Introduction to potato production

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Contents

Foreword

The contents of this book are similar to the syllabi used in the International Potato Course, mainly intended for students from tropical and sub-tropical countries, which is organized annually by the International Agricultural Centre at Wageningen. Soon after the start of the Course in 1972 wider interest was expressed in these syllabi. Therefore it was decided to bring them together in a book in a revised edition.

After 9 years the first edition is out of print. In this second edition some new chapters have been added, some chapters have been drastically revised and in various other chapters only a few minor alterations have been introduced. However, the purpose of this book has not changed. It is still the intention of the authors that the book should help the reader to discover the most important factors which influence the production and development of the potato crop and to comprehend their interaction. For it is only with an adequate understanding of and insight into the crop that reliable proposals for crop improvement can be made. Review literature has been restricted as much as possible to prevent the reader from being unable see the wood for the trees. If he or she needs more information about literature on a specific topic, the existing potato handbooks should be consulted. We believe that our publication does not compete with them, but will serve as a supplement to these handbooks and to existing practical guides for potato production. At least that was our intention, although we have to admit that some chapters more closely resemble the syllabus than others with the consequence that some topics are discussed on more than one place. Nevertheless, we hope that this revised publication will also find its niche.

1 The potato throughout the world, with special reference to the tropics and sub-tropics

1.1 Distribution

After maize the potato is the most widely distributed crop in the world. It is grown in about 140 countries, more than 100 of which are located in the tropical and sub-tropical zones. However, most production is still concentrated in the temperate regions in the industrialized countries. Almost a third of the crop is produced in developing countries, mainly the countries in Asia (table 1).

The potato originates from the mountains of South America where it has been an important food crop for a long time. In the 16th century the potato was introduced to Europe as a curiosity. Gradually it became a food crop, especially when varieties were selected which were adapted to the long day conditions. In the 18th and 19th centuries it was already an important food crop, especially for the poor in various countries in Europe. In North America too, where immigrants from Europe had taken tubers along with them, it found its place among other food crops. During the 19th century the potato was introduced to several tropical and sub-tropical countries, mainly by colonists from Europe.

In more recent years the potato has spread to many countries with warmer and drier climates and it has become important in regions such as North Africa, the plains of India, Bangladesh and Pakistan, Central America, Chile, Argentina, Uruguay and the coastal plains of Peru.

1.2 Recent developments in production

During the last decade the total area of the world cropped with potatoes has decreased slightly. The area decreased in Western Europe, but remained fairly stable

Table 1. Potato production throughout the world (FAO Production Yearbook, 1986).

	Number of countries	Production (10^6 tonnes)
World	129	309
Countries with market economies		
industrialized countries	27	74
developing countries	90	38
Countries with centrally planned economies		
Europe (incl. USSR)	8	150
Asia	4	47

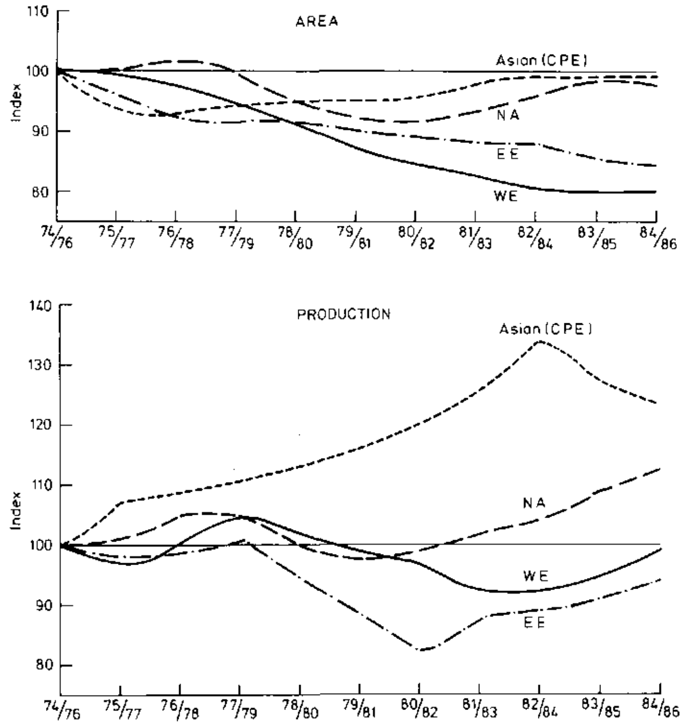

Fig. 1. Land area in potatoes and potato production in countries in the Northern Hemisphere with market economies and in centrally planned economies (CPE) 1974/76–1984/86 (3-year moving averages; 1974/76 = 100; based on data from FAO Production Yearbooks). N.A. = North America; W.E. = Western Europe; E.E. = Eastern Europe (CPE).

in Asian countries with centrally planned economies (CPE) (fig. 1) and increased considerably in the developing countries with the exception of Latin America (fig. 2).

During this period total production in Europe and North America did not change much (fig. 1), but increased considerably in the developing countries (figures 1 and 2). The greatest increase in production occurred in Asia and Africa. Total production almost doubled in the Asian countries with market economies. This increase in production is partly due to increases in yield and area (e.g.in Asia) or only due to an increase in yield (e.g. in Europe, North America and Latin America) or only due to an increase in area (e.g. in Africa).

1.3 Utilization

Less than half of the total potato production is used for human consumption (table 2). In 1982 almost a third was still used for stock feed, mainly in Eastern Europe (Poland and USSR). Potatoes for starch production are concentrated in the Netherlands, Eastern Europe and Japan. The use of potatoes for alcohol production is negligible.

The large amount of potatoes used for fodder is also demonstrated by the big

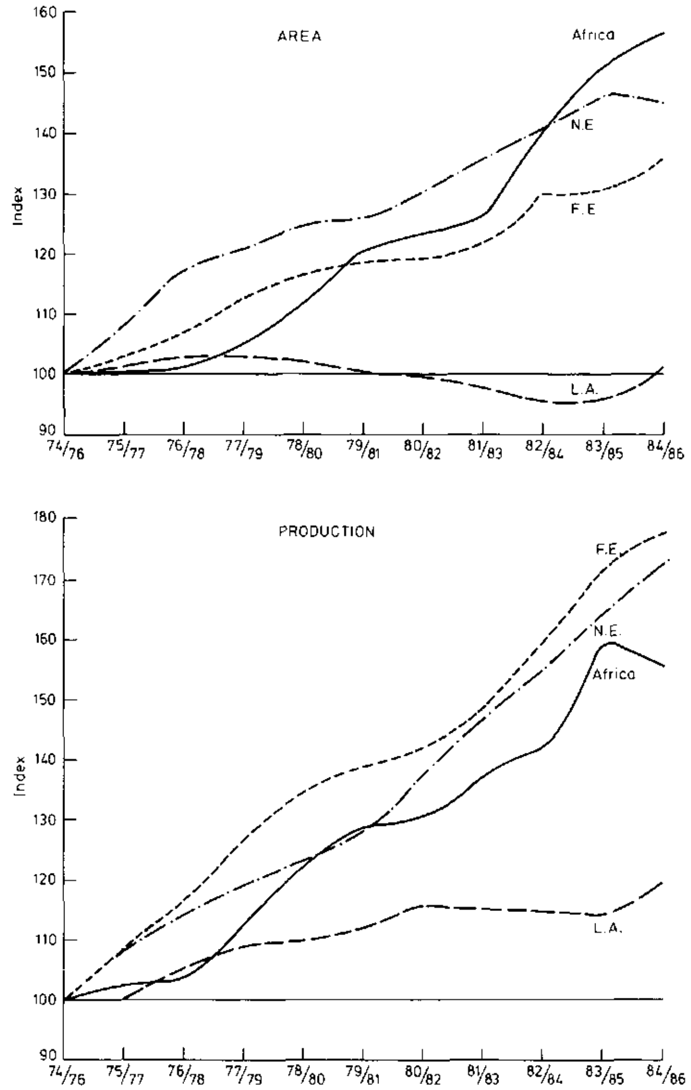

Fig. 2. Land area in potatoes and potato production in developing market economies 1974/76–1984/86 (3-year moving averages; 1974/76 = 100; based on data from FAO Production Yearbooks). F.E. = Far East; N.E. = Near East, L.A. = Latin America.

difference in potato production and consumption per head of population in Eastern Europe (table 3). Production per capita is still low in the developing countries particularly in Africa and the Far East. Consequently, consumption per capita is also low in these regions but is increasing in most developing countries. In Western Europe and North America consumption per capita has decreased, but has remained fairly stable during the last decade. In Eastern Europe consumption per capita is higher than in Western Europe but seems to have decreased slightly.

Table 2. Utilization of the world potato crop (van der Zaag & Horton, 1983; based on data from CIP, 1982).

Use	Quantity (10^6 tonne)	Percentage of total
Human consumption	126	45
Stock feed	88	31
Seed	39	14
Starch	6	2

Table 3. Potato production and consumption (in kg) per capita 1980/'82 (Horton & Fano, 1985).

	Production	Consumption
World	66	28
Developed market economies	89	55
North America	69	54
Western Europe	129	73
Oceania	62	52
Developing market economies	15	11
Africa	9	7
Latin America	31	23
Near East	29	22
Far East	10	7
Centrally planned economies	126	38
Asia	54	28
Eastern Europe (incl. USSR)	331	94

1.4 Production systems

In the industrialized countries, particularly in North America, and in most countries of Western Europe, potato production has been almost completely mechanized. One hectare of ware potatoes (50 tonnes) can now be produced and stored in about 20–40 man hours only, whereas some 30 years ago, one hectare (30 tonnes) required over 200 man hours. This reduction in labour was coupled with heavy investment in machines and stores. Another consequence of this mechanization is the concentration and specialization of the crop on special farms and in certain regions.

In Western Europe potato production has greatly decreased e.g. in West Germany and France, but it has increased in the Netherlands. Approximately two thirds of the Netherlands' total production is exported in fresh or processed form.

There is a wide variation in production systems in the developing countries, depending on local growing and market conditions. In the Andes, Central Africa and the Himalaya region, the potato is produced usually by small subsistence farmers who grow less than 1–2 ha on a number of small scattered fields. In these areas a typical rainfed crop is often subject to poor weather conditions such as drought, heavy rains, frost, hail and typhoons. Part of the crop harvested is kept for seed. In regions where potatoes are relatively cheap, which is usually the case at high altitudes, a large proportion of the crop is stored in a very simple way and used for home consumption.

In regions where potatoes are relatively expensive, such as in Central America and South East Asia, the farmers sell a large proportion to purchase cheaper food with the earnings and possibly means to improve crop production. This is certainly the case in regions where the crop is irrigated e.g. North Africa, the plains in India, Bangladesh and Pakistan. Owing to its short growing season the potato plays an important role in:

- several vegetable production regions e.g. in Sri Lanka
- in crop rotations with rice and wheat e.g. in the Punjab in India
- in intercropping with beans, maize and sugar cane (e.g. on Mauritius).

The potato is not a suitable crop for the hot and humid lowlands where temperature is high the whole year round.

On the upper slopes of the Andes old varieties (usually *S. andigenum*) with a long vegetative period are used. These varieties are highly resistant to *Phytophthora infestans* and are able to regenerate when damaged by extreme weather conditions such as frost or hail. Moreover, the field of crop which is used for home consumption is very often planted with a mixture of several varieties. In Colombia it has been proven that by crossing with *S. tuberosum*, varieties can be developed with a shorter growing period which are still suitable for production in the mountains. In most regions of the world varieties are used with a rather short vegetative period, particularly in the tropics and sub-tropics where under short day conditions the vegetative period of the imported varieties from the temperate zones becomes even shorter.

In comparison with other food crops the production of the potato, expressed in dry matter, energy or protein per hectare and per day, is high (table 4). With regard to energy efficiency the potato may well be the best crop in the tropics and sub-tropics and it is probably one of the best crops for protein production. Owing to its short vegetative period (under short day growing conditions usually less than 100–120 days) and its high efficiency in producing energy and valuable protein it is a favoured crop in rotations where a short growing period fits in well.

Table 4. Top ranking food crops in terms of production of dry matter, edible energy and protein in developing market economies (Horton & Fano, 1985).

Rank	Dry matter (t/ha)		Energy (MJ/ha per day)		Protein (kg/ha per day)	
1	Cassava	3.0	Potatoes	216	Cabbages	2.0
2	Yams	2.4	Yams	182	Dry broad beans	1.6
3	Potatoes	2.2	Carrots	162	Potatoes	1.4
4	Sweet potatoes	2.1	Maize	159	Dry peas	1.4
5	Rice	1.9	Cabbages	156	Eggplants	1.4
6	Carrots	1.7	Sweet potatoes	152	Wheat	1.3
7	Cabbages	1.6	Rice	151	Lentils	1.3
8	Bananas	1.5	Wheat	135	Tomatoes	1.2
9	Wheat	1.3	Cassava	121	Chickpeas	1.1
10	Maize	1.3	Eggplants	120	Carrots	1.0

1.5 Production cost

It is very difficult to make a correct comparison of production costs between regions or countries. This is due to the wide variation in production conditions and production systems and by differences in methods of calculating these costs. Nevertheless it is evident that in the developing countries as a whole, the production cost per unit of energy and protein for potatoes is on average two or three times higher than for rice or wheat (bread), whereas in an industrialized country such as the Netherlands, these costs are only slightly higher for potatoes than for wheat or sugar beet (sugar) (table 5).

Some information about the structure of the production costs may be useful. Table 6 gives some indication about this. In the six developing countries mentioned in this

Table 5. Production cost and consumer price of potatoes and some other foods (in US $) in 1981 (partly after van der Zaag & Horton, 1983).

	Yield (t/ha)	Production cost			Consumer price[1]	
		(ha)	energy (10^6 kJ)	protein (kg)	energy (10^6 kJ)	protein (kg)
Developing countries						
Potatoes	10.5	1520	47	7	114	18
Wheat (bread)	1.4	250	14	2	47	5
Rice	2.1	380	18	4	52	11
Netherlands						
Potatoes	45	2500	18	3	95	15
Wheat (bread)	6.5	1400	17	2	116	13
Sugar beet (sugar)	50	1900	14	-	52	-

1. Edible part of the foods.

Table 6. Cost structure for the potato crop in some selected countries (van der Zaag & Horton, 1983).

Structure	Peru	Colombia	Bangla-desh	India	Kenya	Rwanda	Netherlands[1]
Labour	16	34	20	18	54	62	20
Equipment (incl. fuel)	10	6	15	6	6	0	38
Seed	29	24	36	45	21	38	20
Fertilizers							
chemical	14	22	26	18	4	0	12
organic	14	0	2	9	8	0	0
Pesticides	17	14	1	4	7	0	10

1. Fixed costs not included.

table, labour and seed potatoes form the major costs (34 % and 32 % respectively), whilst in the Netherlands the cost of equipment predominates.

1.6 Farm and consumer prices

Obviously a crop which is liable to wide variation in yield and which cannot be easily stored well in a hot climate, will show wide variations in farm and consumer prices. In almost all developing countries where potato production is of some importance, prices drop sharply at harvest time in spite of growing more than one crop per year (fig. 3).

Nevertheless, the farm price as a percentage of the retail price seems to be much larger in developing countries than in some industrialized countries (table 7).

As the consumer (or retail) price can vary greatly even in one region, it will be difficult to make a correct comparison between the consumer price of potatoes and some other foods for different parts of the world. However, table 8 gives the reader at least some indication about the price ratio between potatoes and other foods in various parts of the world. As bread or wheat flour is often subsidized and, moreover, as in most developing countries potatoes must be considered as a vegetable, it is better to compare potato prices with vegetable prices (table 9). Potatoes appear to be much cheaper than most common vegetables.

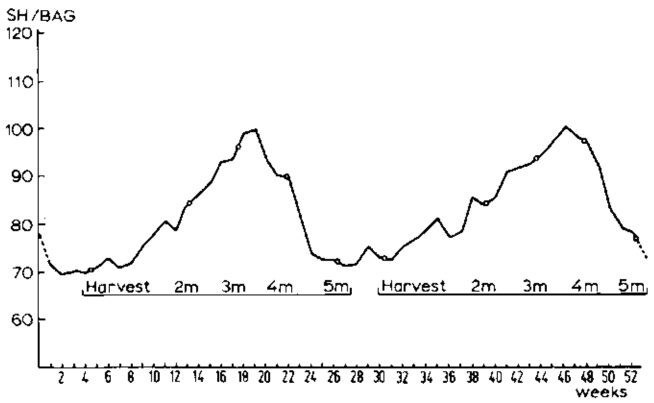

Fig. 3. Average constant weekly wholesale prices for potatoes in Wakulina market, Nairobi 1973-77 (two-week moving average) (source: Ministry of Agriculture in Kenya, published by Durr & Lorenzl, 1980).

Table 7. Farm price as a percentage of retail price in selected regions and countries (number of countries between brackets) based on FAO, unpublished; ILO, 1978; van der Zaag & Horton, 1983).

Africa (10)	52	Far East (7)	61
Latin America (6)	69	North America (2)	22
Near East (2)	54	The Netherlands	33

Table 8. Average cost (in US $) of 10^6 kJ food energy and 1 kg protein from potatoes, bread and rice 1977 (number of countries between brackets) (van der Zaag & Horton, 1983).

	Potatoes		Bread		Rice	
	energy	protein	energy	protein	energy	protein
Developed countries						
USA	129	20	90	10	56	11
Western Europe (14)	87	14	103	12	79	16
Eastern Europe (4)	126	20	83	9	85	17
Developing countries						
Africa (20)	171	27	61	7	50	10
Latin America (13)	129	20	77	9	40	8
Near East (4)	142	22	34	4	61	12
Far East (9)	90	24	61	7	24	5

Table 9. Relationship between the average consumer price of potatoes and some other selected vegetables in the capitals of several developing countries (number of cities on which the price is based is given between brackets) (Preise und Preinsindizes im Ausland, Reihe 11, 1984).

Vegetables	Consumer price per unit		
	fresh weight	energy	protein
Potatoes (10)	100	100	100
Tomatoes (9)	193	911	186
Onions (9)	157	284	314
Carrots (6)	119	338	238
Cabbages (5)	139	459	139

Why is the retail price ratio of potatoes, as expressed in terms of energy and protein, with other staple foods so much higher in developing countries than say, in the Netherlands (tables 5 and 8)? It seems very likely that the relatively high production cost of potatoes in most developing countries is the main reason for this fairly high consumer price and that this high price is largely not caused by a high marketing margin (table 7), as is often supposed. Differences in the position of the potato crop in the various growing regions are so wide that after this very general description and conclusion, a more specific description would be useful.

In the uplands of the tropics and sub-tropics the potato is usually the main food crop and can compete easily in price with other foodstuffs.

In the irrigated regions at harvest and shortly thereafter the potato is competitive in price with non-subsidized staple food, e.g. with rice in Bangladesh. After this period the potato should be considered as a vegetable.

In several regions where the potato has been introduced recently, the potato is still often a luxury vegetable, but with the potential to become a cheap vegetable provided that the production conditions are not marginal.

1.7 Potatoes in comparison with other foodstuffs

From the point of view of nutritive value the potato is competitive with other foodstuffs (table 10). The reader is referred to 'The potato in the human diet' by Jennifer A. Woolfe for further information.

1.8 Possibilities to increase potato consumption in the tropics and sub-tropics

In the industrialized countries potato consumption has decreased with increase in income. But for the 51 developing countries with a low consumption per capita it has been estimated that potato consumption will increase by about 2 % if the price decreases by 1 %, and that consumption will increase by the same percentage as the increase in income (van der Zaag & Horton, 1983). A decrease in the retail price should be accomplished by reducing the production cost per unit weight, which can be done in two ways: by reducing production cost per ha while maintaining yield and by increasing the yield while holding the cost per hectare steady.

Reducing the production cost per hectare will be achieved by reducing the major costs which, in the developing countries, are labour and seed potatoes (table 6). Although this should receive a great deal of attention, even more may be expected from an increase in yield.

Figure 4 shows that during the last 15 years much has been achieved in the developing countries. During the period 1965–1980, the accumulated calculated increase in yield expressed in terms of energy and protein in all developing countries with market economies was even higher for potatoes than for wheat and rice (van der Zaag & Horton, 1983). There is no reason to suppose that this increase in yield cannot be continued, although it should not be expected that a yield level can be attained in the tropics and sub-tropics which is similar to the yield level in the temperate zones. To prove this statement we must introduce the concept of potential yield or biological yield.

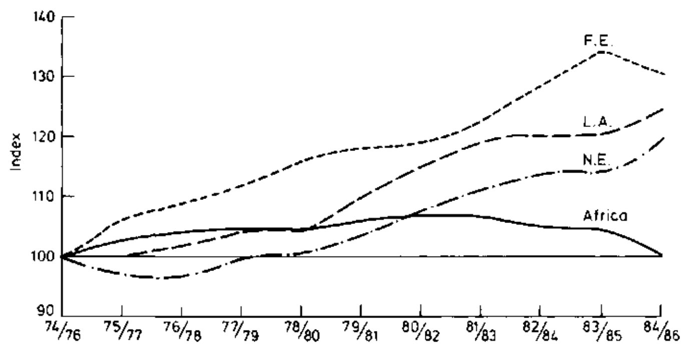

Fig. 4. Potato yields in developing market economies 1974/76–1984/86 (3-year moving averages 1974/76 = 100; based on data from FAO Production Yearbooks). F.E. = Far East; N.E. = Near East; L.A. = Latin America.

Table 10. Composition of raw potato, dried potato and other plant foods per 10 g edible proportion (Woolfe, 1987).

Food	Energy (kJ)	Energy (kcal)	Moisture (%)	Crude protein (g)	Fat (g)	Total carbohydrate (g)	Dietary fibre (crude fibre) (g)	Ash (g)	Ca (mg)	P (mg)	Fe (mg)	β-carotene equivalents (μg)	Tiamin (mg)	Riboflavin (mg)	Niacin (mg	Ascorbic asid (mg)
Potatoes	335	80	78.0	2.1	0.1	18.5	2.1 (0.5)	1.0	9	50	0.8	0-trace	0.10	0.04	1.5	20
Potato (dried)[a]	1343	321	11.7	8.4	0.4	74.3	8.4 (2.0)	4.0	36	201	3.2	Trace	0.40	0.16	6.0	80
Plantain	531	127	64.5	1.2	0.2	33.3	5.8 (0.5)	1.0	9	350	0.9	125-780	0.08	0.04	0.6	22
Corn, sweet	402	96	72.7	3.5	1.0	22.1	3.7 (0.7)	0.7	3	111	0.7	400	0.15	0.12	1.7	12
Corn, mature	540	129	63.5	4.1	1.3	30.3	(1.0)	0.8	5	128	1.1	35	0.18	0.08	1.9	9
Corn, dried	1498	358	11.5	9.5	4.4	73.2	9.3 (2.1)	1.3	12	251	3.4	6[b] 147[d]	0.35	0.11	1.9	Trace
Rice, milled white	1523	364	12.0	6.8	0.5	80.2	2.4 (0.4)	0.6	20	115	1.1	0	0.08	0.04	1.8	0
Wheat, hard	1389	332	12.3	13.3	2.0	70.9	12.1 (2.3)	1.7	44	359	3.9	0	0.52	0.12	4.4	0
Sorghum whole grain	1431	342	10.9	10.1	3.4	73.2	9.0 (2.0)	1.7	32	290	4.9	0-20	0.39	0.15	3.8	0
Beans (*Phaseolus vulgaris*) dry	1414	338	11.8	21.9	1.6	61.2	25.4 (4.4)	3.7	98	247	7.6	0-20	0.53	0.19	2.2	Trace-3
Sweet potato (*Ipomoea batatas*)	485	116	70.2	1.4	0.4	27.4	2.5 (0.9)	0.8	33	46	1.1	47[c] 1468[d] 2108[e]	0.11	0.05	0.7	26
Yam (*Dioscorea* spp.)	444	106	72.0	2.2	0.2	24.2	4.1 (0.7)	1.0	25	53	0.9	Trace-10	0.10	0.03	0.5	9
Cocoyam. taro (*Colocasia* spp.)	423	101	73.2	1.9	0.2	23.5	(0.8)	1.2	38	75	1.2	Trace	0.13	0.03	0.9	6
Cassava (*Manihot esculenta*)	607	145	62.6	1.1	0.3	35.2	5.2 (1.0)	0.9	38	41	1.0	0-30	0.06	0.04	0.6	36

[a] Potato theoretically 'dried' to a moisture content of 11.7%, which is the average moisture content of dry foods shown in the table; [b] White variety; [c] Pale variety; [d] Yellow variety; [e] Deep yellow variety.

1.9 Estimates of potential yield in the temperate zones and in the tropical and sub-tropical zones

A potato improvement programme in a region or country should start with an estimate of the gap between the actual yield and the attainable yield. As it is often very difficult to estimate the attainable yield, an attempt should be made to estimate the potential yield. The potential or biological yield is taken to mean the yield from a crop that has made full use of the whole vegetative period and where the daily tuber production has been optimum (requiring optimum water and mineral supply, an optimum amount of foliage and no diseases or pests). The potential yield is the biological optimum yield but need not be the economic optimum yield, which is similar to the attainable yield.

The yield of an 'ideal' crop of this kind, or of any particular crop, can easily be calculated with a simple method, which is discussed in chapter 5.

For several countries the average potential yield has been calculated and compared with the actual yields of crops which make use of the same growing period which was used to calculate the potential yield (table 11). It is assumed that the ratio of actual/potential yield is a good indication of the technical level of production in a region or country. It is estimated that this ratio is about 1/3 for Western Europe, which means that the technical level of potato production in Egypt is comparable with the production level in Western Europe, although the actual yield is much lower.

