widening of the scope of agronomic research through agro-ecosystem analysis evokes many issues. Some of these issues are touched upon in this thesis. Firstly, system definition, i.e. the boundaries of the system, was discussed in relation to the objectives of the analysis of a specific system. It was concluded that at each particular hierarchical level, many agro-ecosystems can be defined, all depending on the objectives of the study. Such studies can follow an approach that is either more Population-Community or more Process-Functional oriented. Each of these agro-ecosystem studies are legitimate and valuable. However, an additional value is obtained by playing with the objectives, the system boundaries and the approach to follow. Secondly, sustainability of agro-ecosystems in relation to a multiple hierarchical level approach was discussed. It is concluded that to assess the sustainability of agro-ecosystems, we must constantly move between agro-ecosystems at different hierarchical levels. At the same time, we explicitly must take into account the spatial scale and spatial patterns. Thirdly, the transfer of information from lower to higher hierarchical levels, i.e. up-scaling, was discussed. It was concluded that the level of detail in information to be transferred can be reduced through the use of transfer functions developed with simulation models. These transfer functions, together with other equations that summarize information, can assist in integrated up-scaling of crop and soil processes. Also, searching for emerging properties at higher hierarchical levels can facilitate the study of agro-ecosystems at these higher hierarchical levels.

Many other issues are involved in agro-ecosystem analysis at multiple hierarchical levels, such as delimitation of temporal and spatial scales of agro-ecosystems, sustainability of these systems in relation to multiple temporal scales and down-scaling. These issues were not treated in this thesis, but are equally important, if agronomic research wants to meet the new challenges.

From the above conclusions, it might seem that any agro-ecosystem analysis is appropriate, and that agro-ecosystems might always be regarded as sustainable, depending on the temporal and spatial scale one looks at them, and that any method of up-scaling might be appropriate. However, this should not be the final impression. The conclusions underline that we must discover the natural phenomena in agro-ecosystems by "reasoned trial and error". Each of the trials may lift different corners of the veil covering nature's complex face. Several "roads lead to Rome", but only "actually following these roads to Rome" will lead to a more comprehensive understanding of the natural phenomenon under study......

Summary

The subject of this thesis

Today, agronomic research faces the triple challenge to develop knowledge and insight to manage agro-ecosystems which are inherently sustainable, to diminish the undesirable side effects and to meet the increasing demand of food of a still growing world population, without claiming all the available land. Sound management of agro-ecosystems is not solely a matter of the individual farmer, nor of only field and farm level. Local, national and international policy levels demand guidance from the agricultural research community in management of the natural resources. Thus, agronomic processes, so far studied at the level of plots, have to be studied and applied at higher hierarchical levels, i.e. larger entities such as toposequences, watersheds, river systems, continents and even the entire globe, and over longer time periods. Furthermore, agronomic research must switch from a reductionistic to a more holistic approach. Agro-ecosystem analysis at multiple hierarchical levels, the subject of this thesis, is such an approach.

In the first chapter, several issues related to this subject are introduced: agro-ecosystem analysis, hierarchical levels, scales, scaling and spatial up-scaling in agronomy. In the subsequent chapters examples are presented, that deal with agro-ecosystem analysis at hierarchical levels varying from plant to watershed. In addition, they touch upon issues of agro-ecosystem analysis at multiple hierarchical levels.

Agro-ecosystem analysis at multiple hierarchical levels

At the *hierarchical level of the plant* (and crop), the reproductive effort of annual species in Mediterranean pastures is analyzed (Chapter 2). The reproductive effort is defined as the reproductive ratio (proportion of biomass invested in the reproductive organs in relation to the total biomass produced) and as harvest index (proportion of harvestable seed in relation to the total biomass produced). It appears that the proportion of the total production invested in reproductive tissue may be as high as that of cultivated species. The variation within a species of both ratios is high, owing to environmental conditions. A model is introduced which describes the relation between the harvest index and the nutrient (mainly nitrogen) transfer from vegetative organs to the reproductive organs in the period between flowering and maturity. This model explains to a large extent the possible variation within a species.

The Chapters 3 and 4 are examples of agro-ecosystem analysis at the *hierarchical level of cropping and livestock systems*. Traditional livestock systems and

ranching in Botswana are compared in Chapter 3. These systems differ in production objectives. Ranching is solely oriented to meat production in particular for export, while traditional systems have multiple objectives i.e. meat and milk production for self-sufficiency, and provision of animal traction. The systems are compared considering one output (meat) and considering multiple outputs (meat, milk and animal traction), both on a productivity per animal and per hectare basis. It depends on the way that systems are compared, which system is more productive. Ranching is more productive if compared on a per animal basis and only meat is considered as an output. Traditional systems are more productive if compared on a per hectare basis and multiple outputs are considered.