From these comparisons in the technical level of production between countries in the temperate zone and in the tropical and sub-tropical zones two conclusions can be drawn:

- The technical level of production in the developing countries is not as poor as is often assumed on the basis of the average yield.

Table 11. Estimate of the average actual and the average potential tuber yield in selected countries and growing seasons (van der Zaag, 1984).

Country	Growing season	Actual yield (10^3 kg/ha)	Potential yield[1] (10^3 kg/ha)	Actual potential yield
Washington, USA	12/3 -15/10	65	140	0.46
The Netherlands	1/4 - 1/10	45	100	0.45
Egypt	1/1 - 1/5	20	60	0.33
	1/9 - 1/1	15	45	0.33
Algeria	1/12- 1/4	15	45	0.33
	15/3 - 1/7	12	70	0.17
	1/8 - 1/12	8	60	0.13
Tunisia	15/2 - 1/6	15	70	0.21
Morocco	15/1 - 1/5	15	65	0.23
Pakistan	15/1 - 1/5	15	50	0.30
Saudi Arabia	1/1 - 1/5	15	45	0.33
	1/10- 1/1	12	40	0.30

1. Assumed dry matter content 20%; except for Washington and the Netherlands 22%.

- In most countries in the tropics and sub-tropics it will not be possible to reach the level of yields which are obtained in the temperate zone, due to the shorter growing season and a lower efficiency per unit intercepted radiation because of the high temperatures.

Despite these conclusions it is evident that in many countries yields could be doubled by using good seed of the best varieties available and by applying good techniques for production.

2 The potato plant

The potato used for consumption is a tuber bearing herbaceous plant. The following plant parts can be distinguished:
- haulm (foliage): leaves and stems
- tubers and stolons
- roots.

In general only the tubers are utilized.

2.1 Haulm

The aerial stems, which may be branched, are generally hollow and triangular in cross section. The stems have straight or wavy wings. The lower part of the stem is round and solid. The mature leaves are compound, consisting of a petiole with a terminal leaflet, lateral leaflets, secondary leaflets and sometimes tertiary leaflets.

A stem is considered to be a main stem, if it grows directly from the seed tuber. The lower lateral branches from the stem are called secondary stems (fig. 5). If a secondary stem branches off from the main stem very close to the seed and its stolon and tuber formation is similar to that of a main stem, then this secondery stem may be considered as a main stem (fig. 5).

Apart from lateral branching a potato stem may develop apical branches several times during its growth according to the pattern given in figure 6. In this example the stem after the 17th (n) leaf, develops a flower bud which may produce a flower. In the axil of the 16th (n–1) leaf and the 15th (n–2) leaf, (n–1) and (n–2) apical branches may develop. After the development of 6–9 leaves, a flower bud may form on each of the (n–1) and (n–2) apical branches and new terminal branches, (n–1) (n–1), (n–1) (n–2), (n–2) (n–1) and (n–2) (n–2), in their (n–1) and (n–2) axils. As not all the initial apical branches develop under field conditions and the flowers also often abort, unless detailed observations are made, a branched stem of this kind with several flowers gives the impression of being one single main stem with lateral branches.

The lower part of the stem (including its leaves) up to the first flower is called the

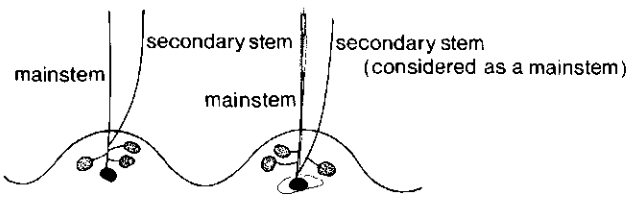

Fig. 5. Main stems and secondary stems.

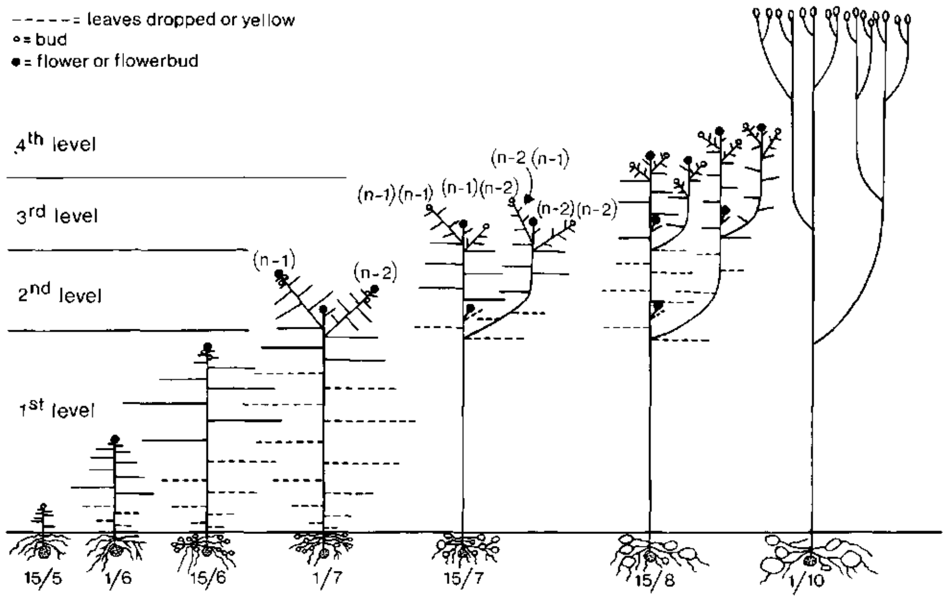

Fig. 6. Morphological growth (schematic) of a main stem of the potato (late variety) on fertile soil and at high nitrogen level (after Reestman & Schepers, 1971).

first level. The section between first and second generation flowers is called the second level and the section between second and third generation flowers is called the third level. The number of levels and the stem length of each level depends on variety, day length, nitrogen, etc. (section 4.3.4). Short cycle crops have fewer levels and limited stem length, whereas long cycle crops develop more levels and longer stems at each level. During crop observations and experiments with potatoes the following haulm and foliage characteristics are usually recorded:

- emergence: percentage of emerged plants
- plant density: number of plants and number of main stems per m^2 (calculated from row distance and number of plants or stems per 10 m of row length)
- estimated percentage of soil surface covered with green leaves
- leaf area index (LAI); leaf area duration (LAD)
- haulm weight (fresh or dried) per m^2
- haulm length: total haulm length or number and length of each level
- leaf colour (e.g. in nitrogen experiments)
- water status of foliage
- percentage of leaves with symptoms of disease
- the position of the leaves attacked by disease
- stage of maturity.

2.2 Roots

Plants grown from true seed develop a slender tap root from which lateral branches arise. Plants growing from tubers develop adventitious roots at the nodes of the

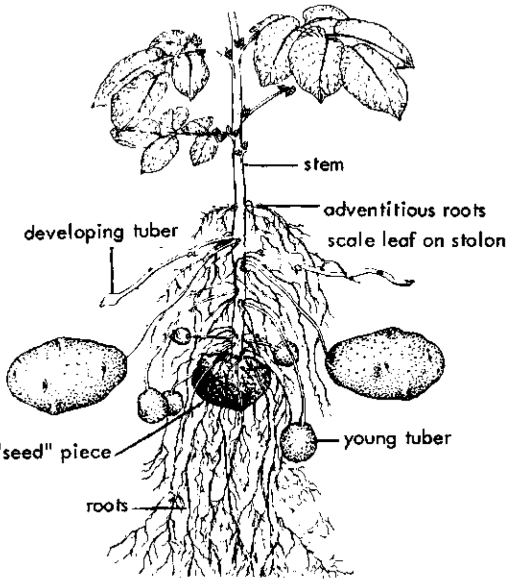

Fig. 7. Underground plant parts of a potato.

underground stems and stolons (fig. 7).

The potato plant generally roots rather shallowly (often no deeper than 40 to 50 cm). If, however, no obstructive layers or sharp transitions from one soil type to another occur in the soil profile, plants may root to as deep as 1 m.

2.3 Tubers

The tuber can be considered as a part of the stem adapted to food storage and reproduction. Aerial tubers sometimes develop in the leaf axils of the stem. This happens when the foliage continues to produce food while the transport of assimilation products to the tubers has been blocked. This blocking may be caused by mechanical injury or attack by a fungus (e.g. *Rhizoctonia solani*) on the lower part of the stem.

The tuber (fig. 8) may be regarded as an enlarged stolon. The rudiments of the scale leaves (the eyebrows) and of the buds (the eyes) in the axils of the scale leaves can still be seen on the skin. Each eye has more than one bud. The skin of the tuber has many lenticels. These may be considered as the stomata of the tuber.

In a cross section of the tuber the following zones are visible: Outer cork layer (periderm), inner storage parenchyma, outer storage parenchyma and vascular ring (fig. 9).

The distance between the skin and the vascular ring is normally about ½ cm, but the skin and the vascular ring are more or less in contact near the eyes and at the stolon attachment.

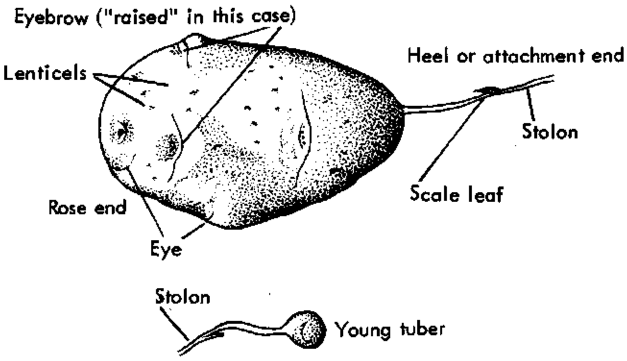

Fig. 8. Potato tuber showing the main morphological features used in identification (Burton, 1966).

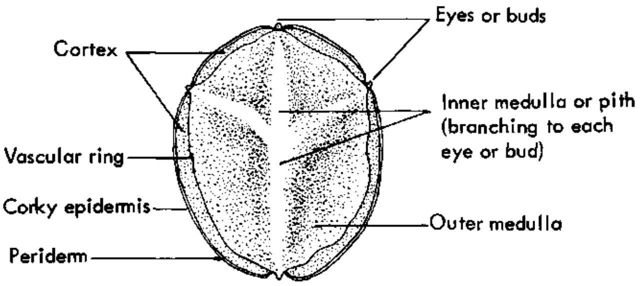

Fig. 9. Cross section of potato tuber (Kehr et al., 1964).

2.3.1 Skin

When the stolon-end starts to enlarge into a tuber (tuber initiation) the skin (periderm) develops. The cell layer directly below the epidermis changes into a cork cambium (phellogen). On the outside, the phellogen produces cells that suberize phellem. The periderm of a mature tuber consists of 5–15 cell layers. The phellem and phellogen together are called the periderm. In immature tubers, where the phellogen is still active and the cambium cells are thin-walled, the skin can easily be removed (scrapers). At maturity, the cork cambium stops its activity, its cell walls as well as the tuber skin become stronger ('setting' of the skin).

The skin of a mature tuber is almost impermeable to chemicals, gases and liquids and also provides good protection against micro-organisms and water loss.

The lenticels act as a communication system between the inside of the tuber and its surroundings. They are essential for the respiration of the tuber since hardly any Carbon dioxide (CO_2), Oxygen (O_2) and water (H_2O) can pass through the skin itself.

If tubers grow in really wet soil, the lenticels open and become very large, thus easily permitting harmful micro- organisms to enter. Micro-organisms can often survive in the lenticels even after tubers have been disinfected.

2.3.2 Cork and wound-periderm formation

Tubers without a sufficiently well-developed skin are easily damaged and will lose much moisture during storage, furthermore, micro-organisms can easily enter such tubers. When a tuber is injured or deliberately cut, the formation of a new cork layer is needed to protect the tissue against infection as well as against excessive loss of moisture.

Wound healing in potato tubers is a regenerative process and comprises both the suberization of cell walls, preventing invasion by micro-organisms and almost all evaporation from the wound surface (Wigginton, 1974), and the formation of a phellogen or cork cambium to produce new cells, the wound periderm on the outside and occasionally phelloderm cells on the inside. For good, quick skin formation or wound healing the following conditions are required:

- high temperature
- high relative humidity
- sufficient oxygen.

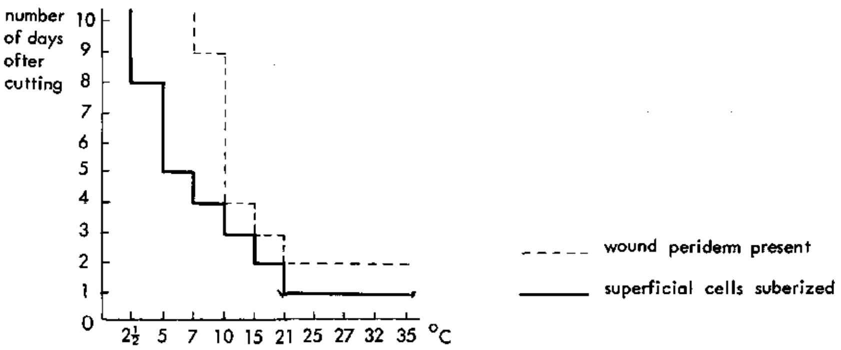

Fig. 10. Cell suberisation and wound periderm formation at various temperatures (Artschwager, 1927).

Table 12. Effect of relative humidity on wound-healing at 10 and 20 °C (Wigginton, 1974).

Day	10 °C								20 °C							
	60%		80%		93%		98%		52%		80%		91-92%		95-97%	
	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P
1	0	0	1	0	1	0	1	0	0	0	1	0	2½	0	3½	0
3	–	–	4	0	3	0	4	0	2	0	2	0	4½	0	–	–
5	2	0	–	–	4	1	–	–	2	0	–	–	6½	2	7	3½
7	3	0	6	1	6	1	–	–	4	2	7	3½	7	4	7	4½

S = Suberization
P = Number of periderm cells

1 - half the surface suberized
2 - whole surface lightly suberized
4 - ½ cell suberized
7 - 2 cells suberized

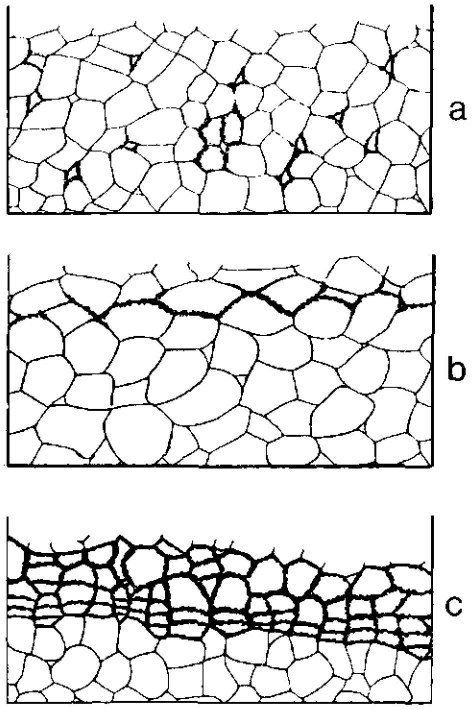

Fig. 11. Cell suberisation under (a) dry and (b) moist conditions, and (c) wound periderm formation (Appel, 1906).

The wound healing process is faster in young tubers than in old ones. Figure 10 shows the rate of periderm formation in relation to time and temperature. At a temperature of 10–20 °C with favourable humidity and sufficient oxygen, it takes 3 to 5 days before a good new skin is formed and wounds are healed as a result.

For good, quick wound healing a relative humidity of about 90 % is required (table 12). In figure 11 wound healing is shown under dry and moist conditions. Although the rate of skin and cork formation increases with rising temperature and relative humidity, for curing purposes, potatoes should not be stored at a temperature of more than 15 °C or at a relative humidity higher than 95 %, because then conditions will be most favourable for the development of harmful micro-organisms.

2.4 Sprouts

The number of eyes in a tuber varies considerably depending on many factors such as variety, size of tuber and growth conditions. Twelve to 15 eyes are quite usual in a 45 mm 'Bintje' tuber. They form a special spiral round the tuber, like the side buds on a stem. The sheath surrounding the buds in the eye is a rudiment of a leaf. The eye is, in fact, the axil of a leaf on part of a stem (fig. 12).

In many cases the main bud lies in the middle of the eye, with a bud on either side, often clearly separated by tuber flesh. These side buds may be regarded as the lowest

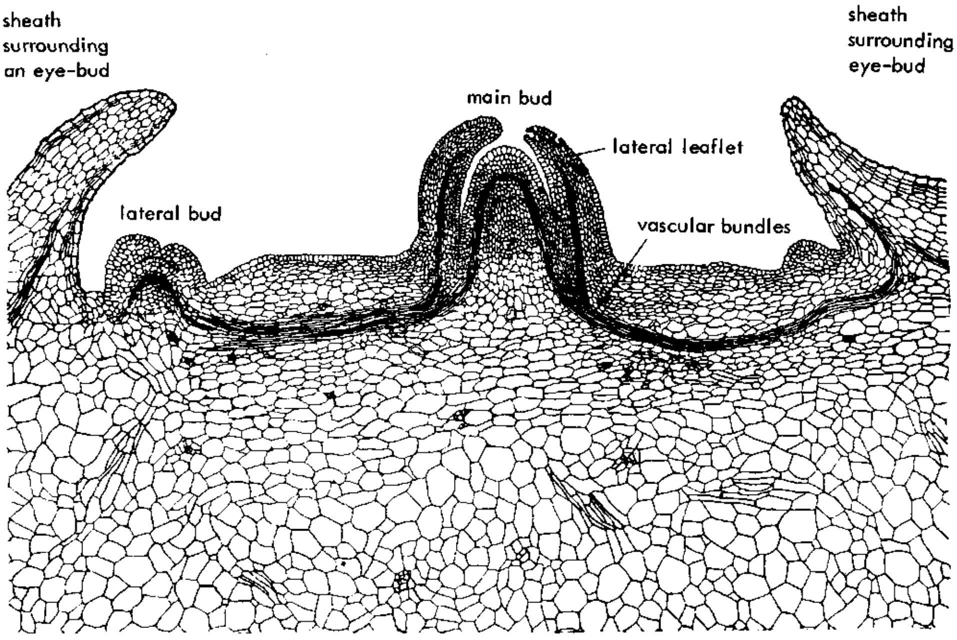

Fig. 12. Cross-section of an eye (Artschwager, 1924).

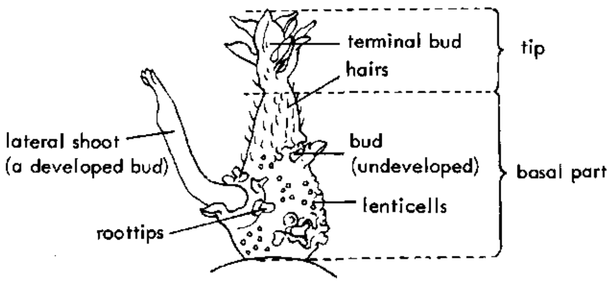

Fig. 13. Sprout developed under light (R. Ros, RIVRO).

lateral buds of a sprout, which have become separated by the growth of the tuber. Normal sprouts can, and often do, grow from them. The main sprout also bears lateral buds which can form lateral stems or stolons. If the sprout breaks off but its base remains, there is a fair chance that the bottom lateral buds, which would normally form stolons, will grow into one or more stems, all of which arise from the same eye. In the case of a sprout which has been allowed to develop in light to an advanced stage, the lateral buds will have sprouted far enough for the terminal and lateral buds to be visible on them also (fig. 13).

3 Dormancy and sprout growth

3.1 Dormancy

Potato tubers may be considered dormant if the buds do not start to grow within 2 weeks under favourable conditions (e.g. 20 °C). Often this is called the rest period. The dormant period is then defined as the period when sprouting is inhibited for any reason, and includes the rest period.

The length of dormancy may be:

- number of weeks (days) between harvest and the start of bud growth
- number of weeks (days) between tuber initiation and the start of bud growth.

In practice, the first definition is used. However, it is often useful to consider the period between tuber initiation and the start of bud growth as the dormant period.

In some cases bud growth starts before harvest (e.g. second growth). It is assumed that dormancy reaches a maximum at the time of tuber initiation and then declines.

3.2 Length of dormancy

The length of dormancy depends on the variety, the maturity of the tuber, soil and weather conditions during growth, storage conditions and whether the tuber has been damaged or not.

3.2.1 Variety

Varieties differ markedly in length of dormancy (table 13), though some of the differences observed can arise from the physiological state of the tuber, e.g. differences in time of tuber initiation. Length of dormancy does not relate to the maturity group to which a variety belongs.

It is possible to breed late varieties with relatively short dormancy and to breed early varieties with relatively long dormancy. No correlation has been found between dry matter content and length of dormancy.

3.2.2 Maturity of the tuber

Fully mature tubers have a shorter dormant period than tubers harvested at an immature stage. This is shown in table 14 where the dormant period of potatoes harvested at different stages of maturity is given. It shows that the period between harvest and the start of sprout growth is longer the less mature the potatoes are when harvested. However, a tuber harvested when immature usually sprouts earlier than a mature tuber (table 14).

Table 13. Dormant period in weeks (called rest period by Emilsson) of different potato varieties in 1946, 1947 and 1948 (Emilsson, 1949).

Variety	Earliness	1946/'47	1947/'48	1948/'49	Mean
Ackersegen	LM	6	8	9	7.7
Alpha	M	9	13	13	11.7
Arran Banner	EM	14	18	16	16.0
Bintje	EM	8	10	11	9.7
Eersteling	E	9	10	8	9.0
Eigenheimer	EM	6	4	5	5.0
Katahdin	EM	12	13	10	11.7
King Edward	M	12	12	11	11.7
Majestic	M	14	17	17	16.0
Up to date	M	14	11	13	12.7

E = early, EM = early main crop, M = main crop, LM = late main crop.

Table 14. Influence of degree of plant maturity at harvest on the length of the dormant period (Emilsson, 1949).

Variety	Date of harvest	Dormant period (weeks)	End of dormant period (date)
Alpha	26/7	19	6/12
	30/8	14	6/12
	20/9	12	13/12
Bintje	26/7	18	29/11
	30/8	12	22/11
	20/9	12	13/12
Majestic	26/7	18	29/11
	30/8	14	6/12
	20/9	14	27/12
Up to date	26/7	18	29/11
	30/8	15	13/12
	20/9	13	20/12

26/7 plants of all varieties at flowering stage
30/8 onset of maturity
29/9 plants more or less mature

3.2.3 Field and weather conditions during growth

The length of the dormant period of any given variety is not constant (table 15). It varies from year to year, in addition to which, the place of cultivation may influence the length of the dormant period.

The effect of day length on the length of the dormant period is not well known,

Table 15. Dormant period (called rest period by Schippers) expressed in weeks after harvest of some varieties at various temperatures in two seasons (Schippers, 1956).

Variety	Earliness[1]	2 °C		5 °C		10 °C		20 °C	
		1953[2]	1954[2]	1953	1954	1953	1954	1953	1954
Bintje	6.5	14	17	12	16	12	15	10	11.5
Eigenheimer	7	9.5	11	9.5	11	9.5	11	6.5	8
IJsselster	6.5	9.5	19	10	19	9.5	16	9	12
Libertas	4.5	12	23	12	19	14	19	10	15

1. Low figure late maturity.
2. 1953 normal temperature, 1954 low temperature.

although it is often assumed that potatoes grown in short days tend to have a rather shorter dormant period (with earlier maturing of the crop).

The temperature at which the potatoes are grown, however, can have a far greater influence on the length of dormancy. Potatoes grown at higher temperatures, particularly at the end of the growing period, have shorter dormancy. In the Netherlands it is usually the case that after a cool and wet summer (e.g. 1954, table 15) the dormant period is much longer than after a warm and dry summer.

3.2.4 Storage conditions

Storage temperature is also an important factor influencing the length of the dormant period. The influence of storage temperature on length of dormancy is shown in table 15. Raising the storage temperature from 10 °C to 20 °C seems to have more effect than raising the temperature from 2 °C to 10 °C. In certain cases, fluctuating storage temperatures shorten dormancy more than constant high temperatures. Schippers (1955) found that the variety Alpha sprouted earlier (2–3 weeks) if stored at fluctuating temperatures (e.g. 2 and 20 °C) than at a constant 20 °C. In other cases and with other varieties this treatment had little or even the opposite effect.

Recently it has been found that a short period of low temperature (say 3 °C for 2 weeks) after curing the seed tubers, can shorten the dormant period of several varieties by 2–3 weeks.

The humidity of the atmosphere during storage can also influence the length of the dormant period. The dormant period is shortened by a high relative humidity.

Exposure to light prolongs the dormant period of mature tubers but may shorten that of immature tubers.

3.2.5 Injuries

Tubers attacked by micro-organisms (*Phytophthora* or *Fusarium*) or insects and those mechanically damaged (also by cutting) have a shorter dormant period than healthy undamaged tubers. Therefore, cutting the seed stimulates early sprout growth.

Table 16. Number of weeks between harvest and beginning of sprout growth of some British varieties, stored at various temperatures (1957 crop, lifted 3rd week of September) (Burton, 1963).

Variety	4.4 °C	10 °C	22.5 °C
Arran Consul	> 28	12	8
Arran Pilot	12	5	5
Arran Victory	12	5	3
Arran Viking	16	5	8
Craig's Defiance	8	6	3
Golden Wonder	26	12	8
Home Guard	12	5	3
King Edward	16	6	5
Majestic	> 28	12	8
Ulster Chieftain	16	5	5
Ulster Prince	14	14	8
Average	17	8	6

3.3 Initiation of sprout growth

During the dormant period, as previously mentioned, buds do not show visible growth. When dormancy is over, the storage temperature determines the initiation of visible sprout growth.

This is clearly shown by Burton (1963) who, like Emilsson (1949) and Schippers (1956), defined the dormant period as the time when the buds do not grow, for whatever reason. (Recently however Burton (1978b) defined: 'a bud is dormant if it does not grow at a favourable temperature'.) By decreasing the storage temperature from 22.5 °C to 10 °C the period without sprout growth is lengthened by about 2 weeks, while by lowering the temperature from 10 °C to 4.4 °C the period is lengthened by 9 weeks for the varieties mentioned in table 16.

Emilsson (1949) found a correlation coefficient of + 0.57 for 51 varieties, between the length of the dormant period as given by our definition and the length of the period without sprout growth when storing the tubers at 5 °C.

3.4 Sprout growth

The pattern of sprout growth of a potato tuber depends on the physiological stage of the tuber (i.e. growing conditions, storage conditions, length of storage period, previous sprout growth), temperature at which sprouting occurs, light conditions, relative humidity and competition between sprouts (tuber size and number of sprouts).

3.4.1 Physiological stage of the tuber

The physiological stage of the tuber can be detected by changes in sprout growth (fig. 14).

<table>
<tr><td colspan="2">young</td><td colspan="2">physiological stage</td><td>old</td></tr>
<tr><td>dormant</td><td>apical dominance</td><td colspan="2">"NORMAL SPROUTING"</td><td>senility</td></tr>
<tr><td>no sprout growth</td><td>one sprout growth</td><td>multiple sprout growth</td><td>branched sprout growth</td><td>hair sprout growth
"little potato" growth</td></tr>
</table>

Fig. 14. Physiological stages of the tuber.

The physiological stage is influenced by the conditions under which the tuber is grown, the duration of the storage period, the storage conditions and previous sprout growth. Seed grown in a warm region and stored at high temperatures physiologically ages sooner than seed grown in a cool region and stored at low temperatures.

Seed of varieties with a short dormant period reach 'old age' (senile stage) earlier than varieties with a long dormant period.

The number of sprouts which develop on a tuber depends on the physiological stage at which sprout growth starts. If a tuber starts sprout growth in its 'apical' stage only one of the buds at the apex develops sprouts. An apical sprout is dominant over the other buds, so these remain dormant. Only when this top sprout is removed (de-sprouted) will the other buds of the tuber develop sprouts.

Figure 15 shows that after the tuber has been de-sprouted for the first time it is still more or less in its 'apical' stage but, after the tuber has been de-sprouted for a second time, a large number of sprouts develop. If a tuber is de-sprouted several times it loses its sprouting capacity. Some varieties lose their sprouting capacity after de-sprouting only twice, while others can be de-sprouted several times. In practice, de- sprouting once usually provides a sufficient number of growing sprouts.

If, owing to a low storage temperature, sprout growth starts late in the season (i.e. after the stage of apical dominance is over), more eyes (or buds) will develop sprouts (table 17).

Table 17. Number of sprouts developing per tuber when kept first at 4 °C and later at 20 °C.

<table>
<tr><td rowspan="2">Interval between harvest and keeping tubers at 20 °C</td><td colspan="3">Number of sprouts per tuber</td></tr>
<tr><td>Eersteling</td><td>Bintje</td><td>Alpha</td></tr>
<tr><td>0 weeks</td><td>1.0</td><td>1.0</td><td>1.0</td></tr>
<tr><td>6 weeks</td><td>1.8</td><td>1.0</td><td>1.0</td></tr>
<tr><td>15 weeks</td><td>3.4</td><td>1.5</td><td>1.8</td></tr>
<tr><td>23 weeks</td><td>3.2</td><td>4.0</td><td>2.3</td></tr>
<tr><td>30 weeks</td><td>6.0</td><td>4.8</td><td>4.6</td></tr>
</table>

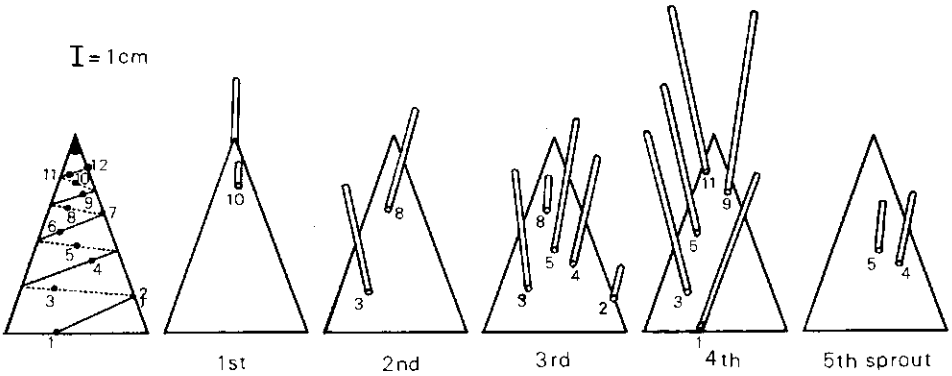

Fig. 15. Bintje tuber de-sprouted every 4 weeks from January onwards; eyes numbered from base to top (Krijthe, 1962a).

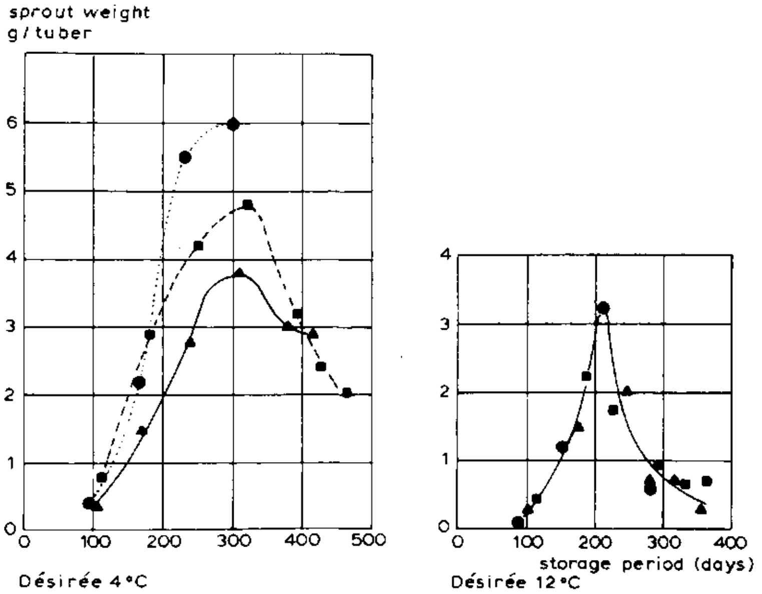

Fig. 16. Influence of the storage period, at 4 °C and 12 °C on the sprouting capacity (g fresh weight/tuber after de-sprouting and subsequent 4 weeks at 18 °C) (Hartmans & van Loon, 1987). Experimental years – ● 1978/79; ▲ 1979/80; ■ 1980/81.

3.4.2 Growth rate of sprouts and physiological age of the seed

Immediately after dormancy ends, sprouts grow at a slower rate than the sprouts of a tuber whose dormancy ended some time before. Furthermore, the stage of maximum sprout growth is reached sooner by seed stored at a high temperature than at a low temperature (fig. 16).

3.4.3 Growth rate and de-sprouting

After a tuber has been de-sprouted once, the next set of sprouts grows faster. If the tuber has been de-sprouted several times, however, the rate of growth of the sprouts decreases.

3.4.4 Growth rate of sprouts and temperature

The temperature influences sprout growth markedly (fig. 17). In the example given 16–20 °C seems to be the optimum temperature for sprout growth. The effects of temperature are also shown in figure 18.

In this case, with an increase in temperature from 4 °C to 25 °C, there is an increase in the initial rate of elongation of the apical sprout of tubers of the Arran Pilot variety (fig. 18). The growth rate at 30 °C is low, however, owing to the death of the sprout apex. This also occurs later in the 25 °C and 20 °C treatments, so that eventually the longest sprouts are produced at 15 °C. Dyson & Digby (1975) showed that the sub-

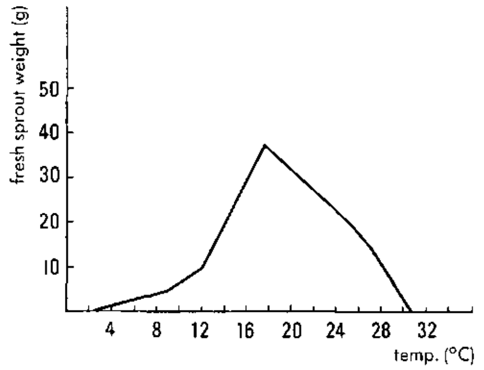

Fig. 17. Influence of temperature on sprout growth (Hogetop, 1930).

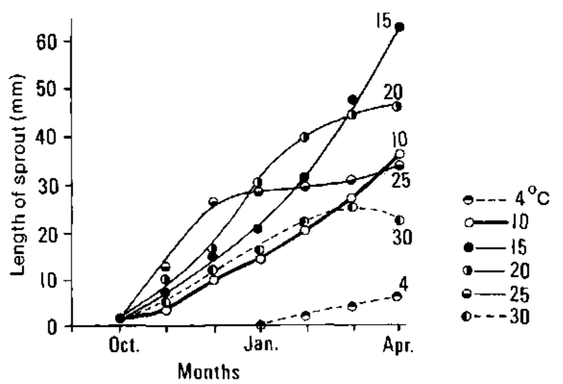

Fig. 18. The changes over time in length of the apical sprout of Arran Pilot tubers stored at different constant temperatures (Headford, 1962; after data from Saddler).

apical necrosis of the sprout tip, which often occurs in fast-growing dark sprouts, is the consequence of failure by the sprout to mobilize sufficient calcium to the tip.

3.4.5 Humidity and sprout growth

A high relative humidity stimulates root formation on the sprouts. The longitudinal growth of the sprouts does not seem to be greatly influenced by the relative humidity at moderate temperatures. At higher temperatures a high relative humidity may stimulate the longitudinal growth of the sprouts. A liberal amount of water also stimulates sprout growth.

3.4.6 Light and sprout growth

Potato sprouts grown in the light develop chlorophyl and are shorter and sturdier than those grown in the dark. After a storage period of 7½ weeks at 17 °C, the average length of the longest sprouts on a tuber grown in the light may be only 3 % of that of the sprouts on tubers grown in the dark, Sprout growth begins to decrease at low light intensities. In the past in Europe seed potatoes were often stored in diffuse light. Diffused-light storage has now been introduced in many developing countries, where cold stores are insufficiently available.

3.4.7 Variety and sprout growth

Not all varieties have the same rate of sprout growth. The number of sprouts which develop on a tuber also depends on the variety. With the same seed treatment and planting methods the tubers of various varieties produce a different number of stems per tuber (table 18).

3.4.8 Tuber size and sprout growth

If the right method of seed preparation is applied, big tubers produce more sprouts than small ones.

Table 18. Average number of stems (and their variation) produced per tuber and plant density attained (4 plants per m²) (1968).

Variety	Average number of stems per tuber	Variation	Number of stems per m²
Bintje	4.8	2- 7	19
Humalda	2.8	1- 6	11
Jearla	4.1	2- 8	16
Lekkerlander	4.0	2- 7	16
Ostara	3.0	1- 5	13
Provita	5.9	1-10	23
Sirtema	3.7	2- 5	15
Tanja	3.8	1- 6	15
Thola	3.9	2- 6	16

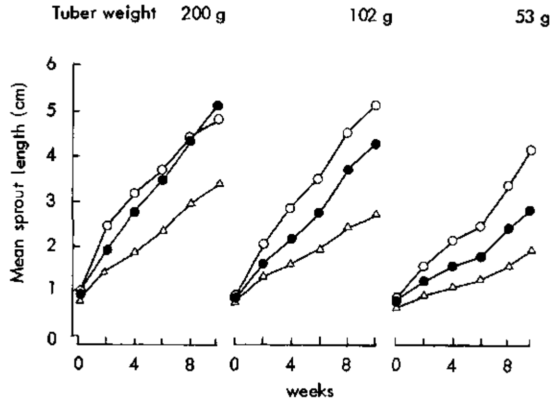

Fig. 19. Effect of tuber size and number of sprouts per tuber on sprout elongation at 15 °C. Circles, dots and triangles correspond with 1, 2 and 4 sprouts per tuber respectively (Morris, 1966).

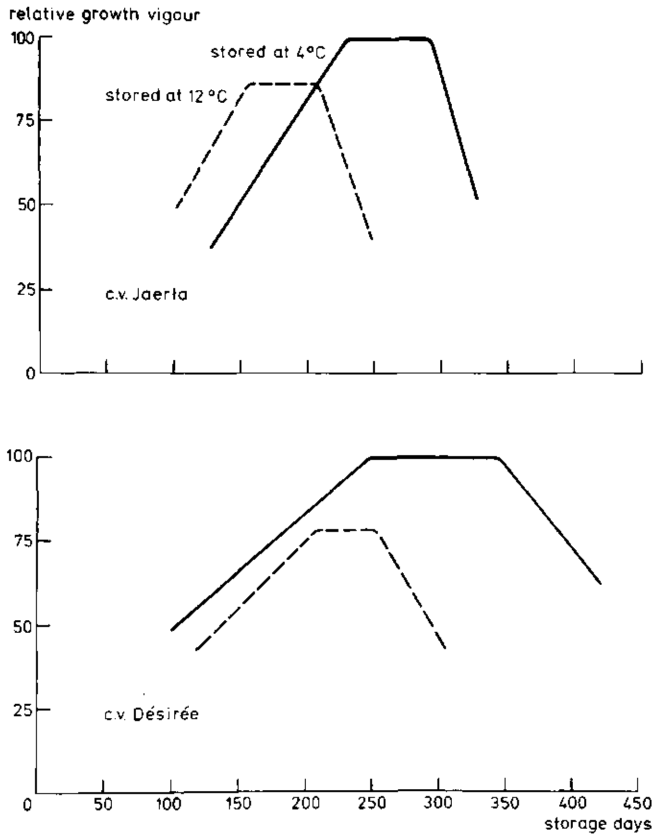

Fig. 20. Estimated relationship between chronological seed age, expressed in storage days after 18 August, and relative growth vigour of seed tubers of cvs. Jaerla and Désirée stored at 4 °C or 12 °C (van der Zaag & van Loon, 1987).

Reestman & de Wit (1959) calculated that the number of main stems developing on a tuber correlates with the surface area of the tuber. The growth rate of sprouts developing on big seed is faster than those developing on small seed. Morris (1966) demonstrated intersprout competition (fig. 19).

The smaller the seed and the more sprouts developing on the seed, the greater the competition between the sprouts will be, and the slower their growth rate.

3.5 Growth vigour

Growth vigour is the potential of a tuber to produce sprouts and plants rapidly under conditions favourable to growth. Growth vigour in figure 20 is expressed as sprouting capacity, stem length, number of stems per plant, LAI and total dry matter production per planted tuber. Figure 20 also shows that the effects of storage duration and storage management of the seed on growth vigour, differ for the individual varieties. It is evident that seed of the variety Désirée maintains its growth vigour better under optimum storage conditions than the variety Jearla. With storage management it is possible to manipulate the growth vigour of the seed. Growth vigour of the seed is an important characteristic of variety.

4 Crop ecophysiology

4.1 Introduction

The production of a crop is the result of photosynthesis and respiration. Both processes are influenced by ecologically and plant physiologically determined factors. Only those parts of the crop that can be used are of importance to the grower (this is the so-called harvest index). In the case of the potato crop tubers are of interest. Tuber production is determined by photosynthesis, respiration, partitioning or distribution of assimilates (harvest index) and dry matter content of tubers.

Tuber yield can be explained in two ways:

- tuber yield = daily tuber production × number of days
- tuber yield = cumulative light interception × utilization coefficient of intercepted light × harvest index × the inverse of dry matter content of tubers.

Before discussing tuber yield along these two lines, various factors influencing photosynthesis, respiration and partitioning will be discussed. Dry matter content will be discussed later, in the chapter dealing with tuber quality (chapter 12).

4.2 Production determining factors

4.2.1 Photosynthesis

4.2.1.1 Introduction

Photosynthesis is a complex process which takes place in green plant parts, mainly the leaves. Carbon dioxide in the leaf tissue is bound to the chlorophyll and reduced to sucrose by the absorbed light energy.

$$CO_2 + H_2O \xrightarrow{\text{light}} CH_2O + O_2$$

The rate of photosynthesis per unit leaf area is determined by:

- temperature
- light intensity
- age of the leaves
- CO_2 concentration in the leaf tissue.

The rate of photosynthesis per unit crop area is determined by the rate of photosynthesis per unit leaf area and the area of green foliage that intercepts light. The latter is determined by the leaf area index, foliage structure and light intensity. The net rate of photosynthesis is the gross rate of photosynthesis minus the rate of respiration. As we will see later, respiration is also influenced by temperature and leaf age.

Table 19. Photosynthesis measured in full daylight at 18-20 °C in Uppsala (Lundegårdh, 1930).

Plant	Net photosynthesis (g CO_2 per m^2 leaf area per hour)
Potato	1.92
Tomato	1.68
Sugar beet	1.86
Spinach	1.96
Broad bean	1.76
Disarf kidney bean	1.86

The plants of agricultural crops can be divided into two groups according to the chemical nature of the early products of carbon combination viz. C_3-plants such as potatoes, sugar beet, wheat (mainly crops of the temperate zone), which produce the three carbon 3-phosphoglyceric acid and C_4-plants such as sugar cane, maize, rice etc., which produce the four carbon malate or aspartate.

The C_3-plants exhibit a very similar rate of photosynthesis per unit leaf area under fairly optimum conditions (table 19). This similarity of rate suggests that there is possibly not much scope to improve production of the potato crop by means of breeding for a higher rate of photosynthesis. However, there are research workers who have found differences in the rate of photosynthesis between genotypes of the potato. The question is still whether the conditions in these experiments were optimum for each genotype studied.

The rate of photosynthesis in C_4-plants is higher, due to a much lower rate of photorespiration, which occurs in light by reactions which involve the early products of photosynthesis.

4.2.1.2 Temperature

The photochemical reaction in photosynthesis is not markedly temperature sensitive. Other reactions in the photosynthetic process, however, are temperature sensitive, with an optimum of around 20–25 °C for potatoes depending on the light intensity (fig. 21).

At higher light intensities the optimum moves to a higher temperature. Cv. Jaerla reacts more strongly in this respect than cv. Kennebec. At high temperatures the enzymes involved become inactivate.

It is generally agreed that a temperature range of between 20–25 °C is optimum for the potato. Although different data can be found in the literature on the effect of high temperatures (i.e. 30–35 °C) on the rate of photosynthesis, Burton (1978c) assumes that at Yurimaguas in Peru (where average day temperatures are about 30 °C and average night temperatures are about 20 °C) the net assimilation rate is about half the assimilation rate at optimum day and night temperatures. That is about the same value as given in table 21.

Respiration losses are included in all this data. However, it should be realized that only the respiration rate of leaves is included in the net rate of photosynthesis determined with leaves, but parts of the plants that do not or hardly assimilate, such

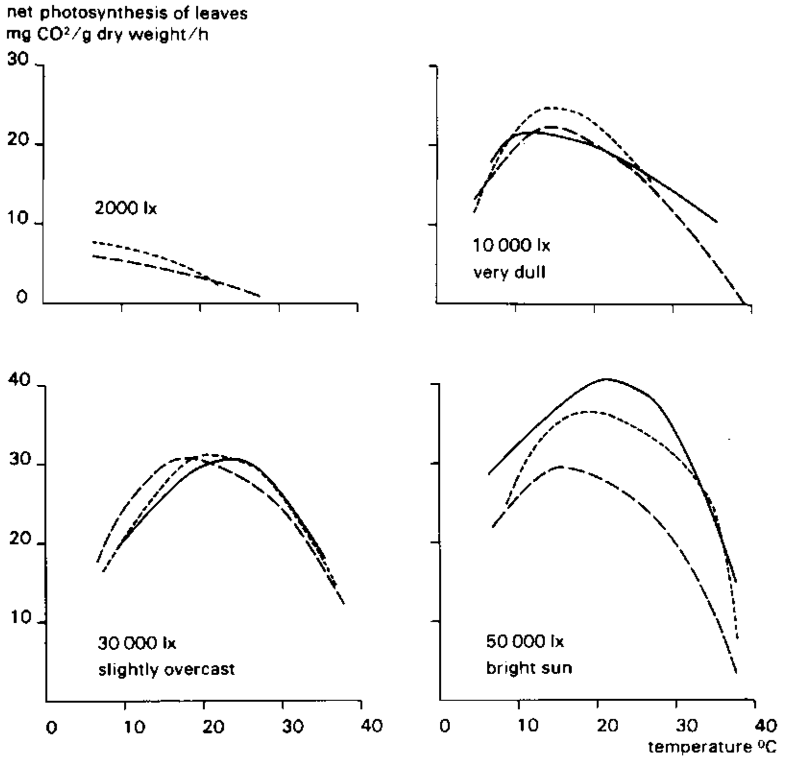

Fig. 21. Net photosynthesis of leaves of the cultivars at different light intensities and temperatures. Jaerla (—), Kennebec (- - -), and Sieglinde (- - - -). (Winkler, 1983).

as stems, tubers and roots are not included. The higher the temperature, the more the net assimilation rate, determined with individual leaves, deviates from the net crop production.

4.2.1.3 Light intensity and light interception

Light intensity The energy needed for the photosynthetic process comes directly or indirectly from sunlight. About half the spectrum of the sun's radiation is the right wavelength to affect this photosynthetic process (400–700 nm), usually abbreviated as PAR (photosynthetically active radiation), which is the visible part of the spectrum. Only a very small part of PAR is actually used for photosynthesis. Based on the production and the evapotranspiration of a crop in full production in Wageningen in July, it has been calculated that at most about 8 % only of PAR is used for photosynthesis, corresponding to about 4 % of the total photo-energy input. Generally more than 1/3 of the total energy input will be used for transpiration and about 10 % of the radiation is reflected back from the leaves.

The effect of light intensity on photosynthesis is shown in figure 22. At about 5 J/cm^2 per minute the maximum production is almost reached. By comparing the light

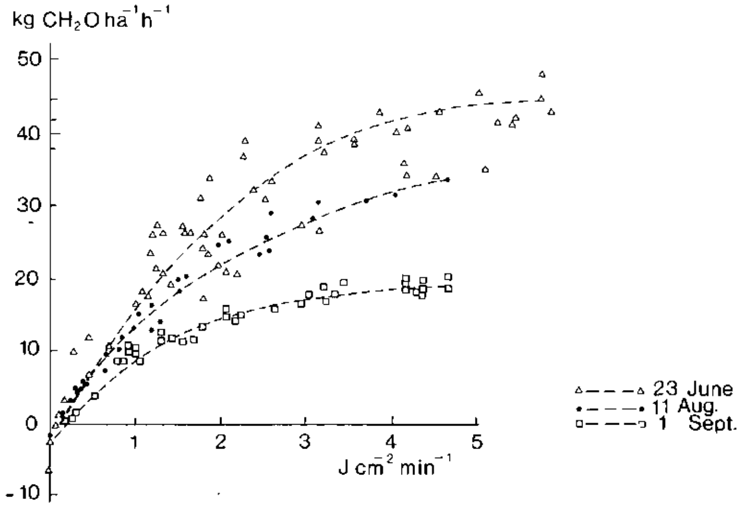

Fig. 22. Light-response curves of a potato crop on several dates (Bodlaender, 1977).

response curves on the three dates it is obvious that young leaves can utilize more light than older leaves. Figure 21 shows that at high light intensity at optimum temperatures, the net photosynthetical rate between cultivars differs (e.g. cv. Jaerla is 30 % higher than cv. Kennebec). At high light intensity cv. Jaerla seems to be considerably more productive per unit leaf area than cv. Kennebec.

Light intensity depends on:

- the angle of incidence of the sun's rays on the foliage. This angle depends on (1) time of the day, (2) latitude and (3) leaf angle distribution of the foliage.
- Clearness of the sky (clouds, dust, pollution, etc.)

At an angle of incidence of 60° on a leaf the light intensity is about 13 % lower than at right angles and half when the angle of incidence is 30°. At the equator the average gross assimilation of a closed canopy with adequate water supply on a clear day is theoretically 41 kg dry matter per hectare per hour, whilst at 50° N. Lat. in June the theoretical production is 32 kg/ha per hour. This can partly be explained by the smaller average angle of incidence of the sun's rays at 50° N. Lat. than at the equator, but a greater part of this difference is caused by the deeper penetration of the light in the leaf canopy at higher light intensity (due to a greater angle of incidence of radiation). Not much is known about the effect of differences in leaf angle distribution for different genotypes (e.g. *tuberosum* type and *andigenum* type) on the rate of photosynthesis per unit leaf area.

Goudriaan & van Laar (1978) estimate that on an overcast day the daily gross assimilation of a crop under a closed canopy with an adequate water supply is about half the assimilation on a clear day (Annex 1). However, Winkler (1983) observed that at an altitude of 610 m there is a lesser effect from light intensity on net photosynthesis (fig. 21).

To estimate crop production, the rate of photosynthesis should be combined with the area of green foliage that intercepts light.

Light interception Light interception is determined by:
- the incoming radiation (light intensity)
- area of the ground covered by green foliage
- foliage structure.

The intercepted light (PAR) can be measured below the canopy with a rod containing photocells, and with a photometer to measure the incident light above the canopy. It is generally assumed that the percentage of light intercepted is equivalent to the percentage ground cover or slightly higher. So a crop with 50 % ground cover intercepts about 50 % of the incoming light. By finding out the global radiation from a nearby meteorological station (PAR is about half of the global radiation) and estimating the percentage ground cover, the intercepted radiation can be calculated.