In Chapter 4, the role of organic matter in intensified arable farming systems in the semi-arid tropical zones of West Africa is discussed. Different aspects are treated: its function as a source of nutrients, its effects on soil physical and on soil chemical properties. It is concluded that often the major effect is through increased nutrient supply, but that in combination with chemical fertilizers - particularly nitrogen - organic matter serves to counteract the negative effects of these fertilizers, such as acidification and the increased removal of nutrients other than the one applied in the chemical fertilizers. Insufficient organic material appears to be available to realize the required production increase and to prevent the negative effects of nitrogen fertilizers. However, application of chemical fertilizer alone can lead to sustainable production systems, provided export and losses of all nutrient elements are sufficiently compensated and acidification is avoided by using the correct type of nitrogen fertilizer, possibly in combination with liming.

Next, two examples are given to *transfer information of lower to higher hierarchical levels*. Chapter 5 describes the development of transfer functions, which are developed at the hierarchical level of crop/vegetation and applied at the hierarchical level of physiographic units. Transfer functions use easily measurable indicators, such as texture of the soil, as independent variables in regression analysis. In order to construct transfer functions many data have to be obtained to carry out the regression analysis. These data are normally obtained in the field, but in this case have been generated with a process-simulation model, which has been fully validated. The transfer functions presented can be used to calculate maximum depth of soil wetting and water losses from the rooting zone or shallow soils, using water content at pF2.5 and average annual infiltration as dependent variables. In comparison to simple rainfall-biomass relations, the application of transfer functions allow more accuracy in estimating biomass production of physio-graphic units.

In Chapter 6 information on evapotranspiration, obtained at the lower hierarchical level (leaf/plant), is extrapolated to higher levels (canopies), showing emerging properties. When moving to this higher hierarchical level the time and spatial scales increase from day to year and leaf to canopy, respectively. Direct comparison of literature data on evapotranspiration of different crops is hardly possible, since differences in soils and climate make data incomparable. Literature data are presented on crop parameters and environmental conditions, that determine transpiration for four crops (oil palm, cocoa, maize and rice), and on evaporation.

Transpiration at leaf scale and soil evaporation as well as evaporation of intercepted rainfall have been computed using these data and scaled up to canopy level. Thus, daily and annual evapotranspiration of the four crops are quantified under identical environmental conditions. Variation among crops in transpiration at the spatial scale of leaves is levelled out in scaling up to the canopy scale. Differences in annual evapotranspiration between perennial and annual crops are mainly due to the fact that perennial crops transpire during the dry season, although at low rates, but still considerably higher than evaporation rates of bare and dry soils. Apparently, the degree of soil cover with vegetation in space and in time is of major importance to evaluate differences in annual evapotranspiration of canopies.

The following two chapters cover the *hierarchical level of watersheds*. They show the effects on system behaviour if the spatial processes of water and nitrogen flows are explicitly taken into account. Chapter 7 considers the possible effect of up-scaling in space of the process of infiltration and run-off to the level of a watershed. A conceptual water balance model is presented, mimicking the scale dependency of the run-off coefficient of watersheds by the introduction of a scale dependent variable (REDF). By using the transfer functions developed in Chapter 5, the water balance is kept simple. Notwithstanding the inherent impossibility to validate this conceptual model, the same kind of scale dependency in run-off coefficients is found as in those obtained from lymnographic data of watersheds in West Africa. The scale dependent variable REDF has to be established in field experiments, where run-off is measured at two or three spatial scales in relation to soil type, vegetation and agronomic practices.

Chapter 8 elaborates on consequences of the scale dependency of run-off if land use changes. An equation to calculate the annual nitrogen balance is included in the water balance model of Chapter 7. This equation uses the calculated infiltration from the water balance as input variable and differentiates between nitrogen uptake efficiency of annual and perennial vegetation. The run-off coefficients and the annual nitrogen balances of a representative watershed in West Africa are calculated for different land use scenario's, replacing perennial by annual vegetation and varying the spatial pattern of these vegetation types. The model runs simulating these different scenario's illustrate that the effects of changes in land use on water and nitrogen flows are not additive. The relationships between the run-off coefficient and the annual nitrogen balance of the watershed on the one hand and the proportion of the two types of land use on the other, cannot be described by a single line. A solution domain exists with each value in this domain representing a specific combination of the proportion of the two types of land use and its spatial pattern in the watershed.

Issues of agro-ecosystem analysis

In Chapter 9, several issues of agro-ecosystems analysis, emerged in the Chapters 2-8, are discussed. These issues are: (1) the interdependence between objectives of study and agro-ecosystem boundaries, (2) sustainability in relation to hierarchical levels, and (3) up-scaling. The latter is discussed in relation to: (i) transfer functions to transfer information to higher hierarchical levels, (ii) emerging properties, (iii) spatial up-scaling of the water balance and (iv) integrated up-scaling of soil and crop processes.

The issue of interdependence between objectives of study and agro-ecosystem boundaries is touched upon in the Chapters 2, 3 and 4. In Chapter 2, three objectives of study are considered resulting in three ways of delimitating the system. The first objective is to study the reproductive effort in relation to survival of annual species. Then, the reproductive ratio in relation to the harvest index is used. The second objective relates to the agricultural efficiency to produce seed, with the harvest index as the appropriate measure. Both approaches implicitly take the genetic variation as the main determinant factor to explain variation between species, and are as such examples of the Population-Community approach. The third objective aims at explaining the variability in reproductive effort within a species. Then, environmental conditions are included in the system analysis, by introducing the relation between these conditions and the transfer of nutrients from vegetative organs to reproductive organs during the period between flowering and maturation. The latter is an example of the Process-Functional approach.