In a crop with a closed canopy the lower leaves receive less light than the upper leaves. The distribution of light may be as follows:
- 10 % of the leaves intercept 60 % of the incoming light
- 60 % of the leaves intercept 30 % of the incoming light
- 30 % of the leaves intercept 10 % of the incoming light.

This distribution of the light in the leaf canopy is determined by the foliage structure and the angle of incidence of the sun's rays. De Wit (1965) calculated that the difference in daily photosynthesis between a planophile and an erectophile canopy cannot be more than about 15 %. It is striking that no exact data are available on differences in the net assimilation rate of a potato crop with more erectophile leaf distribution (i.e. *andigenum* haulm type) and a crop with more planophile leaf distribution (i.e. *tuberosum* haulm type).

Light interception is related not only to the ground cover of the foliage but also to the leaf area index. Taguchi et al. (1970) found that in Japan at a solar radiation of 20.8 MJ/m^2 per day potato production was highest at a LAI of 3.8 and with a radiation of 15.5 MJ/m^2 per day a LAI of 2.2 was optimum. So in regions with high light intensity more foliage is needed than in regions with low light intensity.

Obviously, during a long day more light can be intercepted than on a short day. Consequently, the production per day under long day conditions may be higher. So the theoretical maximum tuber production per day at 23° N. Lat. in December (e.g. Bangladesh) is almost half the daily production at 52° N. Lat. in June (e.g. the Netherlands). (Difference in day length is 10.43' and 16.46' respectively.)

4.2.1.4 Leaf age

Effect of leaf age on rate of photosynthesis is shown in figure 23. In the period between 25 and 75 days after leaf appearance photosynthetic capacity declined in this experiment, to one third of its initial value. To maximize the assimilation rate of a crop, old leaves should be replaced in time by new leaves. The importance of the various levels of new foliage (section 2.1) in relation to the ageing of leaves is clear from this. However, no exact data about photosynthetic rate and leaf age under different conditions are available. It is known that high temperatures, drought periods and shortages of nutrient supply accelerate leaf ageing. Moreover, formation of the various levels of new foliage usually happens in rather rapid succession. Consequently, at the end of a long growing season the leaves of the last level may be old. This is particularly the case when insufficient nitrogen is available (fig. 24). It is

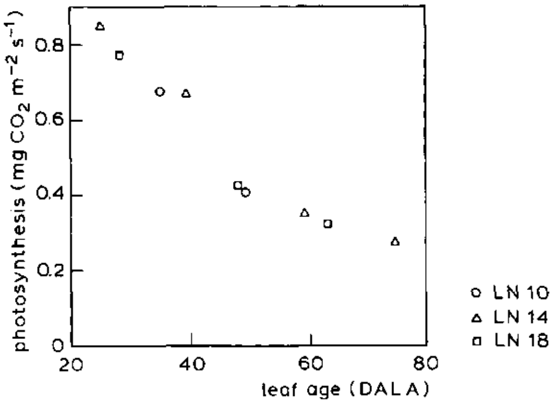

Fig. 23. Effects of leaf age on photosynthetic rate of leaves at different positions on the stem (numbered from the bottom) (Vos & Oyarzum, 1987).

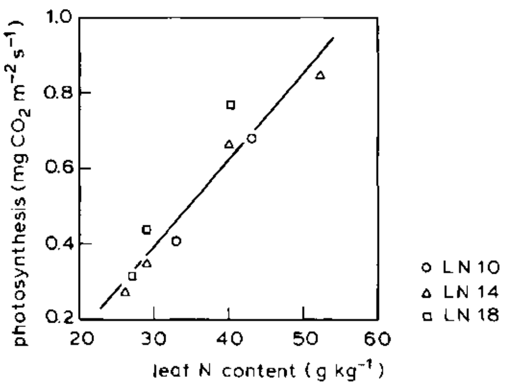

Fig. 24. Effect of nitrogen content of the leaf on photosynthesis ($r = 0.91$) (Vos & Oyarzum, 1987).

suggested that this is because there is a direct relationship between nitrogen content in the leaves and photosynthesis (Vos & Oyarzum, 1987).

4.2.1.5 Carbon dioxide concentration

There is a strong relation between carbon dioxide concentration and assimilation. The CO_2 concentration outside the leaves of a potato crop cannot be influenced appreciably in practice. What matters, in any case, is the concentration inside the leaves. This is governed by the concentration of CO_2 around the leaves (usually 0.03 %) and the degree to which the stomata are open, which in turn is determined by the transpiration rate, the supply of water to the leaves and the radiation.

Water vapour diffuses from within the leaves to the outside and CO_2 enters the leaf tissue via stomata. When the supply of water to the leaves is insufficient to maintain full transpiration the stomata begin to close. Although the diffusion resistance of CO_2

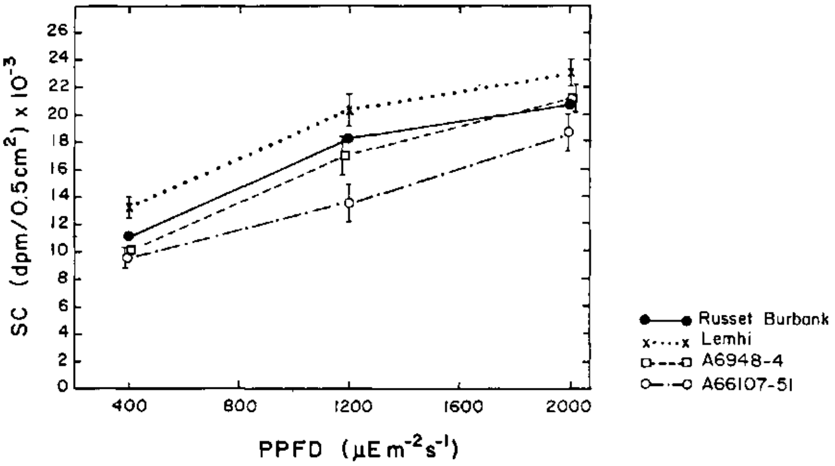

Fig. 25. Stomatal conductance (sc) by lower (abaxial) leaf surface of 4 potato clones as influenced by photosynthetic photo flux density (PPFD), (a measure for light intensity 2000 $\mu E\ m^{-2}s^{-1} \approx 2.6\ J/cm^2$ per minute) (Dwelle et al., 1983).

is greater than that of water vapour, CO_2 encounters a greater mesophyl resistance than water vapour. Consequently the stomata represent a smaller portion of the total resistance to CO_2 than water vapour does. This explains why partial stomata closure reduces transpiration more than it reduces photosynthesis and so water use efficiency is increased (kg water used per kg dry matter produced, fig. 28).

In the dark the stomata are closed, in the light they may be open. Stomatal conductance or resistance (a measure of the degree of aperture of stomata) relates to radiation (fig. 25). There are also cultivar differences in this respect.

Stomatal aperture and thus stomatal resistance or conductance can be determined directly or be derived from the water stress or plant water deficit. The latter can be satisfactorily described by the relative water content or by the energy status of the water content expressed as leaf water potential (LWP). The relative water content (RWC) is calculated as:

$$RWC = \frac{FW - DW}{TW - DW} \times 100$$

FW = fresh weight of leaf samples
DW = dry weight
TW = weight of full, turgid leaf samples

Winkler (1961) found that in field grown potatoes stomata begin to close at a RWC of between 92 % and 96 %. Closure was complete at RWC-values of between 76 % and 80 %. Values lower than 55 % were found to be lethal for potato leaves. However, Stegman & Nelson (1973) reported that transpiration did not begin to decline until RWC-values of 79 % to 80 % were reached. Moorby et al. (1975) found a strong correlation between the RWC of leaves and leaf water potential (LWP). Decreases

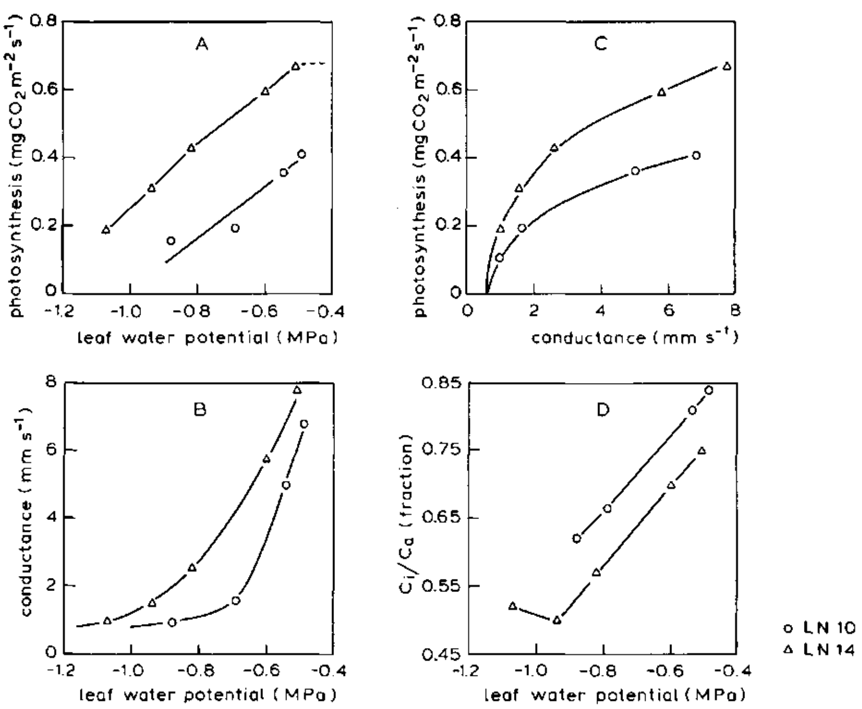

Fig. 26. Relation between leaf water potential and photosynthesis (A), leaf water potential and stomatal conductance (B), stomatal conductance and photosynthesis (C) and leaf water potential on the ratio of CO_2 inside and outside the leaf tissue (D) (Vos & Oyarzum, 1987).

in LWP and PWC were associated with a decline in photosynthesis. Figure 26 shows the relationship between photosynthesis and LWP (A) and stomatal conductance (C) and the relationship between LWP and stomatal conductance (B). LWP is associated with the CO_2 concentration inside and outside the leaf tissue (fig. 26D) and so the effect of CO_2 concentration in the leaf tissue on photosynthesis seems to be the likely cause. However, Schapendonk et al. (1988) concluded in their experiment that stomatal closure is not the cause of the reduction in photosynthetic rate but that both show a correlated response to water stress.

The diurnal changes in radiation, leaf temperature, relative humidity, stomatal conductance and leaf water potential, and net photosynthesis are shown in figure 27. The dramatic reduction in photosynthesis between 13.00 and 14.30 h can only be explained by the change in LWP or stomatal conductance and so by a decline in CO_2 in the leaf tissue. Furthermore these data demonstrate that a crop grown on sandy loam soil that has been irrigated three days before the observations were taken, do not produce to their optimum in the afternoon, due to drought stress. This is a very well-known phenomenon and is clearly shown in figure 28. Even in a well irrigated plot the net photosynthesis between morning and afternoon at the same radiation can differ by 20 % or more. This figure also demonstrates that an increase in the light intensity above 600 W/m^2 increases the transpiration rate more than the rate of photosynthesis, so there is a lower water use efficiency.

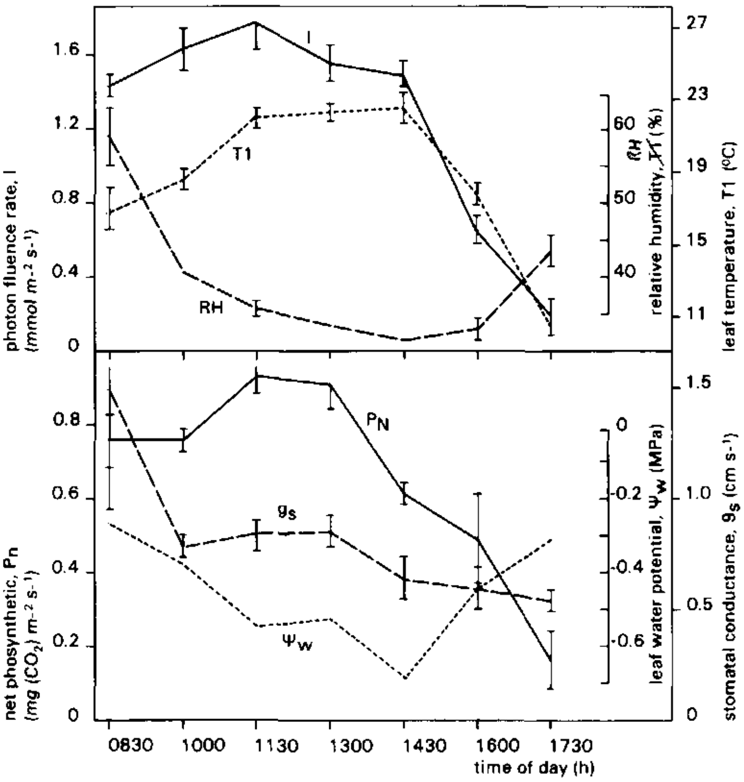

Fig. 27. Diurnal changes in photon fluence rate, leaf temperature (T1), relative humidity (RH), net photosynthetic rate (P_N), stomatal conductance (g_s) and leaf water potential (ψ_w) of a 56 day-old crop of cv. Kufri Sindhuri in the field (Ezekiel et al., 1987).

4.2.2 Respiration

Respiration can be divided into photorespiration and respiration in dark. Photorespiration is part of the photosynthetical process and is sensitive to light. Plants with C_4 assimilation have a much lower rate of photorespiration than the C_3-plants. In data about gross assimilation or gross photosynthesis the values for photorespiration have usually already been subtracted.

Dark respiration, which is not light sensitive, can be divided into maintenance-respiration and growth-respiration. Values of 20–25 % are often found for maintenance-respiration and for growth-respiration values of 5–10 %. Maintenance-respiration is less temperature sensitive than growth-respiration. The effect of temperature on dark respiration is shown in figure 29.

Particularly above 30 °C, respiration increases rapidly resulting in a rapid decrease in net photosynthesis. Even at moderate temperatures, 20–25 °C during the day time and 10–12 °C at night, 25–30 % of the total dry matter produced by a potato crop is respired; at higher temperatures considerably more. The respiratory cycles in the plants are a means of transferring energy from the products of photosynthesis, either

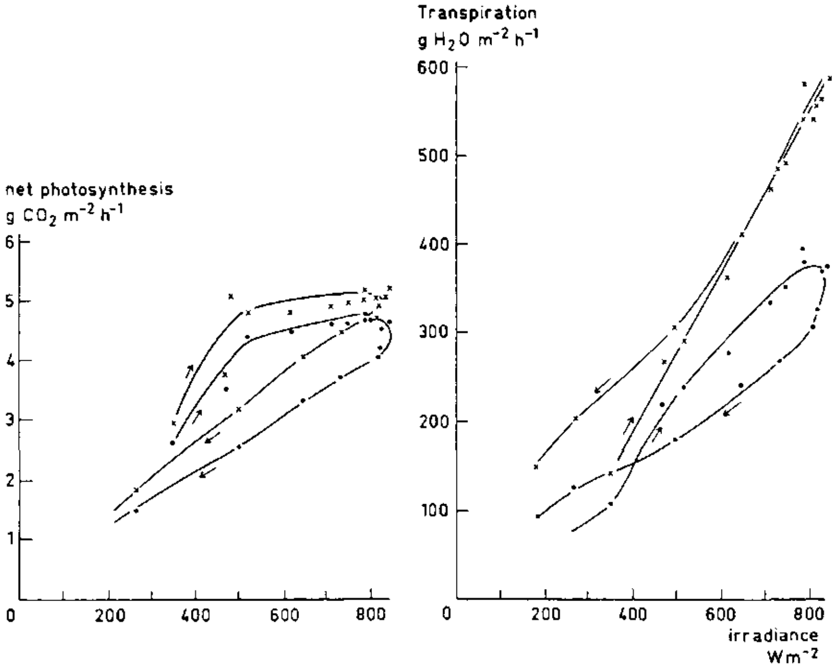

Fig. 28. Light-response curves of net photosynthesis and transpiration of a dry (.) and a wet (x) plot on 20 June 1978. Variety Saturna. Arrows indicate course of time. Photosynthesis measured for a group of plants of 1 m^2 (Bodlaender et al., 1985).

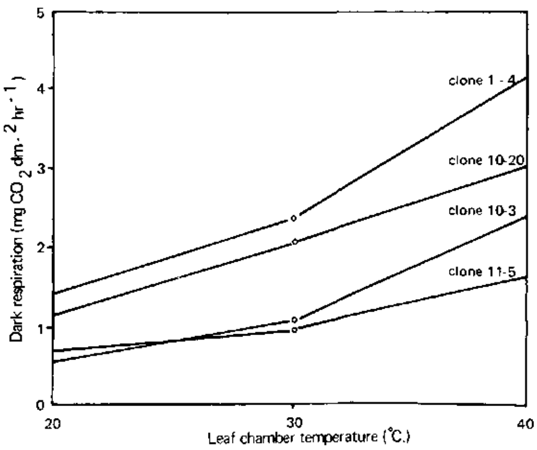

Fig. 29. Dark respiration of potato leaves as affected by leaf chamber temperature 20 minutes prior to measurement. Clones 10-3, 10-10 and 11-5 are *Solanum chacoense*; clone 1-4 is *S. acaule* (CIP Annual report, 1977).

freshly formed or stored, to synthesis and growth. This is accompanied by a loss of assimilated carbon. According to Burton (1978c) this loss is inevitable for a growing plant. A lower respiration rate of a clone (fig. 29) does not mean that the net exportable carbohydrate will be higher (Burton, 1978c).

4.2.3 Partitioning of assimilates

Assimilates produced in light by green foliage can be used for growth of foliage, roots and tubers and the assimilates can be stored in the tubers. During the first stage of growth all the assimilates are used for growth of foliage and roots; some weeks after emergence assimilates are also used for stolon growth and tuber initiation. A few weeks later, tuber growth begins and increasing amounts of assimilates are used for tuber growth and stored as starch in the tubers. In the last stage, all assimilates are transported to the tubers (see also fig. 30).

In the following section the factors influencing partitioning, and therefore the growth pattern of the plant will be discussed. In this section we will restrict ourselves to the part of the crop that can be used. Before that, however, it should be mentioned that partitioning can in itself affect the rate of photosynthesis. It is generally accepted that optimum transport of the assimilates from the leaves to the tubers (i.e. sink-source relationship) stimulates photosynthesis. It has often been observed that net photosynthesis increases with the onset of tuber growth.

The part of the crop that is usable, is called the harvest index and for the potato crop is defined as the total tuber dry weight divided by the total plant dry weight (including fallen leaves and roots). As it is difficult to collect all the fallen leaves and to weigh the roots, haulm weight can be determined roughly at haulm maximum and roots and stolons are usually taken to be 25 % of the total haulm. In the temperate zone harvest indices of 0.75–0.85 are quite common. In warmer climates the harvest indices tend to be lower and often a wider variation is also observed between cultivars or growing conditions. This suggests that temperature can strongly affect partitioning.

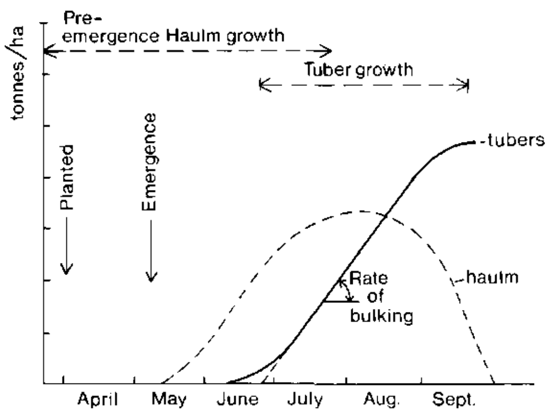

Fig. 30. Growth of a potato crop.

4.3 Factors determining growing pattern

4.3.1 Introduction

The wide differences in yield obtained in the various climatic regions cannot be explained by differences in photosynthesis, respiration and length of growing period alone, it is also necessary to take the growing pattern (i.e. dry matter partitioning in the plant) into consideration. The growing pattern (haulm growth, stolon growth and tuber growth) is influenced by: temperature, day length, light intensity, physiological age of the seed, plant density, nitrogen supply and moisture supply. These factors may have an effect individually, but there is also an interaction between them. This makes it difficult to define the influence of each of them separately. Furthermore, not all varieties and species react in the same way.

The growth of the potato crop shows a certain pattern. Three important periods can be identified in the growth cycle (or growing pattern) of the potato plant (fig. 30):
- pre-emergence/emergence
- haulm growth
- tuber growth.

4.3.2 Pre-emergence and emergence

After planting or even before planting, the seed tuber develops sprouts and roots. If the seed tuber has already developed sprouts before being planted, root formation starts immediately after planting, and emergence will be accelerated. Soil moisture is needed for the formation of roots and the early development of the plant. Low soil moisture and low soil temperatures delay emergence (chapter 8).

4.3.3 Haulm growth – tuber growth

After emergence, the haulm and roots develop simultaneously. Haulm growth and root growth are correlated.

Tuber growth may start slowly about 2–4 weeks after emergence and continue at a constant rate (i.e. bulking rate) over a fairly long period. Under favourable conditions bulking may be as high as 800–1000 kg/ha per day. During part of the growing period haulm and tuber growth proceed simultaneously, showing an interrelation. Late tuber growth is related to excessive haulm development and early tuber growth to less abundant haulm growth.

In figure 31 the growth patterns of two crop types are given: a short cycle crop and a long cycle crop. The features of the short cycle crop are: moderate haulm growth, early tuber growth and early maturity. This type of crop produces a relatively high yield in a relatively short period of time.

On the other hand, a long cycle crop develops a more extensive haulm, tuber growth begins later and maturity also comes later. Early in the growing season this type of crop gives a relatively low yield but later on it usually outyields the short cycle crop owing to the longer growing period. The type of crop which should be grown depends on the available growing period. If the period available is short, i.e. if harvest has to be early, the short cycle crop often produces the highest yield.

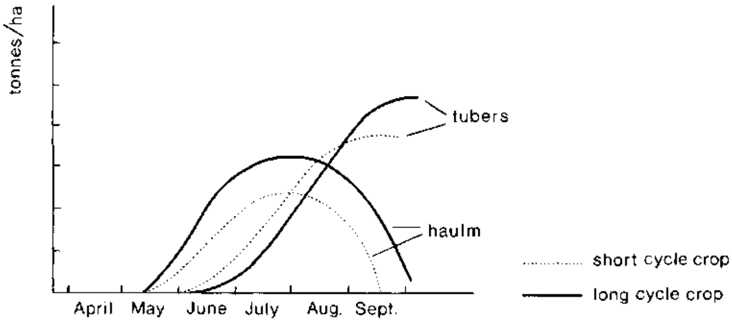

Fig. 31. Growth of a short cycle and a long cycle potato crop.

If, on the contrary, the available growing period is long, a long cycle crop will do better. To obtain the highest possible yield, the growing type of the crop should be matched to the length of time available for growing. However, long cycle crops may be risky, e.g. if a long cycle crop cannot utilize the latter part of the period available because of drought, blight, etc., the yield may be greatly reduced and the crop will have wasted assimilation products on haulm growth, which was not used for increasing tuber yield towards the end of the growing season.

4.3.4 Factors affecting haulm growth and tuber growth

Although there is an interaction between the factors which influence tuber formation, each of them may have an effect of its own on tuber growth and haulm growth (table 20).

4.3.4.1 Day length and temperature

Day length has a considerable influence on the growth habit of the potato. Under short day conditions the plants show early tuber formation, the stolons are short and the haulm remains small. Under long day conditions the plant produces tubers later in the season, the stolons grow longer and haulm growth is more abundant. Under

Table 20. Factors influencing the growth type of a crop.

Long cycle crop	Short cycle crop
Long day	Short day
High temperature	Low temperatur
Low light intensity	High light intensity
Physiologically young seed	Physiologically old seed
Low plant density	High plant density
Heavy nitrogen dressing	Light nitrogen dressing
Liberal moisture supply	Restricted moisture supply
Gibberellic acid	B9 and CCC

long day conditions some varieties and species do not start tuber growth at all. It has been suggested that each variety or species has its own critical day length. According to this view, tuber formation takes place only if the day length is equal to or shorter than the critical day length. The critical day length of European late maturing varieties is shorter than that of the early ones. If placed under short day length conditions the growth habit of European late maturing varieties changes more than that of early maturing varieties. As temperature also influences tuber formation and as there is also an interaction between temperature and day length, it is therefore better to use the word thermophotoperiod than photoperiod.

Krug (1965) studied the influence of temperature and day length on a number of European varieties (fig. 32). This experiment gives the actual yields after a short growing period (48 days after emergence) and is thus an indication for tuber initiation and early tuber growth and not a prediction of the final tuber yield after a long available growing period.