In Chapter 3, the two livestock systems are compared in several ways. These ways indicate different delimitations of the systems. A comparison is made including only one output (meat) and two components (cows and calves). The objective of study is to compare productivity for export. In a second comparison more outputs are considered (meat, milk and draught power) and more components (all the classes in a herd). In that case, the objective is to compare productivity for selfsufficiency of the rural population. Finally, the two ways to compare the systems are applied on a per animal and a per hectare basis.

Comparison on a per animal basis is appropriate if land is abundantly available, whereas comparison on a per hectare basis is appropriate if land is scarce.

In Chapter 4, the viability of an arable farming system in West Africa, based on manure to sustain soil fertility is tested. This farming system seems to be viable if it is regarded in isolation. This is one way to delimitate the system. However, if potential manure production is considered in relation to livestock and rangelands needed to produce that manure, i.e. another way to delimitate the system, the conclusion about viability alters.

All these examples show, that system delimitation changes with the objectives of the study and that the objectives of study determine the approach to follow, whether it be a Process-Functional or Population-Community approach. Each way of delimitating the system is legitimate if in accordance with the objectives of study. However, additional insight is gained by looking at agro-ecosystems from different points of view.

The issue of sustainability in relation to multiple hierarchical levels is touched upon in the Chapters 4, 7 and 8.

Chapter 4 illustrates that, to assess the ecological sustainability of an agro-ecosystem (the arable farming system in isolation), the embedding of this system in the organizational structure at higher hierarchical levels (combination of arable systems and livestock systems) must be considered.

On a completely different subject, the same view is illustrated in the Chapters 7 and 8. The runs with a conceptual model describing water and nitrogen balances, show that the run-off and nitrogen losses at a low hierarchical level (plots of 1 m^2) are higher than at higher hierarchical levels (slopes and entire watersheds). If run-off is considered as the driving force for erosion, sustainability at the plot level may be less than at higher hierarchical levels.

The spatial pattern of isolated units (rangeland and arable land in Chapter 4 and perennial and annual vegetation in Chapter 8) is important as well in judging the sustainability of agro-ecosystems.

The examples in the Chapters 4, 7 and 8 illustrate that the assessment of the sustainability of agro-ecosystems is not possible, without considering multiple hierarchical levels. We constantly have to move between agro-ecosystems at different hierarchical levels. At the same time, we explicitly have to take into account the spatial scale and spatial patterns.

Different aspects of up-scaling are touched upon in the Chapters 5, 6, 7 and 8. The method to develop transfer functions with the use of a simulation model (Chapter 5) shows, that detailed information at the hierarchical level of vegetation can be summarized to obtain a better description of system behaviour at higher hierarchical levels. The process of spatial and temporal up-scaling of evapotranspiration described in Chapter 6 shows, that other properties become determinant at higher hierarchical levels. Thus, to analyze an agro-ecosystem at higher hierarchical levels involves the search for those properties which emerge at these higher levels. The conceptual model presented in Chapter 7 shows, that applying a summation, averaging and aggregation strategy in up-scaling can lead to inaccurate conclusions at higher hierarchical levels if variables and processes, such as run-off, are non-linear. Finally, it is shown that it is not necessary to transfer all details of both plant and soil processes, which are obtained at lower hierarchical levels, to study higher hierarchical levels (Chapter 8). Transfer functions and/or equations can be used to integrate the processes in a simple form, which can be applied at higher hierarchical levels. Then, crop and soil processes can be integrated in up-scaling.

Concluding remarks

It is concluded that at each hierarchical level the objectives of study determine the definition of the agro-ecosystem. Therefore several choices can be made resulting in different agro-ecosystem studies. Each of these agro-ecosystem studies are legitimate and valuable. However, additional insight is obtained by playing with the objectives and the system boundaries. Secondly, it is concluded that we must move constantly between agro-ecosystems at different hierarchical levels to assess sustainability of agro-ecosystems. At the same time, we must take into account explicitly the spatial scale and spatial patterns. Thirdly, in the transfer of information from lower to higher hierarchical levels the level of detail can be reduced through the use of transfer functions, which are developed with simulation models. Such functions, in combination with other functions that summarize information, can assist in integrated up-scaling of crop and soil processes. Finally, searching for emerging properties at higher hierarchical levels can facilitate the analysis of agro-ecosystems at these higher hierarchical levels.

Samenvatting

Het onderwerp van dit proefschrift

Het huidige agronomische onderzoek staat voor een drievoudige uitdaging. Ten eerste dient kennis en inzicht te worden ontwikkeld die leiden tot beheer van agro-ecosystemen met een duurzaam karakter. Ten tweede dienen daarbij de negatieve, ongewenste effecten van deze systemen te worden geminimaliseerd. Ten derde moeten deze systemen voldoen aan de nog steeds groeiende vraag aan voedsel, zonder dat daarbij al het beschikbare land wordt gebruikt. Het beheer van agro-ecosystemen is niet meer alleen een vraagstuk van de individuele boer, noch van alleen het niveau van een akker of een boerderij. Ook lokale, nationale en internationale politieke organisaties vragen steeds vaker de gemeenschap van agronomen om advies in het beheer van onze natuurlijke hulpbronnen. Dit betekent, dat agronomische processen, tot nu toe vaak slechts bestudeerd op het plot niveau, moeten worden bestudeerd en toegepast op hogere hiërarchische niveau's. Kennis en inzicht dienen te worden verkregen over grotere eenheden zoals toposequenties, stroomgebieden, rivier systemen, continenten en zelfs de aarde in zijn geheel. Daarbij dient ook nog een langere tijd-schaal in beschouwing te worden genomen. Verder dient het agronomische onderzoek zijn aanpak te veranderen van een reductionistische naar een holistische. De agro-ecosysteem analyse op meerdere hiërarchische niveau's, het onderwerp van dit proefschrift, is een dergelijke aanpak.

In het eerste hoofdstuk worden verschillende aspecten in relatie tot dit onderwerp geïntroduceerd: agro-ecosysteem analyse, hiërarchische niveau's, schalen, op- en neerschalen en het ruimtelijk opschalen in de agronomie. In de volgende hoofdstukken worden voorbeelden gepresenteerd, die te maken hebben met de agro-ecosysteem analyse op hiërarchische niveau's, die variëren van plant tot stroomgebied. Verschillende aspecten van deze agro-ecosysteem analyse worden in deze voorbeelden aangestipt.

Agro-ecosysteem analyse op verschillende hiërarchische niveau's

Op het *hiërarchische niveau van de plant* (en het gewas) is de investering in de reproduktieve organen geanalyseerd van eenjarige soorten, die voorkomen in graslanden van het Middellandse Zee gebied (Hoofdstuk 2). Deze investering is op twee wijzen gedefinieerd. Ten eerste als de verhouding tussen de biomassa van de reproduktieve organen en de geproduceerde biomassa van de totale plant. Ten tweede als de verhouding tussen de hoeveelheid zaad en de geproduceerde biomassa van de totale plant ('harvest index'). Het blijkt dat het deel, dat deze in het wild voorkomende soorten in hun reproduktieve organen investeren, net zo hoog kan zijn als bij landbouwgewassen. De variatie in beide verhoudingen is groot binnen een soort als gevolg van omgevingsfactoren. Een model is gepresenteerd waarin de relatie wordt beschreven tussen enerzijds de verhouding van zaad/totale biomassa en anderzijds de allocatie van nutriënten (hoofdzakelijk stikstof) van de vegetatieve organen naar de reproduktie organen tijdens de periode van bloei tot afrijpen. Dit model verklaart voor een groot gedeelte de mogelijke variatie binnen een soort.

De Hoofdstukken 3 en 4 zijn voorbeelden van agro-ecosysteem analyses op het *hiërarchische niveau van gewassenteelt en veeteelt systemen.* In Hoofdstuk 3 zijn traditionele veeteelt systemen vergeleken met modernere (zogenaamde 'ranching') systemen. Deze systemen verschillen in hun produktie doelstellingen. In het 'ranching' systeem wordt vooral vlees geproduceerd voor de export, terwijl de traditionele systemen meerdere doelstellingen kennen, met name de produktie van melk en vlees voor eigen consumptie en het leveren van trekkracht. De produktie van beide systemen, uitgedrukt in produktie per dier en per hectare, is vergeleken wanneer slechts één produktie doel (vlees) en wanneer meerdere doelen (vlees, melk en trekkracht) in beschouwing worden genomen. Welk systeem produktiever is hangt af van de wijze waarop de vergelijking plaats vindt. 'Ranching' is produktiever wanneer de vergelijking plaats vindt op basis van de produktiviteit per dier en wanneer slechts één produktie doel (vlees) wordt meegenomen. Traditionele systemen zijn produktiever wanneer de vergelijking plaats vindt op basis van produktiviteit per hectare en wanneer alle produktie doelen worden meegenomen.

In Hoofdstuk 4 is de rol van organisch materiaal in geïntensiveerde akkerbouw systemen in de semi-aride tropen van West Afrika besproken. Er zijn verschillende aspecten behandeld: de functie van organisch materiaal als bron van nutriënten en de effecten ervan op de fysische en chemische eigenschappen van de bodem. Er is geconcludeerd dat toevoeging van organisch materiaal aan de bodem met name de rol vervult van toediening van nutriënten voor plantengroei. In combinatie met kunstmest (in het bijzonder de stikstof houdende), kan het organische materiaal de negatieve effecten van kunstmest tegen gaan. Deze negatieve effecten kunnen zijn: verzuring van de grond en het ontstaan van tekorten aan nutriënten die niet via kunstmest worden toegediend en juist bij verhoogde produktie sneller worden uitgeput. Het blijkt dat er in de West Afrikaanse systemen onvoldoende organische materiaal aanwezig is om de gewenste produktie verhoging te bewerkstelligen en de negatieve effecten van kunstmest tegen te gaan. Gebruik van alleen kunstmest zou toch tot duurzame akkerbouw systemen kunnen leiden, maar dan zal meer gelet moeten worden op het type kunstmest (juiste samenstelling en niet verzurend), mogelijk in combinatie met bekalken om de zuurgraad in de hand te houden.