The following is often observed:

- Short day length and lower temperatures generally stimulate tuber initiation (low night temperatures are more effective than low day temperatures).
- At low and moderate temperatures, day length, as far as its effect on tuber initiation is concerned, has more influence on long cycle than on short cycle varieties.
- Under long day conditions, high temperatures greatly restrict tuber formation.
- Under short day conditions and high temperatures, short cycle (i.e. early maturing) varieties initiate and develop tubers considerably earlier than long cycle varieties.
- At high temperatures tuber initiation starts earlier under short day conditions than

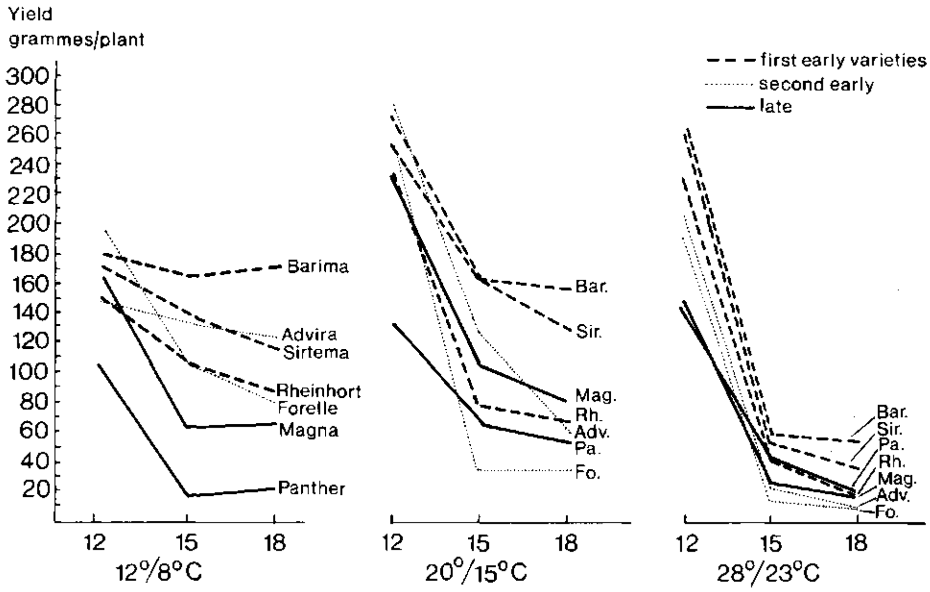

Fig. 32. Tuber yield of various potato varieties (48 days after emergence) at different temperatures (12 °C day - 8 °C night and 20 °C day - 15 °C night and 28 °C day - 23 °C night) and at different day-lengths (12, 15 and 18 hours) (Krug, 1965).

under long day conditions, which makes it possible to produce potatoes in tropical countries where days are short. The short day compensates for the high temperatures.

At high temperatures heavy nitrogen dressings can cause such a delay in tuber formation that yields are greatly reduced. Once tuber growth has been established, day length and temperatures have less effect on the further growth habit of the plant. It is often found that intermediate soil temperatures 15–18 °C are most favourable for potatoes.

4.3.4.2 Light intensity

At lower light intensities haulm growth is stimulated and tuber growth delayed. The difference in light intensity at high and low altitudes may influence the growth habit.

4.3.4.3 Physiological age of the seed

The age of the seed often affects the production pattern of the potato. Kawakami (1952), Madec & Perennec (1955) and others, demonstrated that using old seed induces an earlier crop. The harmful effect of using seed which is too old may be more pronounced under short day conditions than under long day conditions. Seed grown in cool climates and stored at low temperatures still behaves as relatively young seed even after 8 or 9 months storage, while seed grown under high temperatures after the same amount of time in storage may already be relatively physiologically aged. Hence, it is better to use the term physiological age than chronological age (see also fig. 20).

The differences observed between crops grown from old and young seed may partly be due to the greater number of stems produced by older seed.

4.3.4.4 Plant density

A high plant density stimulates early tuber growth (and also an earlier maturing crop). The reason for this may be that in a high plant density crop fewer lateral shoots are formed than in a low density crop. It may also be due to less nitrogen per stem being available in the former case.

4.3.4.5 Nitrogen and water

Crops supplied with high levels of nitrogen reach maximum tuber production at a later date than those where the level is lower. Nitrogen stimulates haulm growth and although tuber initiation may start almost as early with high levels as with low levels, less dry matter is available for the tubers during the first period of their growth. It has been demonstrated that higher amounts of nitrogen can be applied with increasing plant densities.

High levels of nitrogen may lead to haulm development which is too abundant, a delay in tuber initiation, reduced yields, harvest of immature crops and may even affect tuber quality.

With high temperatures and moist soil conditions the effect of nitrogen on the growth habit is more pronounced than with lower temperatures and drier conditions. Plants grown in soil with plenty of moisture (e.g. peat soils) exhibit more abundant haulm growth and later tuber initiation than plants grown in soils with less available water (e.g. clay soils).

4.3.4.6 Varieties and species

Varieties and species which tuberize under short day conditions may, under long day conditions, show a delay in tuber formation, or even form no tubers at all, especially if temperatures are high. Late varieties in long day areas tend to behave as short cycle (e.g. earlier maturing) varieties under short day conditions. Long cycle (late maturing) varieties react more strongly in this way than short cycle (early maturing) varieties.

Moreover, as temperature interacts with day length on the growing pattern of cultivars, it is not always possible to predict how varieties will react under different climatic conditions (fig. 32).

4.3.4.7 Growth regulators

Natural plant hormones are important in the distribution pattern of dry matter in plants. When applied to the seed or the crop, gibberellic acid stimulates haulm growth and delays tuber growth. When B9 or CCC are applied to a growing crop haulm growth is restricted initially and tuber growth is stimulated, but later in the season haulm growth is more abundant if the application was made early. Although favourable effects by the application of growth regulators have been demonstrated in experiments only some are used in commercial crops on a limited scale (e.g. MCPA to reduce second growth), because:

- unfavourable side effects may occur (e.g. mis-shaped tubers)
- timing of application and concentration to be applied depends a great deal on stage of crop growth, weather conditions, etc.

Gibberellic acid is used on tubers for shorten dormancy (section 7.5).

4.3.5 Interaction of factors influencing the growth pattern

Several factors influencing the growth habit of a potato crop have already been mentioned. Factors stimulating growth of the 'short cycle' type and the 'long cycle' type respectively are summarized in table 20. The factors mentioned in table 20 are most influential during the early stages of growth. Once the crop has reached its bulking stage (i.e. 'sink/ source' relationship has been established) the growth type is less affected by environmental conditions.

Although each of these factors may influence the growth of a potato crop individually, they also interact. Furthermore, the reaction of a given variety has to be studied in various ecological environments.

4.3.6 Flowering

Flower development is accelerated under long photoperiods. Flower primordia generally develop into flowers only under long day conditions; under short day conditions buds generally abort before blossoming.

Flowering is also affected by temperature. Although day temperature has little or no effect, Bodlaender (1963) found that at a night temperature of 12 °C buds but no flowers were formed, while at 18 °C abundant flowering occurred. Breeders use several methods for stimulating flower growth:
- providing long days (e.g. additional light of 300 W/m^2)
- removing newly formed tubers (e.g. by planting on stone)
- grafting on tomato.

4.4 Tuber yield

4.4.1 Introduction

Having discussed all the factors determining crop growth and development, we should now discuss the result of all these crop activities, viz. tuber yield. This yield can be expressed as the product of production per day and the number of days. It is also possible to express the yield as the product of the total intercepted PAR of green foliage, the efficiency of foliage to utilize this intercepted radiation, the harvest index and the inverse of the dry matter content of the tubers. Both systems will be discussed.

4.4.2 Tuber yield expressed as daily production and number of days

4.4.2.1 Daily production

In the period between the onset of tuber growth and the end of the growing period, yield increase is almost linear when growing conditions remain constant (fig. 33). This

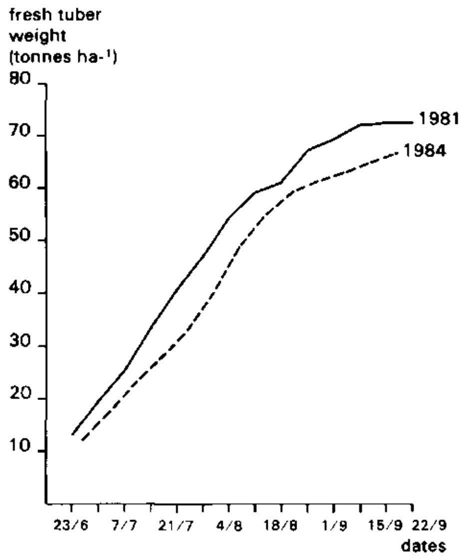

Fig. 33. Growth curves of well developed potato crops in the Netherlands (cv. Bintje) (PAGV; Lelystad).

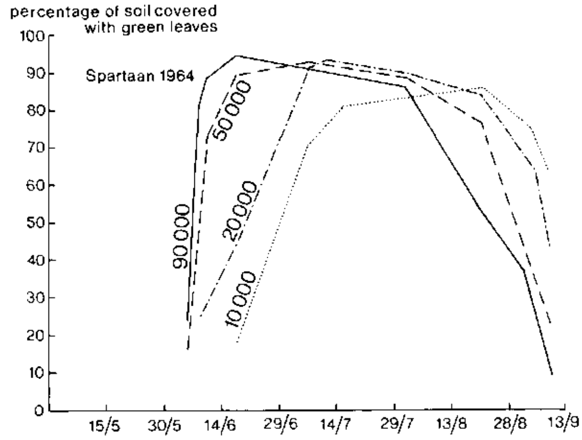

Fig. 34. Time and percentage of soil covering at various plant densities (Reestman, 1968).

phase of linear increase in tuber yield is called the bulking period and the fresh tuber weight increase per hectare and per day is called the bulking rate. A bulking rate of 700–900 kg/ha per day is quite common in the Netherlands. This bulking rate or the daily tuber production in that period is determined by the photosynthesis per unit leaf area, the leaf area absorbing light energy, the radiation, the respiration rate of the crop, the CO_2 concentration in the leaf tissue and the proportion of the assimilates transported to the tubers. All these factors have already been discussed. Now we will bring them together within two parameters, viz. the daily intercepted light (PAR) by green foliage (I) and the efficiency of the foliage to utilize intercepted light for *tuber* production (U_t), such that the harvest index has already been incorporated in U_t, which is not the case in U_p which we define as the efficiency of the foliage to utilize intercepted light for *plant* production.

We assume that I is linearly related to the area of the ground covered with green foliage. Figure 34 shows the ground cover for a cultivar with different plant densities.

If, during the bulking period, the canopy is closed so that 100 % of the light is intercepted, then I is equivalent to about half the daily observed global radiation. In Wageningen the daily global radiation in July and the first 2 weeks in August is about 15 MJ/m^2 on average, ranging between 16 on a clear day and about 4 MJ/m^2 on an overcast day. In a study of 20 cultivars in the Netherlands van der Zaag & Doornbos (1987) found a U_t of 2.25 g tuber dry weight per MJ intercepted PAR on average in 4 different years. This would mean $\frac{1}{2} \times 15\ MJ/m^2 \times 2.25$ g tdw per MJ = about 17 g tuber dry weight per m^2 which is about $10^4 \times 100/20 \times 17$ g = 850 kg tubers per hectare per day (assuming a tuber dry matter content of 20 %). This is in the range of the 700–900 kg/ha per day mentioned earlier. The average is rather lower in commercial fields because the ground is not always 100 % covered by green foliage, moreover U_t is often rather lower than 2.25 g tuber dry weight per MJ in commercial fields where growing conditions are not always optimum.

4.4.2.2 Number of production days

To obtain a high tuber yield the bulking rate should be high and the bulking period should be long. A late maturing cultivar (e.g. long cycle crop, fig. 31) will therefore yield more than an early maturing crop provided that the available growing period is also long. As has been mentioned, when the growing period is short an early maturing cultivar is more efficient.

When studying the possibilities of crop improvement in a region, both the increase in production per day and the increase in the number of production days should be considered. The increase in tuber yield per hectare in the Netherlands in the period 1955–1975 was caused mainly by an increase in number of production days (especially better late blight control, and a higher rate of N-application), whilst the small yield increase over the last decade is mainly due to a small increase in production per day.

4.4.3 Tuber yield explained in terms of intercepted PAR, utilization coefficient of foliage, harvest index and tuber dry matter

To understand crop yield better it may be useful to explain tuber yield (y) in terms of the total intercepted PAR by green foliage during the whole growing period (I), light utilization (U_p), harvest index (R) and tuber dry matter (D).

$$y = I \times U_p \times R \times 1/D$$

An early crop under Dutch conditions will usually intercept about 400–500 MJ/m^2 and a late maturing crop often 500–700 MJ/m^2.

Utilization coefficient (U_p) is calculated on the basis of the total plant dry matter production and cumulated light interception. In our situation 2.0–3.0 g plant dry weight per MJ is fairly common. Values of 0.75–0.85 are often found for harvest indices and tuber dry matter generally varies from 20–24 %.

For early maturing cultivars this would mean a tuber yield of 400 MJ $\times$ 2.5 g/MJ $\times$ 0.80 $\times$ 100/20 = about 40 tonnes/ha and for late maturing cultivars: 600 MJ $\times$ 2.5 g/MJ $\times$ 0.80 $\times$ 100/22 = about 55 tonnes/ha.

In the following chapter examples will be given how such calculations can be used to explain yield differences and how crop improvement activities can be implemented based on these calculations.

5 A method for calculating tuber yield

5.1 Methods for simulating crop growth and/or calculating tuber yield

The growth of plants and crops in the field is subject to many complex interactions with the environment. Changes in temperature (e.g. between day and night), radiation, day length, nitrogen and water supply, diseases and pest attack, etc. can all affect the performance of the crop in various ways. With a computer programme various environmental factors can be followed and continuously integrated. So several dynamic models have been developed which simulate crop growth.

Crop growth may be limited by:
- climate (e.g. day length, temperature and radiation)
- nutrient supply
- water supply
- herbicides
- diseases and pests.

Usually, the models developed are specific to one of these limiting factors, e.g. the model POTATO by Ng & Loomis (1984) is specific to the climate limitation, and the SWACO model by Feddes et al. (1988) to the limitation of water supply.

These dynamic models, which are often complicated, require a considerable amount of knowledge, and data about the crop,with regard to nutrients and water uptake, climate, diseases and pests before they can be successfully applied in practice. Such models have proved to be very instructive to researchers because they clearly show where our knowledge about these interactions is inadequate. If, however, our knowledge is insufficient or only estimates of tuber yield are needed, simple static regression models can be used. The positive aspect of these simple models is their ease of use and how they clearly show the main aspects of crop production. Moreover, it appears that the estimates of crop yield obtained with these simple models is often no less reliable than the estimates from the complicated models.

Examples of these simple static models are the models developed by Sands (1988) in Australia, by MacKerron & Waister (1985) in Scotland and by van der Zaag (1984) based on the model of de Wit (1965), but with a revised function for the dependence of photosynthesis upon day and night temperature, and incorporating the developments of Rijtema and Sibma.

The model developed by MacKerron & Waister (1985) predicts the length of the period between planting and closed canopy, and if the date of haulm destruction is known, the cumulative solar radiation interception can be estimated and thus tuber yield, based on the assumption of a linear relationship between light interception and tuber dry matter production. They assume that 1.43 to 1.89 g tuber dry weight is produced in the UK per MJ/m^2 of intercepted solar radiation. If expressed as intercepted photosynthetically active radiation these figures should be doubled.

In this chapter we will discuss in more detail the simple model used and adapted by van der Zaag, based on de Wit (1965), Rijtema & Endrödi (1970) and Sibma (1977). This model can be used to estimate potential yield, as described in chapter 1 (table 11).

5.2 Explanation of this simple model for calculating tuber yield

The method is based on the following assumptions:

- (1) Daily gross dry matter production (P) of a standard crop with a closed leaf canopy can be calculated from the daily production on a clear day (Pc) and the daily production on an overcast day (Po) according to the formula:

$$P = F \cdot Po + (1 - F) \cdot Pc$$

F = fraction of the day the sky is overcast.

De Wit (1965), later revised by Goudriaan & van Laar (1978), estimated Pc and Po for different latitudes, times of the year and rates of leaf photosynthesis at light saturation. A rate of leaf photosynthesis at light saturation = 3 g CO_2 per m^2 per hour is used for potatoes (Annex 1).

- (2) The proportion or fraction of the day the sky is overcast (F) can be calculated from the actual daily radiation (Ha), which is about half the global radiation and the daily total incoming visible radiation (400–700 nm) on a standard clear day (Hc), (Goudriaan & van Laar, 1978, see Annex 2) with the formula:

$$F = \frac{Hc - Ha}{0.8 \times Hc}$$

- (3) Respiration (both maintenance and growth respiration) and reduction of gross assimilation by non-optimum temperatures are combined in one factor K, which indicates the relationship between Pnet and P, as Pnet = K · P (table 21).

Table 21. Estimate of the effect of temperature on net production in relation to gross production of a crop under standard conditions (van der Zaag, 1984).

Maximum temperature (°C)	Minimum temperature (°C)	Net production in relation to gross production (K)
< 15	< 12	0.70
15-25	< 12	0.75[1]
15-25	> 12	0.70
25-30	< 12	0.60
25-30	> 12	0.55
30-35	< 15	0.45
30-35	> 15	0.40

1. Respiration 25% (probably too low for young plants).

- (4) The percentage of intercepted light (400–700 nm) if it is not measured, can be compared with the estimated percentage of ground cover. Provided no more information is available, it is assumed that these percentages are more or less equal.
- (5) The harvest index can vary considerably (e.g. 0.70–0.90). Usually a harvest index of 0.80 is taken in cool climates and 0.75 in warm climates.
- (6) The dry matter content of tubers can also vary from 15–25 %. Usually a dry matter content of 20 % is taken.

5.3 An example of how to calculate tuber yield, cumulative light interception and utilization efficiency of foliage

The model can be used to calculate the yield of any crop of which the foliage development is known, e.g. for an 'ideal' crop on which the estimate of potential yield is based.

The potential yield is taken to mean the yield from a crop that has made full use of the whole vegetative period and where the daily tuber production is optimum. This potential yield is the biological optimum yield, not the economic optimum yield. The latter is similar to the attainable yield. When a reliable estimate can be made of the foliage development of a crop, which may be considered economically optimum, the attainable yield can also be calculated.

As an example the following calculations will be given for a recently developed potato production region: El Kharj (south of Riyadh) in Saudi Arabia:

- potential yield based on an 'ideal' crop
- calculated and observed yield of a given crop
- comparison of the accumulated light interception and efficiency of the foliage of these two crops in utilizing the intercepted light.

From the climatical data of El Kharj given in table 22 it can be derived that the 'ideal' crop should be planted on 1 January, will emerge by 20 January, show a closed canopy by 1 March and that growth should be stopped by 1 May, due to the high temperatures and the high evaporation rate. The estimated ground cover of such a crop is given in figure 35 and the calculated average potential yield of 45 tonnes/ha is given in table 23.

Based on the ground cover and thus on the percentage of intercepted light and actual visible radiation, the accumulated intercepted light of the 'ideal' crop has been

Table 22. Climatical data at El Kharj (24 °C N. Lat) (average of 6 years). Chance of severe night frost till about the end of January.

Month	Temperature (°C)		Global radiation (10^6 J/m^2 per day)	Evaporation (mm/day)
	min.	max.		
January	6.0	22.0	14.97	3.8
February	8.0	25.7	18.23	5.7
March	12.4	29.3	20.23	7.7
April	17.0	34.9	22.10	9.0
1st decade May	20.1	37.0	–	10.3

Table 23. Calculation of the potential yield of the spring crop at El Kharj, based on the development of an 'ideal' crop as shown in fig. 35.

Month	Po[1]	Pc	F	P	K	Pnet	Intercepted[2] light (%)	Dry matter production (kg/ha per month)
	kg CH_2O ha/day							
January	135	307	0.22	269	0.75	202	2	125
February	160	353	0.20	314	0.60	188	50	2632
March	188	404	0.28	344	0.55	189	95	5566
April	215	452	0.34	371	0.40	148	90	3996
							Total plant dry weight	12319 kg/ha
							Haulm + roots (25%)[3]	3080
							Total tuber dry weight	9239 kg/ha

Total tuber fresh weight 100/20 × 9239 = 46.2 tonnes/ha
Average potential yield = about 45 tonnes/ha

1. Po, etc. see text.
2. See fig. 35.
3. Harvest index 0.75 is taken, due to the high temperatures at the end of the growing season.

Table 24. Accumulated intercepted light of on 'ideal' crop in El Kharj.

Month	Actual visible radiation (½ global radiation) (MJ/m^2 per day)	Intercepted light (%)	Intercepted light (MJ/m^2)
January	7.49[1]	2	5
February	9.12	50	128
March	10.12	95	298
April	11.05	90	298
Total			729

1. See table 22.

calculated and is given in table 24.

Similar calculations can be made to estimate the potential yield for a specific season and the yields of specific crops for which the foliage development is known. Let us assume that for a specific crop under research in El Kharj the foliage development is expressed by the dashed line in figure 35, that the observed tuber yield is 25 tonnes/ha with a dry matter content of 20 % and that the climatic data for that specific crop are similar to the data given in table 22.

The calculated tuber dry weight yield is then 6.9 tonnes/ha (or about 35 tonnes/ha tuber fresh weight) and the accumulated intercepted light is 554 MJ/m^2. These data have been presented in table 25. This table shows that the gap between the actual and

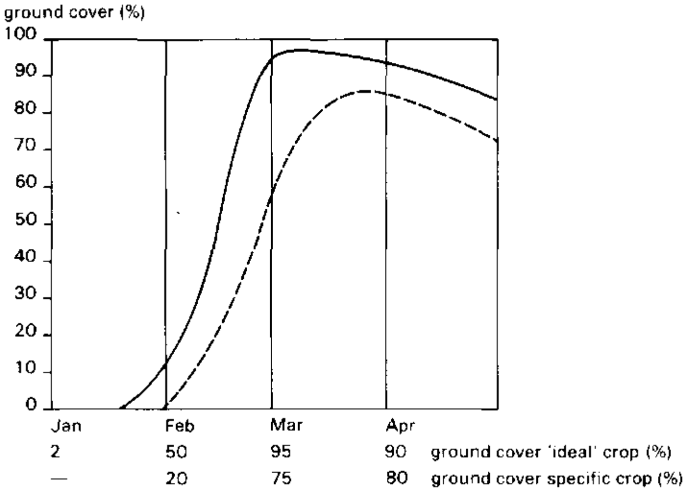

Fig. 35. Ground cover of an 'ideal' crop on which the potential yield is based (—) and the ground cover of a specific crop (- - -) at El Kharj.

Table 25. Comparison between an actual crop and an 'ideal' crop (table 23) in El Kharj.

	Actual	'Ideal'
Observed tuber dry weight (tdw) (g/m^2)	500	-
Calculated tdw	690	924
Cumulative light interception (MJ/m^2)	554	729
Utilization coefficient[1] (g tdw per MJ)		
based on the observed yield	0.90	-
based on the calculated yield	1.25	1.27

1. In this calculation the utilization coefficient is the efficiency of the foliage in using intercepted light for tuber dry weight production.

potential yield is almost 50 % caused by a lower light interception by the foliage of the actual crop (24 % less than the 'ideal' crop) and by slightly more than 50 % by a lower efficiency of the foliage utilizing the intercepted light for tuber production than the 'ideal' crop (utilization coefficient 29 % lower).

5.4 Application of the model

5.4.1 Calculating potential yield

The average potential yield for countries or production regions can be calculated and compared with the actual tuber yield. The actual yield to potential yield ratio gives an indication of the technical level of production in a given region (section 1.9).

Table 26. Estimates of fresh tuber yield, tuber dry weight yield of the actual and the attainable crop and calculations of tuber fresh weight and tuber dry weight of the 'ideal' crop as well as the cumulative light interception and utilization efficiency of the foliage of all three crops in Algeria (van der Zaag, 1987).

	Actual	Attainable	'Ideal'[1]
Culture de primeur			
Tuber fresh weight (kg/m^2)	1.2	2.5	3.0
Tuber dry weight (tdw) (kg/m^2)	0.24	0.5	0.6
Cumulative light interception (MJ/m^2)	100	190	235
Utilization efficiency (g tdw per MJ)	2.4	2.6	2.6
Culture de saison			
Tuber fresh weight (kg/m^2)	1.5	3.0	8.0
Tuber dry weight (tdw) (kg/m^2)	0.3	0.6	1.6
Cumulative light interception (MJ/m^2)	440	705	885
Utilization efficiency (g tdw per MJ)	0.7	0.9	2.2

1. On which the potential yield is based.

5.4.2 Identifying production constrains in a region

To demonstrate how this method can be used to identify the most significant yield reducing factors, Algeria will be taken as an example.

The actual tuber yield and foliage development of the average crop have been estimated for two growing seasons (culture de primeur: planting 1 November and harvest 15 February, and culture de saison: planting 1 March and harvest 1 July) by Algerian potato specialists. The foliage development of the economically optimum crop (i.e. attainable crop) and the tuber yield of the attainable crop have also been estimated by these specialists. The tuber yield of the 'ideal' crop and the accumulated intercepted light and the efficiency of the foliage to utilize the intercepted light (utilization coefficient) for all three crops have been calculated. All the data are summarized in table 26.

In the early growing season the gap between the actual yield on the one hand and the attainable and potential yield on the other is mainly caused by insufficient light interception, which means insufficient foliage growth. Factors that favour foliage growth, such as increasing the rate of nitrogen and the number of stems per plant (i.e. the seed tubers are physiologically too young!) should be considered to increase yield. The differences between the actual yield and the attainable and potential yield of the main season crop can be explained partly by differences in cumulated light interception and partly by differences in light use efficiency. Thus to improve the yield of the 'culture de saison' all the factors which influence these two parameters should be considered.

5.4.3 Explaining differences in yield in field experiments

Van der Zaag & Doornbos (1987) tried to indicate to what extent differences in cumulative light interception, utilization efficiency of foliage and harvest index have contributed to differences in the yield of varieties studied in 7 trials.