Vervolgens zijn twee voorbeelden gegeven hoe *informatie van lagere naar hogere hiërarchische niveau's* kan worden overgebracht. Hoofdstuk 5 beschrijft transfer functies, die op het hiërarchische niveau van vegetatie/gewas zijn ontwikkeld en worden toegepast op het hiërarchische niveau van fysiografische eenheden. Transfer functies maken gebruik van gemakkelijk meetbare indicatoren in regressie analyses, zoals de textuur van de grond, als onafhankelijke variabelen en moeilijk te meten indicatoren, zoals de pF-waarden van een grond, als afhankelijke variabelen. Voor het opstellen van deze functies met behulp van regressie analyse zijn veel gegevens nodig. Normaal worden deze gegevens in het veld verkregen. In dit geval zijn ze gegenereerd met behulp van een simulatie model dat op voorhand voldoende is gevalideerd. De ontwikkelde transfer functies kunnen worden gebruikt om de diepte van bevochtigen van een bodem en de percolatie van water uit de bewortelingszone te schatten, waarbij het water gehalte bij veldcapaciteit en de gemiddelde jaarlijkse regenval de onafhankelijke variabelen zijn. In vergelijking tot simpele empirische relaties tussen gemiddelde jaarlijkse regenval en biomassa produktie, staat de toepassing van deze transfer functies een meer nauwkeurige schatting toe van de biomassa produktie per physiografische eenheid.

In Hoofdstuk 6, is de informatie, die op het lagere hiërarchische niveau van blad/plant is verkregen, geëxtrapoleerd naar het hogere hiërarchische niveau van gewassen en vegetatie. Daarbij wordt duidelijk dat op dit hogere niveau nieuwe eigenschappen van het systeem ontstaan. In dit proces van opschalen worden de tijd- en ruimte-schaal respectievelijk veranderd van dag tot jaar en van enkelvoudig blad tot gewas/vegetatie. Directe vergelijking van evapotranspiratie gegevens uit de literatuur van verschillende gewassen is nauwelijks mogelijk door de verschillen in bodem en klimaat. Literatuur gegevens van gewas parameters en omgevingsfactoren, die de transpiratie van vier gewassen (oliepalm, cacao, maïs en rijst) bepalen en gegevens die de evaporatie bepalen, zijn verzameld. Deze zijn vervolgens gebruikt om de transpiratie van een blad in een dag, de verdamping van de bodem en de verdamping van water op het blad oppervlak te berekenen. Vervolgens zijn deze gegevens gebruikt voor het opschalen naar een gewas. Dus, de dagelijkse en jaarlijkse evapotranspiratie van de vier gewassen zijn gekwantificeerd bij gelijk veronderstelde condities van klimaat en bodem. De variatie tussen gewassen in transpiratie per dag, die op het niveau van een blad bestaan, verdwijnen voor een groot gedeelte, wanneer wordt opgeschaald naar gewas. De verschillen in jaarlijkse evapotranspiratie tussen eenjarige en overblijvende gewassen worden hoofdzakelijk veroorzaakt doordat overblijvende gewassen ook in het droge seizoen transpireren. Hoewel de transpiratie in die periode laag is, is de onttrekking van water uit de bodem hoger dan in de situatie waarbij de bodem kaal is (eenjarig gewas is geoogst) en de bovenlaag van de bodem is uitgedroogd. Blijkbaar is op dit hiërarchische niveau de mate van bodembedekking in de tijd en de ruimte van meer belang voor het bepalen van verschillen in de jaarlijkse evapotranspiratie van gewas dan de op het lagere (blad) niveau voorkomende processen.

Het onderwerp van de volgende twee Hoofdstukken speelt zich af op het *hiërarchische niveau van een (klein) stroomgebied.* Deze Hoofdstukken laten zien dat de effecten op het gedrag van een systeem veranderen wanneer expliciet rekening wordt gehouden met de ruimtelijke aspecten van water en stikstof stromen. In Hoofdstuk 7 is het effect beschreven van het ruimtelijke opschalen van het proces van infiltratie en afstroming van regenwater van het niveau van een plot tot het niveau van een stroomgebied. Een conceptueel model voor de water balans werd in dit Hoofdstuk gepresenteerd, dat de schaal afhankelijkheid van de afstromingscoëfficiënt van stroomgebieden nabootst door de introductie van een schaal afhankelijke variabele (REDF). Het model is simpel gehouden door gebruik te maken van de transfer functies uit Hoofdstuk 5. Het is vrijwel onmogelijk dit conceptuele model te valideren. Desondanks, met dit model werd een zelfde soort schaal afhankelijkheid van de afstromingscoëfficiënt gevonden als bij gebruik van lymnografische gegevens van kleine stroomgebieden in West Afrika. De schaal afhankelijke variabele REDF moet in veld experimenten worden vastgesteld. In deze experimenten zal de afstroming op meerdere plot grootten moeten worden gemeten, en in relatie tot bodem type, vegetatie en teelt maatregelen.

Hoofdstuk 8 werkt de gevolgen verder uit van deze schaal afhankelijke afstromingscoëfficiënt, wanneer het land gebruik in een stroomgebied verandert. In het model is een stikstof balans, in de vorm van een simpele vergelijking, toegevoegd. Deze vergelijking gebruikt de in de water balans berekende infiltratie, en maakt een onderscheid in efficiëntie van stikstof opname bij eenjarige en overblijvende vegetatie. De afstromingscoëfficiënt en de stikstof balans per jaar zijn berekend voor een representatief stroomgebied uit West Afrika, waarbij het land gebruik is veranderd door overblijvende vegetatie te vervangen door een eenjarige vegetatie, daarbij verschillende ruimtelijk patronen van beide vegetatie typen in het stroomgebied in beschouwing nemend. De resultaten van de model berekeningen illustreren dat veranderingen van het land gebruik in een stroomgebied geen simpele optelsom is van de afzonderlijke delen. De relatie tussen de afstromingscoëfficiënt en de jaarlijkse stikstof balans aan de ene kant en de verhouding van de twee typen land gebruik aan de andere kant, kan niet door een rechte lijn worden beschreven. Er bestaat een domein van oplossingen, waarbij elke waarde binnen dit domein staat voor een specifieke combinatie van de verhouding van de twee typen land gebruik en het ruimtelijke patroon binnen het stroomgebied.

Onderwerpen van agro-systeem analyse

Verschillende onderwerpen in relatie tot de analyse van agro-ecosystemen, die in de Hoofdstukken 2 tot en met 8 aan de orde zijn gekomen, zijn in Hoofdstuk 9 bediscussieerd. Deze onderwerpen zijn: (1) de onderlinge afhankelijkheid van doelstellingen van studie en de grenzen van agro-ecosystemen, (2) duurzaamheid in relatie tot hiërarchische niveau's, en (3) het opschalen. Het laatste onderwerp is besproken in relatie tot: (i) transfer functies voor de overdracht van informatie naar hogere hiërarchische niveau's, (ii) systeem eigenschappen die op hogere niveau's tevoorschijn komen, (iii) het ruimtelijk opschalen van de water balans, en (iv) het geïntegreerde opschalen van bodem en gewas processen.

Het onderwerp van onderlinge afhankelijkheid tussen doelstellingen van een studie en de grenzen van het te bestuderen systeem, is aan de orde gekomen in de Hoofdstukken 2, 3 en 4. In Hoofdstuk 2, hebben drie verschillende doelstellingen van studie geleid tot drie verschillend begrensde systemen. De eerste doelstelling is de studie van de relatie tussen de investering in biomassa van de reproduktieve organen door eenjarigen en de overlevingsstrategie van deze soorten. Daarvoor is de verhouding tussen de biomassa geinvesteerd in de reproductieve organen en de biomassa van de totale plant gebruikt als maat, in relatie tot de verhouding tussen het geproduceerde zaad en de biomassa van de totale plant. De tweede doelstelling van studie is de bepaling van de landbouwkundige efficiëntie van soorten om zaad te produceren. Daarbij wordt de verhouding tussen het geproduceerde zaad en de biomassa van de totale plant gebruikt. Beide benaderingen gaan impliciet uit van de gedachte, dat de genetische variatie de belangrijkste factor is in de verklaring van het voorkomen van grote variatie tussen soorten. Deze benaderingen zijn voorbeelden van de in de ecologie bekende Populatie-Gemeenschap aanpak. De derde doelstelling wil de variatie binnen een soort verklaren in de verhouding tussen de biomassa geïnvesteerd in de reproductieve organen en de biomassa van de totale plant. Daarvoor werden groei beperkende factoren in de systeem analyse betrokken. Dit is gedaan door in een model de relatie te beschrijven tussen deze factoren enerzijds en de mate van allocatie van nutriënten van vegetatieve naar reproductieve organen tijdens de periode van bloei tot afrijpen anderzijds. Deze benadering is een voorbeeld van de in de ecologie bekende Proces-Functionele aanpak.