Two experiments done on the same soil type in two different years (fig. 36) will be used as an example to demonstrate that some extra observations can give valuable information. In 1984 the yield of the best yielding variety was less than 12 % below the potential yield, whilst in 1982 this was 26 % which shows that growing conditions were more optimum in 1984 than in 1982. This was also demonstrated by differences in the correlation coefficients between accumulated light interception and yield.

In 1984 when the harvest index was also determined, it was differences in light interception: 72 % (0.85^2), harvest index: 4 % ($(100\,\% - 98\,\%)^2$) and utilization effi-

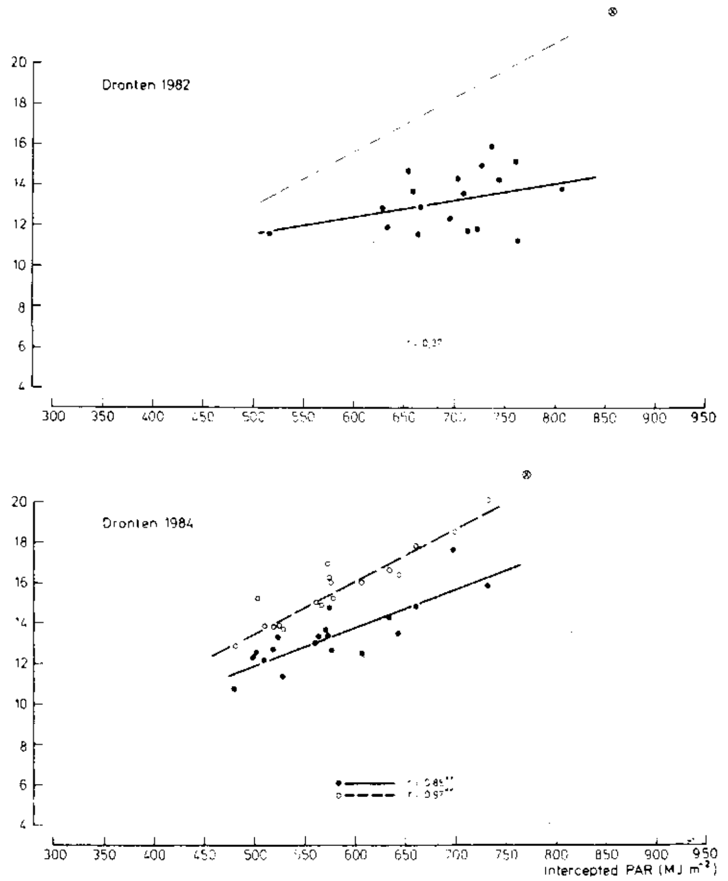

Fig. 36. Relationship between the accumulated light interception and tuber dry weight yield of two varietal trials with the same varieties in 1982 and 1984 in Dronten (van der Zaag & Doornbos, 1987). •observed tdw; ○ calculated tdw (in 1982 no harvest index available); ⊗ potential yield.

Table 27. Observed and calculated tuber dry weight, and calculated accumulated intercepted visible radiation and utilization efficiency of foliage of three soil treatments; I loose irrigated, II non-irrigated with a slightly compacted layer at ploughing depth, III non-irrigated with compacted plough pan. (Field trial by van Loon et al., 1985.)

	Treatments		
	I	II	III
Observed yield (kg/m²)			
tuber fresh weight	6.21	5.68	4.92
tuber dry weight (tdw)	1.34	1.24	1.05
Calculated tdw	1.41	1.29	1.07
Calculated accumulated intercepted light (MJ/m²)	580	530	460
Utilization coefficient			
observed g tdw per MJ	2.30	2.33	2.28
calculated g tdw per MJ	2.43	2.43	2.41

Potential yield in 1977 was about 2.0 kg tdw per m².
Accumulated light interception of the 'ideal' crop was 812 MJ/m² and its utilization coefficient was 2.46 g tdw per MJ.

ciency: 24 % (100 % - (72 % + 4 %)) which contributed to the differences in yield between the varieties. In 1982, however, only 12 % (0.37^2) of the differences in yield can be explained by differences in light interception and if we assume that differences in harvest index did not play an important role, as in 1984, the main cause of the yield difference must be put down to differences in the utilization efficiency of the foliage to utilize intercepted light.

To demonstrate that this method can be applied to all field trials, the research results of van Loon et al. (1985) have been used. They studied the effect of soil compaction at ploughing depth (plough pan). Based on their work, done in 1977, some calculations have been made and are summarized in table 27.

From this table it may be concluded that:

- Accumulated light interception with the best treatment is considerably less than the light interception for an 'ideal' crop, on which the potential yield is based (580–812 MJ/m²).
- The efficiency of the foliage to utilize light for tuber production was almost optimum for all three treatments, so the effect of irrigation or soil compaction on tuber yield in this experiment must be explained by its effect on foliage development and so on light interception, and not on the efficiency of the foliage to utilize this light.

Marshall et al. (1988) applied this method in Scotland to explain yield reduction in plots where all plants were secondarily infected with potato leafroll virus. The average yield reduction in four varieties was 50 % (see also fig. 44) and both the decrease in accumulated light interception and in efficiency of the foliage to utilize intercepted light contributed to this tuber yield reduction to the same extent.

6 Marketable yield and plant population

The tuber size is a more important indication of 'marketable yield' than the total tuber yield; this aspect should not be overlooked.

Big tubers are required (French fried) in some markets, in other markets smaller tubers are preferred (seed potatoes). Figure 37 shows what factors may influence total yield and marketable yield (e.g. tuber size, grading of harvested tubers, etc.). It provides a useful guide for analyzing a potato crop.

The tuber size-grading (or marketable yield) is influenced by two major factors, total yield and the number of tubers growing per unit area. The number of tubers is highly dependent on plant density.

6.1 Yield and tuber size

The number of tubers which will develop on the plants in a field is already determined early in the season. As the yield increases during the growing season, the

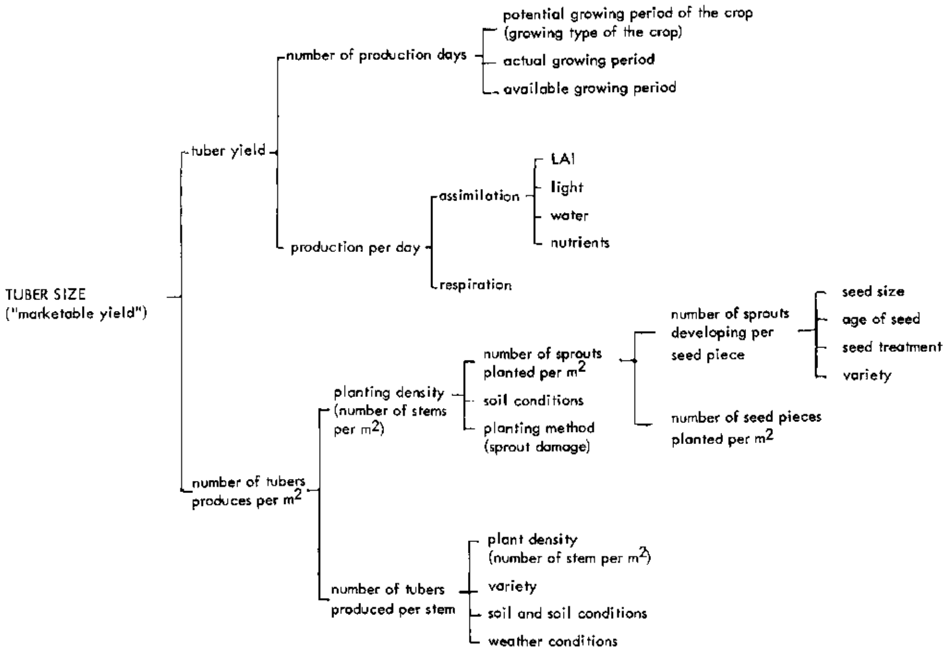

Fig. 37. Factors affecting total yield and marketable yield.

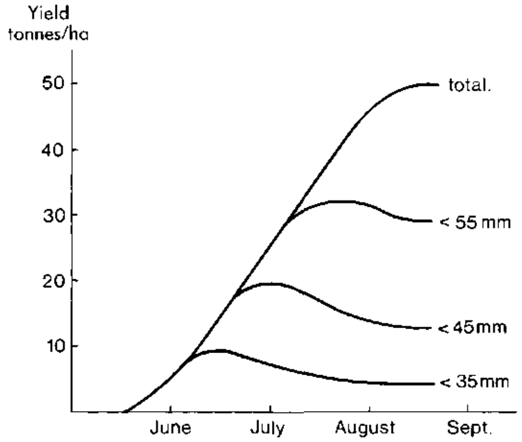

Fig. 38. Yield and tuber grading at different stages of growth (Bintje at a density of 20 stems per m^2).

average tuber size will also increase. In figure 38 an example is given of tuber yield during the growth of a potato crop. Early in the season, when the yield is still low, the average tuber size is small. Later on, the yield increases but so does the average tuber size. It may be concluded that in low yielding crops the average tuber size is generally small, while in high yielding crops the average tuber size tends to be large.

6.2 Plant density and tuber size

Plant density affects the total yield as well as the average tuber size. By increasing plant density, yield increases, but the average tuber size decreases. The increased yield at higher plant densities may be due to:

- the ground being covered with green leaves earlier (earlier in the season more light is intercepted and used for assimilation, fig. 34)
- fewer lateral branches being formed
- tuber growth starting earlier.

In figure 39 an example is given of the effect of plant density (expressed in stems per m^2) on tuber yield and tuber size. Increasing the plant density from low to high affects the yield more than increasing it from high to very high. The average tuber size is affected over a wide range of plant densities.

As previously explained, tuber size is influenced by plant density and yield. In areas or fields with low yields the plant densities should be lower than in areas with high yields, if the same tuber size is wanted. In low yielding areas, tubers of sufficiently large size can be harvested if the plant populations are kept low. However, as the growing methods in these areas are improved and yields increased, plant densities should also be increased. To produce small tubers, higher plant densities are needed than for the production of big tubers. It is possible, of course, to grow small tubers with low plant densities, but then the crop has to be harvested when it is still immature, resulting in low total yields. The average desired tuber size is the main characteristic which indicates the required plant density.

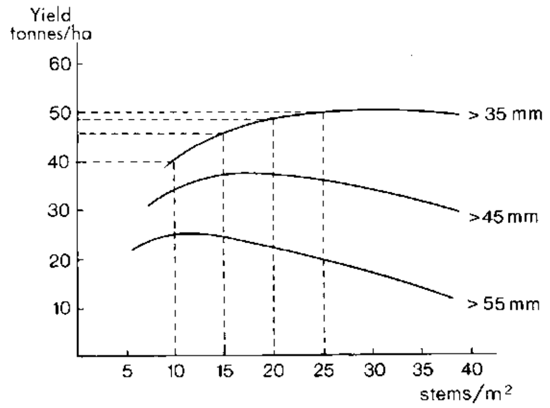

Fig. 39. Relationship between number of main stems per m^2 and tuber yield of the various grades (van der Zaag, 1972; after data from Reestman and Bodlaender).

6.3 Plant density and seed rate

The plant density of a potato crop is often given as the number of plants (sets, hills) per unit area. This definition of plant density is not very satisfactory since it is difficult to define a plant. As regards plant density it makes all the difference whether a plant develops 1, 2, 3 or even more stems. If, for example, 40 000 tubers are planted per hectare in a certain field and each tuber develops 2 stems, the density is 80 000 : 10 000 = 8 stems per m^2, whereas an average of 5 stems per tuber would have led to a density of 200 000 : 10 000 = 20 stems per m^2.

For most purposes it is sufficient to indicate plant density as the number of stems per m^2 (fig. 39). It is important to distinguish main stems from secondary stems. Counting at several (3 or 4) places in the field, the number of stems per 10 m row gives a good indication of the plant density (section 2.1). As indicated in figure 37, the density (number of stems per m^2) results from the amount of seed planted and the number of stems which eventually develop from the seed.

6.3.1 Number of sprouts per seed tuber

The number of sprouts developing from a seed tuber is influenced by the size of the seed, seed treatment and variety. This was discussed in chapter 2. The size of a tuber can be indicated either by its diameter or its weight. If grading is done by means of a grader or riddle, the size is determined by tuber diameter. A size indicated as 35/45 mm means that none of the tubers will pass through a square mesh of 35 mm, but that all the tubers will go through a square mesh of 45 mm.

In many cases tuber size is indicated as tuber weight. A long- shaped tuber of a certain riddle size weighs more than a roundish one of the same diameter (fig. 40).

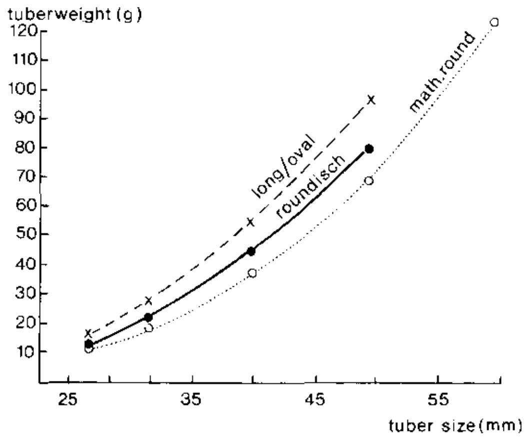

Fig. 40. Relationship between tuber size and tuber weight.

6.3.2 Potential number of sprouts and plant density

The number of sprouts developing on a seed tuber and the number of seed tubers planted may give an advance indication of the stem density to be expected. The actual stem density achieved, depends not only on the total number of sprouts planted, but also on the sprouting stage of the tuber, the occurrence of sprout damage and soil conditions.

6.3.2.1 Number of sprouts planted and number of main stems

Not all sprouts planted develop main stems. When a seed tuber has small and large sprouts, more large than small sprouts will develop into stems. A correlation has been demonstrated between the length of the longest sprout on a seed tuber and the length of the sprouts which do not develop into stems. There is a critical sprout length; sprouts which are shorter than this critical length will not develop into stems. The critical sprout length depends on the length of the longest sprout on the tuber (Goodwin, 1967).

Schepers & Hoogland (1969) demonstrated that, after planting, only 30 % of all the sprouts on a seed tuber developed into stems. They also demonstrated that a high percentage (more than 90 %) of the sprouts with visible root growing points developed into stems whereas only a low percentage (less than 1 %) of the sprouts without root growing points did the same. In a number of field experiments a high correlation was found between the number of sprouts planted with visible root points and the number of main stems which finally developed. The number of main stems was 98 % of the number of sprouts planted with visible root points. Sprouts with visible root points showed root growth one week after planting in moist soil.

6.3.2.2 Sprout damage and number of stems

A large number of sprouts will often be damaged, especially when planted mechanically. When a small number of sprouts on a tuber are broken, no new sprouts will replace the broken ones. If, however, a large percentage of the sprouts is damaged, new sprouts will develop (often more than were broken). Little sprout damage leads to low plant densities as the broken sprouts are not replaced. Heavy sprout damage of vigorous seed leads to high stem densities, as each of the broken sprouts is replaced by one or more new ones. The development of these new sprouts is, however, delayed. Heavy sprout damage leads to late and irregular crops.

6.3.2.3 Soil conditions and number of stems

Soil conditions greatly affect the percentage of sprouts which eventually develop into stems. Seed tubers planted in dry and/or cloddy soil not only produce a small number of stems but also show retarded emergence. Therefore, seed should always be planted in moist soil free from clods. In addition, seed should be covered immediately after planting to prevent the soil surrounding the tubers from drying out rapidly. It is easier to achieve the 'ideal' conditions for optimum sprout growth in a light soil than in a heavy clay soil.

6.4 Distribution of stems

If high yields per plant are desired, plant density should be low, whereas it should be high when high yields per hectare are required.

Two kinds of competition may occur in a potato field: competition between plants and competition within the plant (i.e. competition between stems). Competition between plants becomes increasingly important the smaller the distance between the plants. Competition within the plant becomes increasingly important the wider the distance between the plants and the larger the number of stems per plant (fig. 41).

6.4.1 Seed size and distribution of stems

If a reasonably high plant density (e.g. 20 stems per m^2) is achieved, seed size has no great influence on yield (fig. 39). Where the harvested crop should contain a high

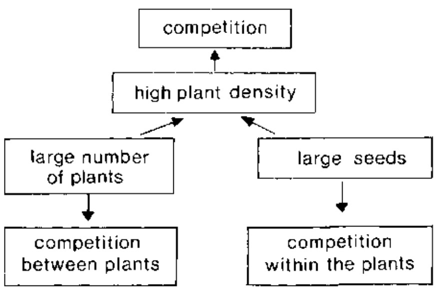

Fig. 41. Competition and plant density.

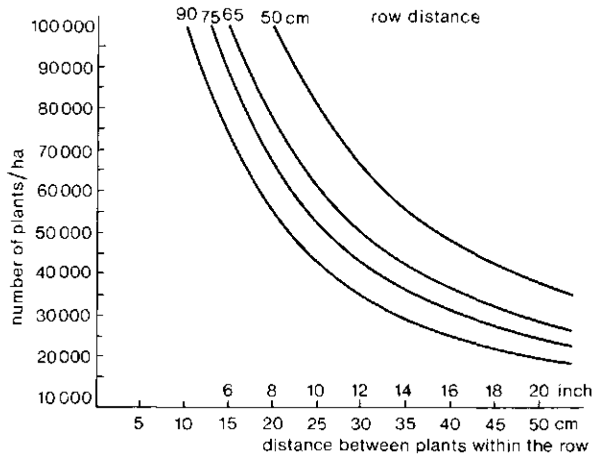

Fig. 42. Relationship between number of plants per hectare and row distance.

percentage of large tubers, plant density should be fairly low (especially in low yield areas). In such cases, the use of smaller seed may be an advantage (less competition between plants). In countries where seed cutting is not practiced it is important to produce seed tubers which are relatively small. In this case high plant densities are needed. In order to achieve this, big seed is often used for planting. In high plant density crops competition between plants is encouraged, therefore, competition within plants should also be accepted. In many countries seed cutting is practiced, especially when the seed size is large and a low plant density is required.

6.4.2 Row distance and distribution of stems

Potatoes can be grown in rows 50-100 cm apart. A narrow row distance may give a better distribution of the stems, but for technical reasons (possibility to make good-sized ridges to protect the tubers) it is much better to grow potatoes at wider row distances (75-90 cm). These do not affect yield, provided the growing conditions are such that haulm development is good. If, however, the row distance is wide and haulm growth is poor, the soil will not be covered with green leaves, resulting in low production. If the desired number of plants and the row distance are given, the distance to allow between plants within the row can easily be calculated (fig. 42).

6.5 Optimum density - seed rate

In Europe, it is generally assumed that 15-20 stems per m^2 are needed for a normal crop (of ware potatoes)and for a seed crop more than 30 stems per m^2. As the number of stems is not only determined by seed size, the required seed rate is more difficult to predict. Usually for ware crops 35 000-45 000 plants per ha (1.5-2.5 tonnes seed) are used but for seed crops more than 60 000 plants per hectare (3-5 tonnes seed) are needed. In the high yielding areas (with rain and/or irrigation) in the USA an average of 40 000 sets per hectare are used (1.2-2.5 tonnes of seed per hectare). The present tendency is to increase plant densities. In dry land production the number of plants per hectare is 15 000–30 000. However, if the fields in dry areas are irrigated, the number should be increased.

Depending on the purpose of the crop (big or small tubers), different seed rates are required. The average size of the harvested tubers is the main indication of the plant density (section 6.2). Low yields require lower densities than high yields. The worse the seed is in producing stems, the more seed must be planted (section 6.3). If large seed is used instead of small seed, an increased weight of seed has to be planted.

The economically optimum plant density is also influenced by the price of the seed and the price the farmer receives for his potatoes (table 28). This example shows that (within the range of prices given in table 28) it is unwise to increase plant density to more than 20 stems per m^2 if the price of the seed is twice the price of the ware potatoes. This is true for crops where the price obtained for both small and large tubers is about the same. In cases where the larger tubers fetch a much higher price than the small tubers, plant density should be lowered, while in cases where the small tubers fetch a higher price (e.g. seed crops) plant density should be even higher than that shown in table 28.

Table 28. Effect of increasing plant densities, increase in yield (35 mm) and increase in seed used (data from fig. 39).

Plant density (stems/m^2)	Increase in yield (tonnes/ha)	Increase in return (guilders per ha) at various prices per kg of yield			Increase in seed used, (kg/ha)	Increased seed costs (guilders per ha) at various prices per kg of seed		
		10 ct[1]	20 ct	30 ct		30 ct	50 ct	80 ct
10-15	5.9	590	1180	1770	600	180	300	480
15-20	2.6	260	520	780	650	195	325	520
20-25	1.3	130	260	390	700	210	350	560
25-30	0				750	225	375	600

1. Dutch cents

Table 29. Demonstration of increasing yield with increasing growing period.

Additional growing period	Increase in yield (700 kg/ha per day)	Increase in return (guilders per ha) at various prices per kg		
		10 ct	20 ct	30 ct
1 day	700 kg	70	140	210
3 days	2100 kg	210	420	630
1 week	4900 kg	490	980	1470
2 weeks	9800 kg	980	1960	2940
3 weeks	14700 kg	1470	2940	4410

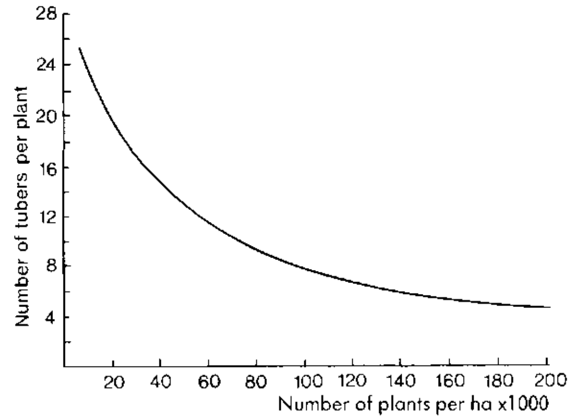

Fig. 43. Effect of the number of plants per hectare (plant density) on the number of tubers per plant (Schepers & Bus, 1977).

It should be taken into consideration that tuber size is also affected by yield (fig. 37). Crops often have to be harvested before maturity, as the tubers would otherwise grow too big. By increasing the plant density it may be possible to allow the crop to grow for several days, or even weeks, longer without this risk. Table 29 shows increasing yield and return.

Plant density also affects tuber quality. In low plant density crops the tubers grow too big. This may cause hollow heart, growth cracks, and mis-shaped tubers. There is also a tendency for more second growth to occur.

6.6 Density and multiplication rate

Plant density greatly affects multiplication rate. With increasing plant population the number of stems growing from a seed tuber decreases and the number of tubers per stem is less. Hence, the number of tubers produced per seed tuber will be reduced when higher plant populations are used.

In the example given in figure 43 the number of tubers produced per plant is in the order of 19, 14 or 12 respectively with a density of 20 000, 40 000 or 60 000 plants per hectare respectively. For the further multiplication of high class basic seed, low plant densities could be considered (e.g. 35 000) to achieve a high rate of multiplication. While for the production of cheaper certified seed, in which a high multiplication rate is less important, high plant densities should be used to produce relatively large numbers of small (i.e. seed size) tubers. Cutting of seed also leads to a higher multiplication rate (section 7.6).

7 Seed requirements – seed treatment

At planting time, the seed should be at such a stage that emergence takes place not too long after planting. The period between planting and emergence is the most delicate stage of a potato crop. A sufficient number of strong stems should develop per seed tuber. The seed should be free from serious diseases. Special care should be taken that no dangerous soil-borne diseases spread to fields, which have so far been free (e.g. *Pseudomonas, Corynebacterium*, etc.). In addition, care should be taken that the seed is not infected with diseases which are easily spread during the growing season and which may destroy the crop (e.g. *Phytophthora infestans*). The size of the seed planted should not vary too widely.

Seed can be obtained from various sources (section 16.2). Seed programmes aim at the production of quality seed and at reducing the risks of spreading dangerous soil-borne diseases.

7.1 Standards of health in relation to virus diseases

Much work has been done on the effect of virus diseases on yield. This effect depends on:

– Type of virus. One of the main effects of a virus on yield is caused by reduction in haulm size. From many data in the literature it may be assumed that if in the first

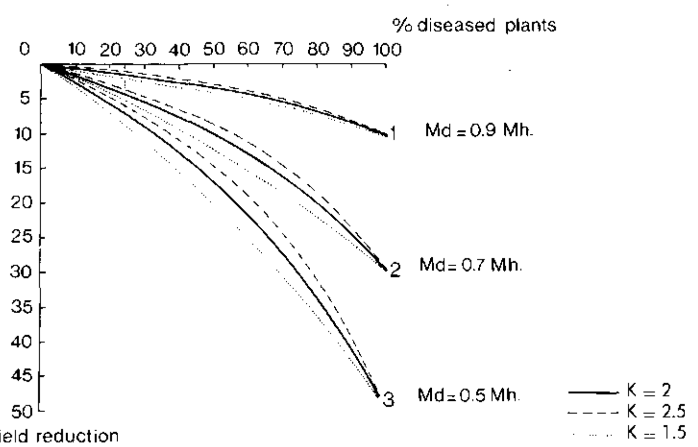

Fig. 44. Relationship between percentage of secondarily virus infected plants and yield reduction for three groups of viruses and for three compensation coefficients (van der Zaag, 1973; based on data from Reestman, 1970).

generation there is 100 % infection with secondary leafroll virus or Y-virus exhibiting severe mosaic symptoms, yield will be reduced by about 40–60 %. Viruses that produce less reduction in haulm growth, e.g. Y^N, may reduce yield by 20–30 %, while for viruses like S and X it is often stated that yield is reduced by no more than 10 %.
– Variety. The haulm growth of some potato varieties reacts strongly to virus infection while in others it is much less affected.
– Growing conditions. In a well developed crop the haulm of the neighbouring healthy plants will compensate for the reduced haulm growth of the diseased plants. Moreover, the diseased plants will produce a larger haulm under good than under poor conditions. The crowding coefficient depends on (1) weather conditions, (2) soil conditions (incl. manuring) and (3) variety.