In Hoofdstuk 3 zijn twee veeteelt systemen op verschillende wijzen met elkaar vergeleken. De wijzen van vergelijken geven een verschillende begrenzing van de systemen aan. Eén wijze van vergelijking maakt gebruik van slechts één opbrengst variabele (vlees) en twee systeem componenten (koeien met hun kalveren). De doelstelling is dan om de produktiviteit van vlees voor export in beide systemen met elkaar te vergelijken. In de tweede vergelijking worden meerdere opbrengst variabelen (vlees, melk en trekkracht) en meer systeem componenten (alle dier-klassen in een kudde) in de analyse betrokken. In dat geval is het beoordelen van de produktie voor zelfvoorziening van de rurale bevolking de doelstelling. Tenslotte, zijn beide wijzen van vergelijken uitgevoerd op basis van een berekende produktie uitgedrukt per dier en uitgedrukt per hectare. De vergelijking waarbij de produktie is uitgedrukt per dier, is geschikt wanneer er geen gebrek is aan land, terwijl de produktie moet worden uitgedrukt per hectare wanneer er een gebrek is aan land.

In Hoofdstuk 4, is de levensvatbaarheid getest van akkerbouw systemen in West Afrika, die gebruik maken van organische mest om de bodemvruchtbaarheid op peil te houden. Wanneer deze systemen geisoleerd bekeken worden, lijkt dat ook mogelijk te zijn. Dit is één manier om een systeem te begrenzen. Indien echter het potentieel aan mestproduktie in beschouwing wordt genomen in relatie tot het aantal stuks vee en de graslanden die voor die produktie nodig zijn, - dus een verandering van de systeem grenzen -, dan verandert de konklusie.

Alle gepresenteerde voorbeelden tonen aan dat de begrenzing van een systeem verandert met veranderingen in de doelstellingen van de studie. De doelstellingen van de studie bepalen ook de aanpak die moet worden gevolgd, de Proces-Functionele dan wel de Populatie-Gemeenschap benadering. Ieder van deze wijzen van begrenzing van systemen is legitiem, zolang deze in overeenstemming is met de doelstelling van de studie. Er wordt echter meer inzicht in het functioneren van agro-ecosystemen verkregen, wanneer meerdere wijzen van systeem begrenzing worden gebruikt.

Het onderwerp van duurzaamheid in relatie tot meerdere hiërarchische niveau's komt in de Hoofdstukken 4, 7 en 8 aan de orde.

Hoofdstuk 4 illustreert dat, - om de ecologische duurzaamheid van een agro-ecosysteem (het akkerbouw systeem in isolatie) te kunnen beoordelen -, de plaats van dit systeem in de organisatie struktuur op hogere hiërarchische niveau's moet worden bekeken.

Het zelfde gezichtspunt, maar dan aan de hand van een volledig ander onderwerp, wordt in de Hoofdstukken 7 en 8 geillustreerd. De resultaten van het conceptuele model, dat de water en stikstof balans beschrijft, tonen aan, dat de afstroming en de verliezen aan stikstof op lagere hiërarchische niveau's (plots van 1 m^2) hoger zijn dan op hogere hiërarchische niveau's (hellingen en een stroomgebied). Wanneer de afstroming van water als de sturende kracht voor erosie wordt beschouwd, betekent dit dat de duurzaamheid op het plot niveau minder is dan op hogere hiërarchische niveau's.

Het ruimtelijke patroon van de geïsoleerde eenheden (graslanden en akkers in Hoofdstuk 4 en overblijvende en eenjarige vegetatie in Hoofdstuk 8) is belangrijk in de beoordeling van de duurzaamheid van agro-ecosystemen.

De voorbeelden in de Hoofdstukken 4, 7 en 8 illustreren dat het niet mogelijk is de duurzaamheid van agro-ecosystemen te beoordelen, wanneer niet meerdere hiërarchische niveau's in de analyse worden betrokken. We moeten ons dus steeds tussen de agro-ecosystemen op verschillende hiërarchische niveau's heen en weer bewegen. Tegelijkertijd moeten we expliciet rekening houden met de ruimtelijke schaal en het ruimtelijke patroon.

Verschillende aspekten van het opschalen worden aangeroerd in de Hoofdstukken 5, 6, 7 en 8. De methode waarmee transfer functies zijn ontwikkeld door gebruik te maken van een simulatie model (Hoofdstuk 5) toont aan, dat gedetailleerde informatie op het hiërarchische niveau van vegetatie kan worden samengevat om een betere beschrijving te verkrijgen van het gedrag van een systeem op een hoger hiërarchisch niveau. Het proces van het ruimtelijk opschalen en het opschalen in de tijd van de evapotranspiratie (Hoofdstuk 6) illustreert, dat andere eigenschappen van een systeem belangrijk worden op een hoger hiërarchisch niveau. Dus, het analyseren van agro-ecosystemen op hogere hiërarchische niveau's houdt in, dat naar de op dat niveau verschijnende eigenschappen moet worden gezocht. Het in Hoofdstuk 7 gepresenteerde conceptuele model geeft aan, dat het toepassen van een strategie van optellen, middelen en aggregeren in het proces van opschalen kan leiden tot onjuiste conclusies op hogere hiërarchische niveau's als variabelen en processen bij dat opschalen niet-lineair veranderen. Tenslotte wordt aangetoond, dat het niet noodzakelijk is om alle details van bodemkundige en plantaardige processen, die op een laag hiërarchisch niveau zijn verkregen, moeten worden meegenomen bij de overdracht van informatie naar een hoger hiërarchisch niveau (Hoofdstuk 8). Transfer functies en/of vergelijkingen kunnen worden gebruikt om de processen te integreren tot een simpele vorm, en kunnen vervolgens op hogere hiërarchische niveau's worden toegepast. Op die manier kunnen gewas en bodemkundige processen worden geïntegreerd in het opschalen.

Afsluitende opmerkingen

Er is geconcludeerd dat op ieder hiërarchisch niveau de begrenzing van een agro-ecosysteem wordt bepaald door de doelstelling van de studie. Daardoor kunnen verschillende keuzes worden gemaakt, resulterend in verschillende agro-ecosysteem studies. Ieder van deze studies is legitiem en waardevol. Echter, er wordt meer inzicht verkregen wanneer met zowel de systeem grenzen als de doelstellingen van studie wordt gespeeld. Ten tweede wordt geconcludeerd, dat we steeds heen en weer moeten bewegen tussen de agro-ecosystemen op verschillende hiërarchische niveau's, willen we de duurzaamheid van agro-ecosystemen juist kunnen bepalen. Tegelijkertijd moeten we expliciet rekening houden met de ruimtelijke schaal en de ruimtelijke patronen. Ten derde kan de mate van detail in de overdracht van informatie van lagere naar hogere hiërarchische niveau's sterk worden gereduceerd door gebruik te maken van transfer functies, die met behulp van simulatie modellen zijn ontwikkeld. Deze functies, in combinatie met andere functies die informatie kunnen samenvatten, helpen bij het geïntegreerd opschalen van plantaardige en bodemkundige processen. Tenslotte kan het zoeken naar eigenschappen, die op hogere hiërarchische niveau's verschijnen, een grote dienst bewijzen bij de analyse van agro-ecosystemen op deze hogere niveau's.

Curriculum vitae

Born on the 24th of March 1950 in Kabandjahé, a small village near the Toba-lake on Sumatra (Indonesia), Nicolaas de Ridder receives his HAVO-diploma in 1969 and subsequently joins the army to do his military service. He starts his study MO-Biology at the University of Utrecht in 1971. However, in 1976 he switches to the "doctoraal" of Mathematical and Physical Sciences (Biology), after passing the "Colloquim Doctum". In 1979, he graduates (cum laude) in Botanical Oecophysiology with Soil Science, Biology and Society, and Pedagogic and Didactic of Biology as additional subjects. In 1978 he does field work for his thesis on Botanical Oecophysiology in Mali in the project "Production Primaire au Sahel", in short known as the PPS-project, a joint project of the former department of "Theoretische Teeltkunde" of the Agricultural University of Wageningen, the former Centre for Agro-Biological Research (CABO) and the Institut d'Economie Rural of Mali.

The Hebrew University in Jerusalem is his first employer in 1979. Attached to the Migda/Gilat Research Station near Beersheva, he works as a scientist on the relationship between quantity and quality of natural pastures and the productivity of sheep.

The Agricultural University of Wageningen, at that time still called "Landbouw Hogeschool", is his second employer. From 1980 to November 1983, he is attached to the department of Theoretical Production Ecology, then called "Theoretische Teeltkunde". During this period, he transfers research results of the above mentioned PPS-project to young engineers in the Sahelian countries. For that purpose he develops a course, entitled "Productivity of Sahelian rangelands", and runs this course four times in Mali. In total about 80 engineers coming from all Sahelian countries have followed this course.

From November 1983 to June 1986, he is posted at the headquarters of the International Livestock Centre for Africa (ILCA), a CGIAR institute in Addis Abeba (Ethiopia). He is head the Range Science Unit with the task to stimulate, coordinate and execute research on the topic of pasture systems in sub-Saharan Africa. The development of early warning systems based on satellite images is one of the research issues.

Subsequently, he is an employee of the former Centre for Agro-Biological Research (CABO). Attached as a scientist to the department of Agro-Ecosystems Analysis, he contributes to the development and writing of a manual to evaluate the productivity of pastures in Sahelian countries and to the acquisition of research projects.

The University of Groningen is his next employer in 1990 and 1991. In the context of the project "Ecologie et Ecophysiologie" he is attached as a lecturer and scientist to the University of Ouagadougou in Burkina Faso. During these years he is responsible for the construction and the equipment of a laboratory for ecology. He trains a laboratory worker for the analysis of plant and soil samples, runs several courses and participates in the training of MSc students.

Since May 1992 he is employed by the Agricultural University of Wageningen. As a lecturer at the department of Agronomy, he develops and teaches the course "Quantitative Analysis of Agro-Ecosystems at Higher Integration Levels", better known as QUASI, in close cooperation with a colleague of the department of Theoretical Production Ecology, Martin van Ittersum. Furthermore, he trains students in research. At present, he does research on the topic "Influences of agronomic practices on water and nutrient flows at different hierarchical levels" as part of the VF-program "Sustainable land use in the tropics".

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