For a crop showing 'normal' development Reestman (1970) found a crowding coefficient of about 2. Reestman applied the formula developed for crop growth in mixed cropping to fields with healthy and secondarily diseased plants.

$$Y = K \frac{Z_h}{(K \times Z_h + Z_d)} \times M_h + \frac{Z_d}{(K \times Z_h + Z_d)} \times M_d$$

Y = yield
K = crowding coefficient
Z_h = proportion of healthy plants
Z_d = proportion of secondarily diseased plants
M_h = yield of a crop with only healthy plants
M_d = yield of a crop with only secondarily infected plants.

In figure 44 the influence of secondarily virus-infected plants on yield has been estimated by applying the formula to three types of viruses and three crowding coefficients. Line one is $M_d = 0.9\ M_h$ (e.g. viruses X and S); line two is $M_d = 0.7\ M_h$ (e.g. Y^Nvirus); line three is $M_d = 0.5\ M_h$ (e.g. leafroll virus and Y^0). From this it can be concluded that type of virus is more important than the growing conditions.

By means of this graph the value of seed with different degrees of virus infection can be calculated, assuming that the financial return (yield × price) minus seed cost (seed rate × price) must be simular for different seed qualities.

The following formula can then be used:

$$a \cdot p - b \cdot x = (a - a \cdot z) \cdot p - b \cdot y$$

$$ap - bx = ap - a \cdot z \cdot p - by$$

$$x - y = \frac{a \cdot z \cdot p}{b} = \frac{a}{b} \cdot z \cdot p$$

x = price of healthy seed per tonne
y = price of poor seed per tonne
a = yield of healthy seed (tonnes/ha)
b = quantity of seed used (tonnes/ha)
z = reduction in yield
p = price of ware potatoes per tonne

Let us take the following example:
a = 30 tonnes/ha
b = 2 tonnes/ha
Seed I has 2 % leafroll virus
Seed II has 25 % leafroll virus
K = 2.

At what price difference between Seed I and II, expressed in multiples of the expected ware price, should the grower decide to use Seed I, assuming that Seed I and II are equivalent in all other respects?

According to figure 44 the reduction in yield due to using Seed II is about 8 % (i.e 8/100). So using the mentioned formula the break-even point is 1.2 p.

$$x - y = \frac{30}{2} \cdot \frac{8}{100} \cdot p = 1.2\ p$$

If the price difference between Seed I and Seed II is less than 1.2 times the price of the ware potatoes produced from the seed, the grower should use the healthy Seed I; if the price difference is more, he should use the poor Seed II.

7.2 Seed size - sorting and grading

In practice, seed of 35-80 g is usually used for potato production, but the use of both smaller and larger seed is common in certain areas. In general, it may be said that small and large seed give the same results provided the required stem density is achieved (table 30). Large seed is advantageous:
- if soil and weather conditions at planting are unfavourable
- if the growing season is short (faster sprout growth and earlier emergence)
- if there is the risk that during the first part of the growing season the crop will be damaged by night frost, hail or drought.

In the Netherlands about the same plant density (stems per m^2) is reached, on average with the variety Bintje, when seed rates (i.e. weight) of seed sizes 28/45, 35/45

Table 30. Small seed versus large seed.

Small seed	Large seed
More sprouts per kg of tubers	Fewer sprouts per kg of tubers
More difficult to reach high plant densities	Easier to reach high plant densities
Fewer stems per plant, may give better distribution of stems	More stems per plant, may give an unfavourable distribution of stems
Later emergence	Earlier emergence
Poor emergence if planted in unfavourable soil conditions	Better emergence if planted in unfavourable conditions
Difficult recovery of crop if damaged in the early part of the growing season	Easier recovery

and 45/55 are used in a ratio of about 4 : 6 : 9. The fact that the price ratios of this seed are often about 10 : 7 : 5 indicates that Dutch farmers not only consider the number of stems but also place additional value on larger seed (van der Zaag, 1973).

It is recommended to sort seed before planting. All tubers infected with serious diseases should be discarded, since these infected tubers may develop plants that could become new foci of infection in the field. Some diseases may lead to irregular emergence.

Grading is also important. Using seed with a wide variation in size will not produce a uniform crop. It is also much more difficult to predict the plant density if such seed is used. Care should be taken that during grading and sorting no serious diseases are spread to healthy tubers.

7.3 Physiological age and storage of seed

Besides its influence on the number of sprouts, physiological age may affect the growth pattern of the potato crop (section 4.3.4.3). When physiologically old seed is used, haulm growth is less abundant, tuber initiation starts earlier and the crop matures earlier. In a short growing period the use of physiologically old seed may lead to higher yields, whereas in a longer growing season the reverse is often true (fig. 31).

Plants grown from seed which is too old are often weak and low yielding. Such seed produces grows weak sprouts and 'little potato' frequently occurs, especially if the seed is planted in cold wet soil.

If the time between harvest and planting is too short, the seed will still be dormant or produce apical sprouts. Methods are available to break dormancy or to avoid apical sprouts (chapter 3). If the time between harvest and planting is too long the seed may be physiologically too old and produce too many sprouts or weak sprouts. The risk of seed being too old can be avoided to some extent if good growing and storage methods are available.

If the seed has to be stored for a long period (e.g. 5 months) the storage temperature should be 2-4 °C. Seed to be planted soon after harvest (e.g. within 1 or 2 months) should be stored at higher temperatures (e.g. 10-15 °C), as this shortens the dormant period (section 3.2.4).

7.4 Temporary storage of seed

When good storage facilities are available and large quantities of seed can be stored at source, the user of the seed should not take delivery of the seed too long before planting. However, if such facilities are not available, the seed should be delivered sooner so that the farmer can ensure that his relatively small quantity is better treated than it could be under non-optimum conditions among larger quantities by the vendor.

If tubers are already sprouting, further sprout growth should be restricted to a minimum (light, low temperature, ventilation).

- Never place potatoes in direct sunlight, always in the shade.
- Wherever possible,place the tubers in a well ventilated space, in chitting trays or in thin layers on the floor, not in deep crates.
- When ambient air temperatures are high, place opened bags upright on the floor,

never piled up.
- Protect tubers from rain and frost.

7.5 Breaking dormancy

If the time between harvesting and planting is too short, the potato seed may be still dormant and sprouts will not develop even in favourable conditions (section 3.3). Experiments have shown many chemicals to be effective in breaking dormancy. There are many problems involved in applying chemicals on a commercial scale: sprouting may be insufficient, tubers may rot and/or plant growth may be disturbed.

The chemical concentration and the time of application will depend on the conditions, the variety, stage of dormancy, method of application, temperature during treatment, etc. The following dormancy breaking techniques can be used:
- Storing. Storing seed in the dark under moist and dark conditions (risk of rotting).
- Cutting. Cutting of tubers breaks dormancy. In some cases this may be sufficient.
- Carbon disulphide (CS_2). This is a liquid which evaporates quickly (boiling point 46.3 °C). The gas is 2.5 times heavier than air, making air circulation necessary if the treatment takes place indoors. The gas is explosive and poisonous. Treatment should preferably take place in gas-tight containers or in trenches in the soil. The concentrations used vary between 30–35 ml/m^3 (in Brazil) and 50 ml per 800–1000 kg of potatoes (in Sri Lanka) . In experiments, 12.5–25 ml/m^3 room volume, at 20 °C for three days, have been successful (Meijers, 1972). Too high a dose may cause needle sprouts, death of sprouts and tuber rot.
- Thiourea (NH_2CSNH_2). Cut tubers are immersed in a 1–2 % solution for 1–2 hours.
- Ethylene-chlorhydrin ($CLCH_2CH_2OH$). This chemical, which is very poisonous and explosive, is applied in gas chambers at a rate of 1 litre (40 %) per 250–275 kg of potatoes for a period of 5 days.
- Rindite (Mixture: 7 parts $CLCH_2CH_2OH$, 3 parts C_2H_4CL 2, 1 part CCL_4). Tubers are treated with this very poisonous gas in a gas chamber for 4 days at 22 °C with 0.3 ml/kg of potatoes or for 2–3 days at 26–28 °C with 0.8–1.0 ml/kg of potatoes. The material is very phytotoxic.
- Gibberellic acid (GA). GA can successfully break dormancy if it penetrates the tuber. Since the skin does not allow the chemical to penetrate, it is only effective on cut pieces or on tubers with skin damage (e.g. freshly harvested tubers). An overdose of the chemical often causes elongated stem growth, reduced root formation and tuber deformation.

7.6 Seed cutting

In many countries seed cutting is practiced, especially if the seed size is large. This is done to:
- save seed and improve the multiplication rate
- improve distribution of the stem population
- increase the number of stems per seed tuber
- stimulate sprout growth.

The results of experiments in which cut seed was compared with whole seed, differ. The reason for this may be that the experiments were carried out with different plant densities, with various seed sizes and with various cutting methods. Differences in the physiological age of the seed may also have influenced the results.

By comparing the productivity of cut seed pieces and whole seed of the same weight, it is usually found that whole seed gives better yields. A whole seed tuber of a given weight has more skin surface than a cut seed piece of the same weight and consequently whole seed can produce more stems than cut seed. If at planting time, however, the tubers are still dormant or in the apical stage, cutting may lead to earlier emergence and development of more stems per seed. In this case the use of cut seed can give better results, when the same quantity of seed is planted per m^2.

Normally the percentage emergence is lower if cut seed is used (due to seed piece decay). It has been found that, in general, the percentage emergence is inversely proportional to the size of the cut tuber pieces. Another disadvantage of cutting may be the transmission of certain diseases with the knife: e.g. virus X, virus S, ring rot (*Corynebacterium sepedonicum*), black leg (*Erwinia carotovora* var. *atroseptica*), bacterial wilt or brown rot (*Pseudomonas solanacearum*), etc. This direct effect of cutting can be partly remedied by disinfecting the knife.

As a large number of problems may be introduced by cutting the seed, it should never be done if no great benefit is expected. When soil conditions are unfavourable (e.g. dry, wet, warm or cold) or the seed is physiologically old cutting should never be practiced. The tuber should never be cut into pieces which are too small. The seed pieces should generally weigh about 40 g (= 35 mm) and have 2 or 3 eyes (note: a tuber has more eyes at its rose end than at its heel end).

Under European conditions (plant numbers about 40 000; dormant period ended) it was found that cutting seed of 55 mm (i.e. using the same quantity of seed per unit area) did not increase yield. In areas with lower plant densities and seed nearer dormancy, cutting even smaller seed may be useful.

7.6.1 Measures to prevent seed piece decay

By taking measures to promote healing of the cut surface, seed piece decay can be prevented. After cutting, the superficial cells of the cut surface suberize and wound peridorm is formed below this suberized layer. The time needed for the formation of the protective layer depends on variety, age of the seed, temperature, humidity and the oxygen content of the surrounding atmosphere (section 2.3.2).

- Variety. Some varieties, especially early ones, are susceptible to *Fusarium* and are slow in forming wound healing substances. It is pointless to cut such varieties.
- Age of the tubers. Freshly harvested tubers suberize best. The formation of wound healing substances is delayed once the stage of apical dominance is over. Cutting seed which has been stored for a longer period of time is risky. Furthermore, potatoes become more susceptible to *Fusarium* with age.
- Humidity, temperature and O_2. Quick and complete wound healing requires high humidity, a temperature higher than approx. 12 °C and a sufficiently high oxygen content in the surrounding atmosphere. An oxygen content of less than 15 % results in incomplete wound healing.

The best results may be expected from measures that stimulate wound healing. Treating the cut surface with a dust containing at least 15 % carbamate may also help to reduce seed piece decay (see also section 13.2.1.2).

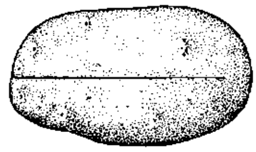

Fig. 45. A partly cut seed potato with the halves placed against each other.

7.6.2 Seed cutting in practice

In North America, seed is generally cut, in contrast to European practice. Seed is often cut just before planting, care being taken that the cut surface does not dry out, not only before but also after planting. Immediately after planting the seed pieces are covered with soil. To save labour at planting time seed is often cut in advance. Suberization is accomplished by maintaining the seed at a temperature of about 15 °C and a relative humidity of 85 % for approx. 4 days.

Slatted crates covered with damp sacks are good containers in which to suberize cut seed. To prevent the seed pieces from sticking together the containers are rocked from side to side within 24 hours of cutting the seed. Seed can also be suberized in sacks which are only half filled and stacked in such a way as to avoid undue heating. The stacks may be covered with moist sacks. Excess water is harmful.

A laborious but very good method of cutting is shown in figure 45. The seed is cut from rose end to stem, leaving the two halves together. This way the humidity at the cut surface remains high.

7.7 Pre-sprouting

Potato tubers should not be planted straight from cold storage. The eyes should at least be 'open' i.e. the greenish- yellow coloured buds should be visible. A tuber planted with the eyes 'closed' will emerge too slowly and the developing sprout is then easily attacked by micro-organisms. In many countries seed is pre-sprouted at the time of planting, showing sprouts of 1–2 cm.

Pre-sprouting leads to an early crop, early emergence and early tuber initiation (fig. 46). The resulting crop often gives a high yield, especially if the available growing season is restricted. Pre-sprouting also leads to regular emergence and to a regular crop (less subject to *Rhizoctonia solani*). The seed should be pre-sprouted correctly. The sprouts should be strong and firm at planting time. If the sprouts are too young or too long and consequently weak, they may easily break during planting. By correct pre-sprouting the seed is exposed to daylight at not too high a temperature, to harden the sprouts. Although pre-sprouting leads to earlier emergence and earlier tuber initiation it does not always result in a higher yield. This is the case if, for example, a variety is used with a growing pattern which is short in relation to the available period. Furthermore, weather conditions during the growing period influence the results obtained from pre-sprouting. Ideal pre-sprouting produces strong 1–2 cm long sprouts.

Light and ventilation are needed to harden the sprouts and avoid excessive sprout growth. In order to expose tubers to light and supply the necessary ventilation, they

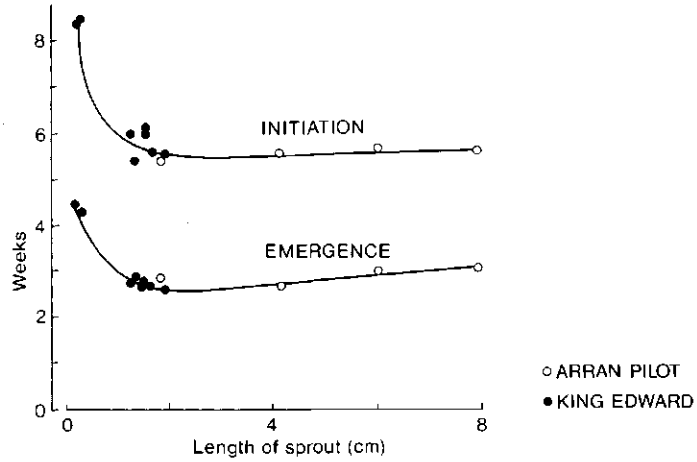

Fig. 46. The time from planting to emergence and to tuber initiation of Arran Pilot and King Edward varieties grown in the field from tubers with apical sprouts of the lengths shown (Headford, 1962; after data from Saddler).

are placed in thin layers on the ground or in chitting trays. Under these conditions, tubers with developing sprouts can be kept for a considerable length of time.

When pre-sprouting seed, tubers stored at a low temperature are first given a heat treatment (e.g. 3–4 days at 18–20 °C) until sprouts a few mm long develop. After this the tubers are given light and ventilation at a lower temperature (e.g. 10 °C).

Mini-chitting is much easier and less labour intensive. 1–3 weeks before planting, tubers are taken from the cold store and placed in bags in a ventilated area at a moderate temperature. The bags are not piled up. However, if planting is delayed the sprouts become too long. If tubers have apical sprouts before pre-sprouting starts, these sprouts should be first removed.

Pre-sprouting is expensive (in terms of labour and equipment) and should only be done if it gives far better results than mini-chitting. This may be the case if:
- the available growing period is short
- the seed is weak
- the soil temperatures are low at planting time
- there is a risk of seed piece decay and/or a risk of attack by *Rhizoctonia solani*
- it may be likely that planting will be delayed for a long time
- even emergence is needed (e.g. in seed potato production).

8 Soil requirements: seed bed preparation, planting and ridging

Soil tillage, seed bed preparation, planting and ridging should be done in such a way that it ensures not only quick emergence but also deep penetration of the roots and good drainage. It must also be possible to cover the developing tubers with sufficient soil. Tubers not covered with a sufficient layer of soil become green, are easily attacked by insects (e.g. tuber moth) or fungi (e.g. *Phytophthora infestans*) and their temperature may rise too high (section 11.2).

8.1 Impermeable layers

It is known that the potato has a weak root system, and that impermeable layers in the soil greatly reduce yield (table 27). Such layers limit rooting depth and thus the available water is limited in dry periods. Irrigation has to be applied much more frequently to soils of this type than where the roots are able to penetrate deeply. Another disadvantage of soil compaction and dense layers may be that after abundant irrigation or heavy rainfall the soil is saturated for too long, causing roots to die and tubers to rot. In figure 47 an example is given of root development and tuber growth in soil with an impermeable layer and in soil where this layer has been broken.

Felipe Canale (personal communication) in Uruguay found a positive correlation between potato yield and the depth of the A-horizon (fig. 48). It is advisable to break up existing dense layers and to avoid soil compaction during tillage operations.

8.2 Emergence and seed bed

At higher temperatures sprouts grow faster (chapter 3) and consequently higher soil temperatures promote quick emergence. However, at soil temperatures above 30° C

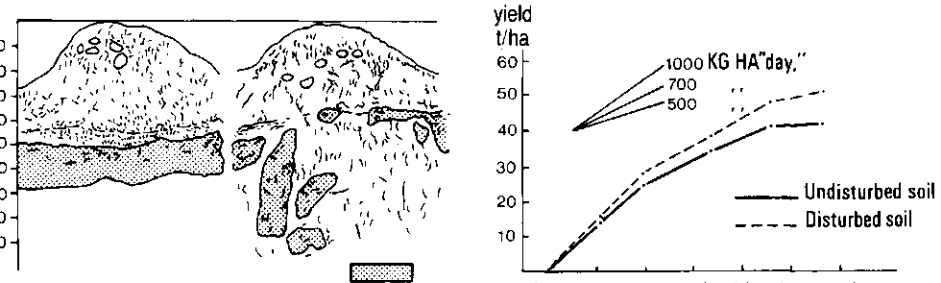

Fig. 47. Root development and tuber growth in soil with an impermeable layer and in soil where this layer has been broken (Wiebing & Schepers, 1977).

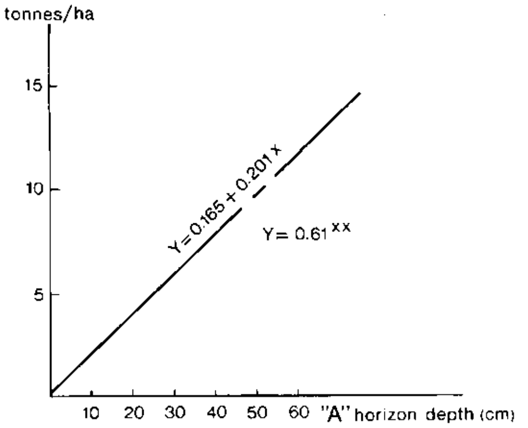

Fig. 48. Correlation and regression between depth of A-horizon and potato yield (Canale, personal communication).

Table 31. Average weight of seed tubers at given intervals after planting (percentage of weight when planted) (Letnes, 1958).

1952	Air-dry soil	Normal soil moisture	Saturated soil
10/5	100	100	100
15/5	100	106	103
23/5	96	110	106
29/5	97	121	-
4/6	95		
13/6	92		
1/7	74		
	sprouting failed, or weak sprouts were produced: no roots	all potatoes sprouted	all potatoes decayed

emergence can be very poor. After a cold season the temperatures are higher in the superficial soil layers than in the lower ones. Old, weak seed (physiologically old) is especially susceptible to low temperatures. If soil temperatures are low, shallow planting may be an advantage; higher soil temperatures allow deeper planting.

Soil moisture markedly influences germination of the seed. This was shown in an experiment by Letnes (1958), (table 31). Potato tubers were placed in air-dry soil, in soil with normal soil moisture and in water-saturated soil. Tuber weight and germination were recorded at various intervals after planting. Potato tubers require moist soil conditions at this stage. If the soil is too dry, the tubers lose weight, emergence is delayed and the number of stems is reduced (see also section 6.3.2.3). With normal soil moisture, emergence occurs rapidly and soon after planting the sprouts produce roots which take up water from the soil. This water uptake increases the weight of the seed.

In saturated soil the seed decays due to lack of oxygen. For this reason heavy irrigation soon after planting is detrimental. Thus, seed potatoes should be surrounded by moist soil or at least be planted on moist soil. The seed should be covered with a layer of soil sufficient to prevent the soil around the tuber from drying out too soon.

8.3 Planting depth and emergence

The time between planting and emergence is the most delicate period of a potato crop. Emergence is influenced by:
- quality of the seed (age and sprouting stage)
- soil temperature
- soil moisture.

If the seed quality is poor, particular attention should be paid to planting. Planting depth and method of soil preparation affect soil temperature and moisture conditions around the planted tuber. The planting depth should be adjusted according to the soil conditions (fig. 49). As soil in the deeper layers dries out more slowly than surface soil, planting should be deeper in dry conditions. Warm conditions make deeper planting possible; this is an advantage if temperatures are very high.

Deep planting is not necessary in moist conditions as there is no risk that the surface soil will dry out. In cool conditions too, shallow planting is advantageous.

8.4 Planting depth and covering the developing tubers with soil

The tubers of a developing crop should be covered with a sufficiently deep layer of soil. This is done to protect the tubers from direct light (which causes them to become green), from high temperatures (second growth), and from insect damage (e.g. tuber moth).

Where the stolons are formed depends on the position of the mother tuber. The location of the newly formed tubers in the soil depends on the position of the stolons and their length. The length of the stolons depends not only on the type of the plant or crop (variety, temperature, day length, etc., section 4.3) but also on the ridge size.

Good cover for the newly formed tubers can be obtained by planting deeply and by building a heavy ridge. As planting too deeply often delays emergence, it may be better to restrict planting depth provided the requirements of soil moisture, soil temperature and covering of the new tubers are met.

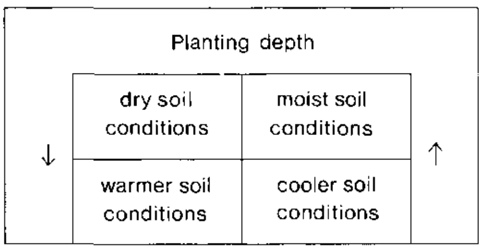

Fig. 49. Influence of planting depth on soil temperature and soil moisture.

The more shallowly the seed is planted, the higher and heavier the ridge should be. The ridge should not only be high but also broad at the top. The time of earthing up depends on soil moisture and soil temperature. The method of weed control should also be considered. When earthing up, green leaves, the top leaves in particular, should not be covered with soil.

8.5 Seed bed preparation

Seed bed preparation should start when the moisture content is right. Clods formed during soil tillage operations often remain in the ground until harvest (clod formation during soil tillage should be avoided, especially if harvesting is done mechanically).

In some soils and under certain conditions it is damaging to make the tilth too fine. This is the case with lighter soils, where heavy rainfall (or irrigation) may cause the surface to seal up and severe erosion of the ridges. Under dry soil conditions it is difficult to break down the soil, while cultivation of wet soil causes smearing. The soil should not be cultivated deeper than the moisture content of the soil allows. Since soil moisture is lost with each cultivation, the number of operations should be restricted to a minimum and done shortly before planting. Immediately after planting the tubers should be covered with an adequate layer of moist soil.

8.6 Ridging and time for final earthing up

Potatoes are generally grown on ridges. Ridges have the advantage that planting does not have to be done too deeply, while later in the season a ridge can be built up to ensure that the developing tubers are covered with an adequate layer of soil. The time at which the ridge should be made depends on planting depth, soil temperature, moisture conditions and the method of weed control used.

8.6.1 Soil moisture and soil temperature

If, after planting, it is expected that the soil temperature will be low and/or the soil surface may seal up then it is advisable not to make the final ridge too soon after planting but to wait until emergence or even until the plants are 15-20 cm high. If, on the other hand, the soil temperatures are higher and a drought period is expected

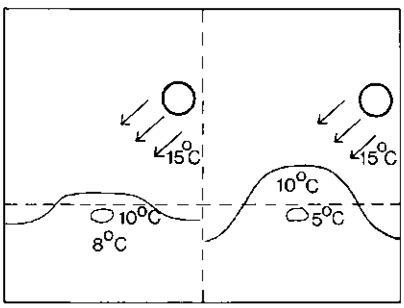

Fig. 50. The effect of ridge size on soil temperature at various places in the ridge.

after planting, it is recommended to make the final ridge soon after planting.

If the final ridge is made soon after planting, the seed will be covered with 12–14 cm of soil during its early stages of growth, whereas if the final ridge is made later, the seed is initially only covered with approx. 6 cm of soil.

In figure 50 an example is given of the influence of ridge size and soil temperature near the seed. In the example shown, the seed temperature is higher when covered with 6 cm of soil than with 12–14 cm. It should be noted, however, that too thin a layer may cause the soil around the seed to dry out quickly.

8.6.2 Weed control

- If mechanical weed control is applied in a number of operations the ridge is built up gradually. Each new operation takes place when fresh weeds start growing. The top layers of the ridge are removed first with a light harrow and later brought back onto the ridge with ridging implements.
- If using contact herbicides (e.g. Paraquat) which only kill growing weeds, the seed is covered with about 6 cm of soil after planting, and just before the potatoes emerge, the weeds then present, are destroyed by the contact herbicides. Weeds germinating later can be mechanically controlled by further ridging with ridging implements. The final ridge is made in one or two operations and is usually completed just before the leaf canopy closes.
- If using soil herbicides which have a residual effect but do not kill weeds that have already emerged (e.g. Linuron, Sencor), the final ridge has to be made and the chemicals applied before the weed germinates. Herbicides with residual and contact effects (e.g. Metribuzin) or mixtures of contact herbicides and soil herbicides are also applied when the final ridge has been made, but can be applied when weeds have already germinated.

8.7 Planting and ridging systems in the Netherlands

Before winter, the soil is ploughed to a depth of 25 cm (fig. 51A). In spring the soil is levelled and the seed bed prepared (fig. 51B). When planting, the seed is put in a small furrow and a small ridge is formed (fig. 51C). Some time after planting, the final ridge is made in one or more operations depending on the soil type (fig. 51D, E).

8.7.1 Light soils

A sufficiently deep layer of soil can be loosened on light soils with simple implements (e.g. a harrow) not only to cover the seed at planting time (small ridge see fig. 51C), but also to build up the final ridge with simple ridging bodies.

8.7.2 Medium light soils

On these soils simple implements can be used to loosen a sufficiently deep layer of soil to cover the seed at planting time (i.e. to create a small ridge), but it is often difficult to provide sufficient loose soil to make the final ridge. This can be overcome by using inter-row rotovators.

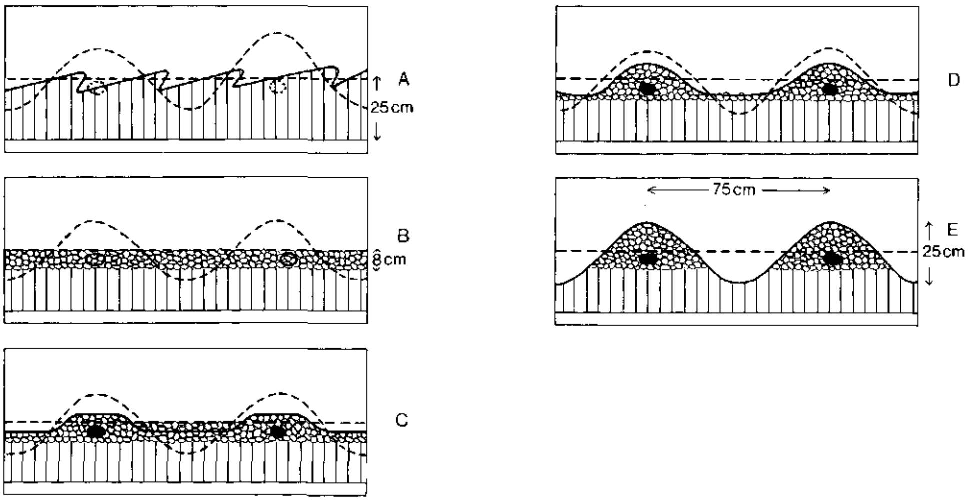

Fig. 51. Method of planting and ridging in the Netherlands.

On medium light soils power take-off driven harrows are often used for seed bed preparation. With these implements it is possible to loosen the soil sufficiently deeply to cover the planted seed and have enough soil to make the final ridge as well.

8.7.3 Medium heavy soils

On medium heavy soils power take-off driven harrows are normally used, although the layer of soil that can be loosened with these harrows without smearing is not much deeper than with simple harrows. Later the soil between the ridges is loosened with an inter-row rotovator to make the final ridge.

8.8 Planting and ridging in other regions

In the Netherlands the seed tubers are planted very shallowly. The often cool and moist weather conditions at planting time make this possible. Later on the ridge is built up to a height of approx. 25 cm.

In regions with higher temperatures and dry conditions the seed should be planted deeper. It is often recommended to plant the potatoes 3–5 cm deep below the levelled soil surface and, in very dry regions, even at a depth of 5–10 cm. In the Netherlands all potatoes are harvested mechanically. As it is difficult to separate clods and tubers when harvesting mechanically, the formation of clods is prevented by seed bed preparation and ridging. Shallow planting also facilitates mechanical harvesting. In countries where harvesting is not fully mechanized it is less important to avoid clod formation and shallow planting is not as necessary. Various systems of planting and ridging are summarized in figure 52.

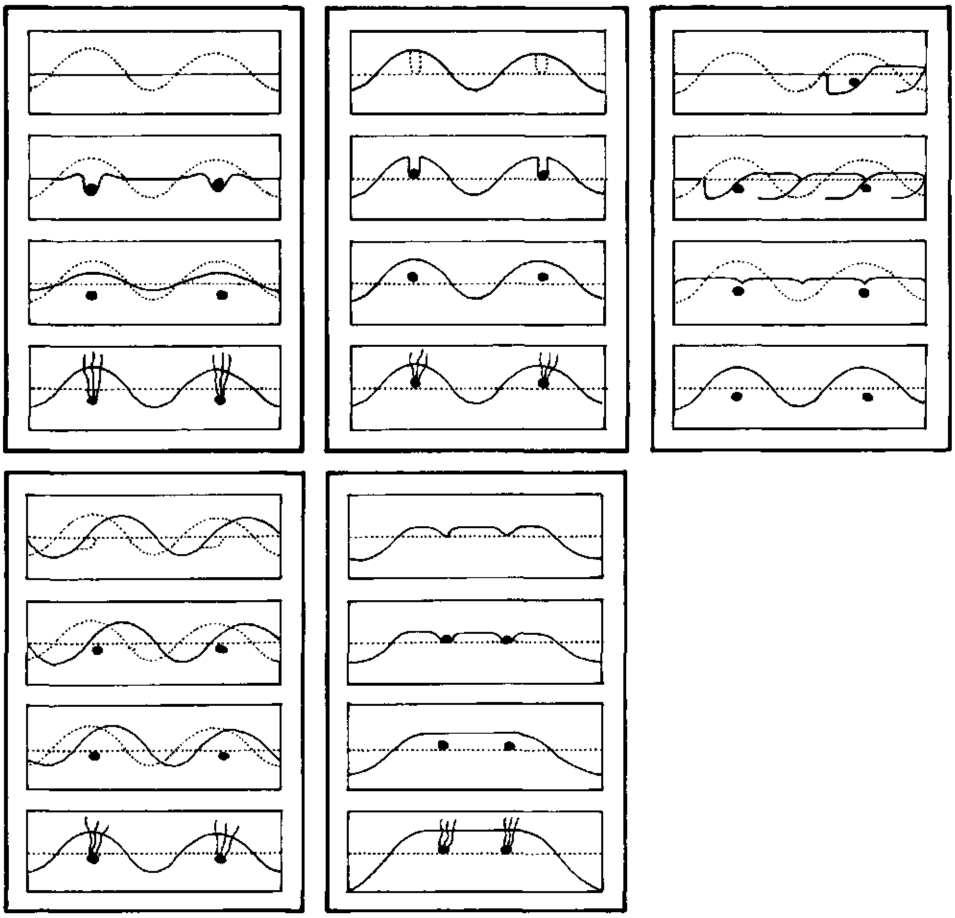

Fig. 52. Planting and ridging systems.

9 Manuring

Potatoes respond extremely well to the application of both farmyard manure and mineral fertilizers. The crop benefits from the application of farmyard manure not only from the amounts of nitrogen, phosphate and potash it contains but also from its improving effects on the tilth and the moisture retaining properties of the soil.

A crop yielding 30 tonnes of potatoes may take from the soil during growth:

- 150 kg of N
- 60 kg of P_2O_5
- 350 kg of K_2O
- 90 kg of CaO
- 30 kg of MgO.

As only the tubers are harvested from the field a part of this quantity of minerals remains behind.

9.1 Nutrients affecting yield and quality

Although fertilizer application should be based on check tests the uptake data give an indication of the required rates. For normal soils the ratio of N : P_2O_5 : K_2O in the fertilizer is usually 1 : 1 : 2, but other ratios are required under certain conditions:

- On organic sandy soils and peat soils N should be kept low.
- On phosphorus and potash fixing soils these minerals should be applied in large

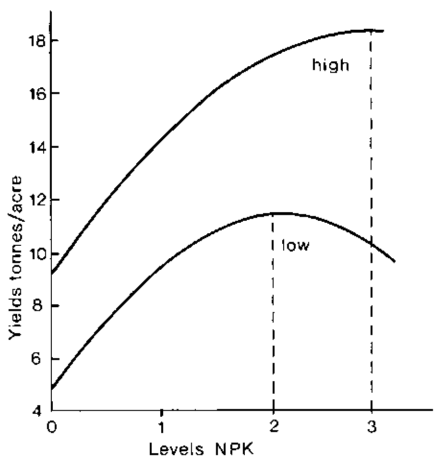

Fig. 53. Yield response of plants grown on high and low yielding fields (Holliday, 1963).

quantities.

- On soils rich in potassium the application of this element may need to be reduced.

It should be appreciated that crop response to fertilizers will vary from field to field. The response to major elements on high yielding fields is better and the optimum rates are higher than on low yielding soils.

Figure 53 shows potato yields in relation to N, P and K levels on soils of low and high potential. This indicates that fertilizer experiments should preferably be carried out on the same kind of soil types as those to which the results are going to be applied. When soils are being improved, fertilizer rates have to be adjusted accordingly.

Nitrogen The amount of nitrogen given to a potato crop varies from 100–200 kg/ha (occasionally 300 kg) depending on the purpose of the crop and the soil. High nitrogen dressing stimulates haulm growth and delays tuber formation. A crop with more nitrogen will mature later in the season than a crop with less nitrogen. If the crop matures before the end of the available growing period this indicates that the amount of nitrogen dressing should be increased. Excessive nitrogen may cause low dry matter content, high reducing sugar content and high protein and nitrate content, especially if it leads to harvesting the crop before it reaches its natural maturity. Crops with high nitrogen dressings are more susceptible to secondary growth. Immaturely harvested tubers are easily damaged and difficult to store. Less nitrogen is given to seed crops and early harvested potatoes than to main crops.

If the compound fertilizer does not closely match requirements, it is most important to apply the correct amount of nitrogen.

Nitrogen is given shortly before, or at, planting time but a split application may be better if there is a risk of leaching (e.g. with light soils – heavy watering), or if the application of large quantities of fertilizer under dry conditions may cause scorching. The second nitrogen application should, in general, be given no later than 3 weeks after emergence. For crops with sprinkler-irrigation systems nitrogen is applied in small quantities with each irrigation. This application is continued until about 4 weeks before the haulm is killed.

Phosphorus The yield response to this element can be considerable, especially if soils are low in phosphorus. If the rates of nitrogen and potassium application are increased, then that of phosphorus should be also. Phosphorus contributes to the early development of the crop and early tuberization. It has been reported that phosphorus increases the number of tubers produced per plant. Relatively high rates are applied to seed potato crops because phosphorus may reduce virus infection. Often more than 100 kg/ha is applied, while on phosphorus fixing soils much higher quantities are applied. Since phosphorus is not easily leached and potatoes give a high level of response, in non-phosphorus fixing soils it is possible to concentrate phosphorus fertilization on the potato crop, thus reducing the application required for other crops in the rotation. The total amount of phosphorus should be applied before or during planting.

Potassium Potassium does not always affect yield but it has relatively more influence on the quality of the crop, dry matter content, black-spot, damage, blue discolouration after cooking, and storage quality. Potassium sulphate reduces dry matter content less than potassium chloride (muriate of potash) because chloride reduces also dry matter content. However, if muriate of potash is cheaper than potassium sulphate, it should therefore be applied to the soil far before planting.

Magnesium Close attention has to be paid to magnesium particularly when potatoes are grown on a light acid soil. High rates of potassium and nitrogen application in the ammonium form reduce the uptake of magnesium.

Calcium Potatoes are tolerant to soil acidity. Below pH 4.8., however, the crop can fail due to calcium deficiency; sprouts may not emerge and, if they do, the plants remain stunted and produce a lot of small potatoes. As calcium improves soil structure and as other crops which will be grown later on the same field require a relatively high pH, it is important to maintain the soil pH at a reasonable level.

Many fertilizers have an acidifying effect on some soils. If such fertilizers are used, lime has to be added from time to time. As the application of lime shortly before growing a potato crop can increase the incidence of common scab, it is advisable to lime these soils at some other time in the rotation. Liming lateritic soils improves the uptake of phosphorus when such soils have a low pH and are rich in aluminium and iron.

9.2 Placing fertilizers

Fertilizers are most effective at the deeper layers in moist soil, where the roots are found. Contrary to nitrogen and to some extent potassium, phosphates are transported very slowly by water in the soil. For this reason phosphates are more effective when placed in the root area. Broadcasting the fertilizer is considered to be a drawback in areas where phosphorus and potassium become fixed quickly when mixed with the soil.

In areas where high fertilizer levels are applied, soil fertility is high, and no fixation takes place, broadcasting fertilizers is good practice. If the levels of soil fertility and fertilizer application are low, and fixation may occur, placement of fertilizers is advantageous.

In table 32 the results of fertilizer placement experiments are summarized. Large amounts of fertilizer in close contact with the seed will cause scorching, especially under dry soil conditions. In figure 54 various methods of fertilizer application are

Table 32. Relative response values of fertilizers in placement experiments in the Netherlands (broadcasting = 100) (Prummel, 1957).

	Nitrogen	Phosphate	Potassium
Cereals	125	245	365
Maize	–	290	–
Pulse crops	–	670	–
Potatoes	115	190	135[1]

1. Higher values found in potassium-fixing soils.

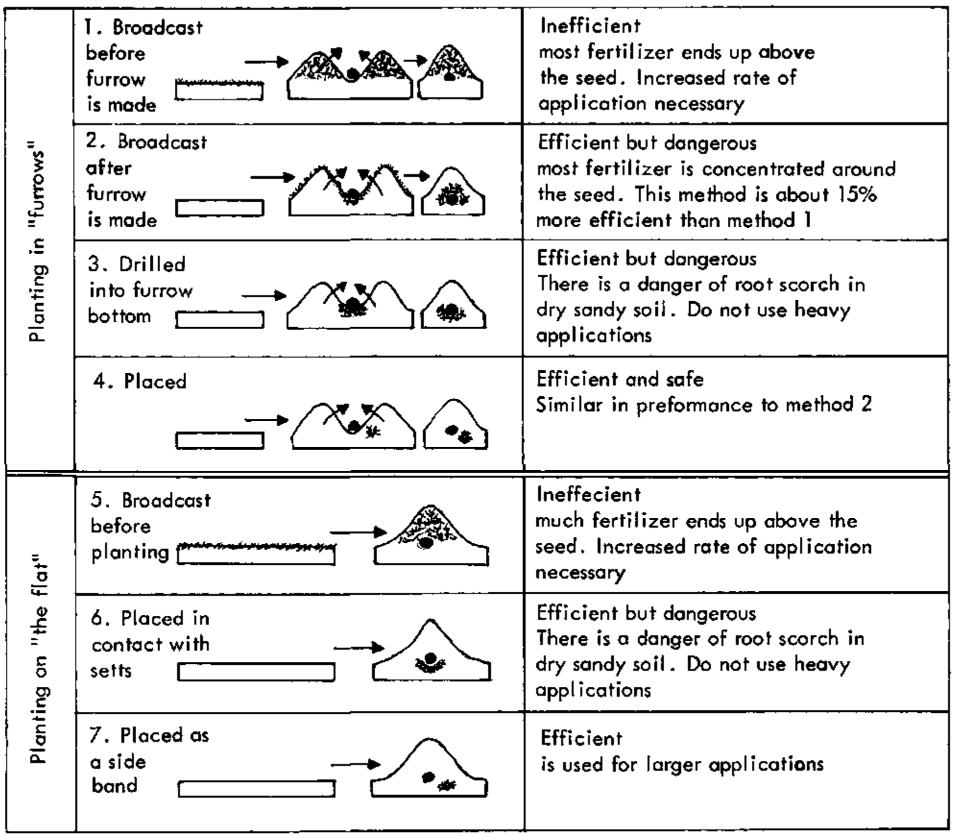

Fig. 54. Methods of fertilizer application.

compared.

Three safe methods of fertilizer placement are:

- bands of fertilizer 5 cm away from and below the seed
- distribution of fertilizer at the bottom of the furrow and mixed with the soil before the tubers are planted
- placing the fertilizer in small heaps between the seed pieces at the bottom of the furrow.

9.3 Farmyard manure

Of all field crops, the potato has the best response to farmyard manure. Although the macro and minor elements applied to the field contribute to soil fertility, the soil improving effect of organic matter is often considered to be of major importance. Humus improves the soil structure of heavy soils, while in light soils the moisture retaining properties are improved. By applying farmyard manure, the effect of nitrogen given as a mineral fertilizer may be increased by 20 %. Decomposed farmyard manure is preferred, since fresh, incompletely decomposed manure will become active too late in the season and may reduce dry matter content, impair flavour and delay maturity (which may cause extra tuber damage and thus storage problems).

Fresh manure may also cause the seed bed to dry out rapidly after planting. No more than 15–20 tonnes of well decomposed farmyard manure should be applied per hectare. Depending on the animal, the feeding and strawing methods, 10 tonnes of farmyard manure could include: 15 kg of N, 6 kg of P_2O_5, 40 kg of K_2O, 50 kg of CaO, 17 kg of MgO, 300 g of Mn, 40 g of Cu and 50 g of B.

10 Water supply

In potato production, shortage of water is usually one of the most important yield reducing factors. Even in countries like the Netherlands with an average rainfall of about 60 mm per month during the growing period and a fairly even rainfall distribution, shortage of water which affects tuber yield and quality, often occurs. In many countries the average rainfall is much lower and the distribution far less regular so that crop production without irrigation is difficult. In this chapter we will discuss:
- the effect of water supply on crop growth, yield and quality
- the amount of water that a crop needs
- the different irrigation systems.

10.1 Effect on growth, yield and tuber quality

Water is essential to plant growth. It is needed for the most vital plant processes such as photosynthesis and mineral uptake, and it affects the partitioning of dry matter, senescence of leaves and tuber quality, both the external and the internal quality. The effect of water supply on growth and development in different phases of the crop, will be briefly discussed.

10.1.1 Period between planting and emergence

After planting the seed tuber should be moist and the sprouts should also be surrounded by moist soil to stimulate root growth and thus a rapid and even emergence. Too much water can cause a shortage of oxygen and the seed tubers to rot. On some soils, liable to compaction, high intensity rainfall or sprinkler irrigation can cause soil compaction or sealing to such a degree that emergence is delayed. Water supply after planting and before emergence is therefore very critical to rapid and even emergence and to the number of stems that will be formed per plant.

Water can also be used to reduce soil temperature when temperatures are high, but then small amounts of water should be supplied frequently by means of sprinkler irrigation. A reduction of 5–10 °C in soil temperature can be obtained which may be very significant but over-irrigation and thus a shortage of oxygen can cause tuber decay or a delay in emergence, may even have a far worse effect.

10.1.2 Period between emergence and beginning of tuber growth

During this period, both haulm and root growth should be stimulated. For rapid haulm development the stems and leaves need sufficient water. Gandar & Tanner (1976) found that leaf elongation of potato plants begins to reduce at a leaf water potential of about -0.3 MPa (= -3 bars) and that in the field leaf enlargement ceases completely at -0.5 MPa. Figure 27 shows a field experiment in India where the leaf water potential of a crop on a sandy loam soil has already fallen below -0.3 MPa at about 09.00 h in the morning three days after irrigation. This is a very common phenomenon. On days with an evapotranspiration rate of 3 mm per day or more in the day time cell elongation is small or almost negligible. It is important that during the night the plant can rapidly increase the water content in its leaves so that leaf elongation can take place at night and in the early morning.

Too much water supply during this period will produce a superficial root system, and as we will see in the following paragraph, a deep root system is extremely important in ensuring a regular water supply to the foliage. Therefore, over- irrigation in this period is harmful; the water supply should be in proportion to rapid foliage development and the rapid development of a root system which penetrates deeply into the soil.

The short period just before and during tuber initiation requires particular attention as the plant is very sensitive to various growth factors such as temperature, day length, nitrogen and water supply. These and other factors can effect the hormone balance which in turn regulates tuber initiation.

The various effects of water supply on tuber initiation can be found in the literature. It is generally assumed that drought during this period speeds up the process but that the number of tubers initiated which start to grow is reduced by drought. Very wet conditions are also unfavourable to the formation of many tubers. Cultivars react differently. Some cultivars may produce too many tubers in moist soil in this period, whilst other cultivars need a moist soil to obtain optimal yield of marketable sized tubers.

If irrigation is used to control common scab during tuber initiation, care should be taken not to over-irrigate the crop, particularly with cultivars which react to moist soil with too many tubers.

10.1.3 Period after the beginning of tuber growth (bulking period)

As soon as the crop is in the phase of tuber growth a great deal of water is needed to obtain optimum yield, as a result of an optimum rate of photosynthesis of a large leaf area. This is only possible if the CO_2 concentration in the leaf tissue has not been

Table 33. Effect of additional irrigation on tuber yield in field experiments in the period 1981-1985 in Jena region (DDR) (Roth et al., 1987).

	Extra water supply (in mm)	Relative tuber yield
Rainfall only	-	100
Additional water supply		
plant height 20-30 cm - maturity	168	124
begin flowering stage - maturity	141	127
end flowering stage - maturity	111	130
during flowering stage	60	110

reduced by stomatal resistance, so that an adequate water supply reaches the leaves. The importance of an adequate water supply in the bulking period, is shown in table 33, which summarises the average results of field experiments in East Germany in the period 1981–1985.

Shortage of water can have a direct effect on the net assimilation rate, as well as an indirect effect by speeding up leaf senescence which also reduces assimilation, moreover, an early leaf senescence shortens the duration of the growing period. So a drought period can reduce both the cumulative light interception and the efficiency of the foliage to utilize this light. It depends on the circumstances which parameter is most influenced (see also table 27).

Shortage of water not only reduces tuber yield but also tuber quality. Irregular water supply to the foliage will cause irregular tuber growth, which may promote misshapen tubers and growth cracks. Severe drought periods combined with high temperatures, particularly during the first part of the bulking period when the soil is not totally covered by green foliage, can stimulate second growth.

Water supply to the crop also affects the dry matter content of the tubers. A water supply to the crop which is adequate for optimum growth will slightly reduce the dry matter content of the tuber, particularly if a large amount of water is supplied in the last phase of this period. However, the dry matter content of tubers is controlled by so many factors which also interact with each other, that the effect of a single factor is difficult to predict (fig. 60).

10.2 Amount of water needed

The total amount of water a potato crop needs for optimum production depends on:

- evapotranspiration
- length of the growing period.

The water used by the crop should be available in the root zone. However, it is very unlikely that the root zone will be able to contain sufficient water for the whole growing period, therefore it should be replenished by rainfall, ground water or irrigation or by all three together.

Almost all the water that a plant needs is used for transpiration. On a clear day in the Netherlands a well developed crop transpires at a rate of about 5 l water per m^2 per day, at the end of July the crop also contains about 5 l water per m^2 of which less than 0.1 l water per m^2 is needed directly for assimilation.

10.2.1 Evapotranspiration and transpiration

Evapotranspiration is a process whereby water evaporates directly from the crop or bare soil and is transpired by the foliage. Evaporation is measured at most meteorological stations. The Class-A pan evaporation system is often used in agriculture (E_o = open water evaporation). The potential evapotranspiration of a crop is proportional to E_o according to the equation $E_{pot} = f\ E_o$. The value of f depends on foliage ground cover and foliage structure and height. Before emergence f depends on the wetness of the soil surface. When the top layer is wind dry, f is about 0.2–0.3. Based on the data of Doorenbos & Pruitt (1975) it may be assumed that for a crop with about 50 % ground cover and well supplied with water, f is about 0.5–0.6; and a crop with 80 % or more ground cover it is about 0.7–0.8.

The correlation between transpiration and dry matter production is of particular interest in estimating the amount of water needed. This correlation between transpiration and dry matter production is affected by the evaporation. The greater the evaporation, the more water is needed for transpiration. A well developed and irrigated crop in Egypt in April needs about 70 l water to produce 1 kg tubers, whilst in the Netherlands in July a well developed crop needs no more than about 40 l of water to produce the same amount.

Evaporation is determined by several meteorological factors such as temperature, radiation, wind velocity and vapour pressure deficit. Rijtema & Endrödi (1970) found that in the period 1959–1966 in the Netherlands the well-irrigated crops of four different cultivars transpired about 275 mm water on average to produce about 12 tonnes total plant dry matter per hectare, this is about 230 l water for 1 kg dry matter. But variations between the years were very wide. However, taking the ratio between transpiration and vapour pressure deficit these varations become much smaller and the correlation between total plant dry matter and this ratio more narrow (fig. 55).

A crop in full growth with 80 % ground cover needs about 0.8 E_0. As not all the water supplied by irrigation will reach the roots, it is generally accepted that water supply to such a crop should be about equal to the measured E_0. which was also

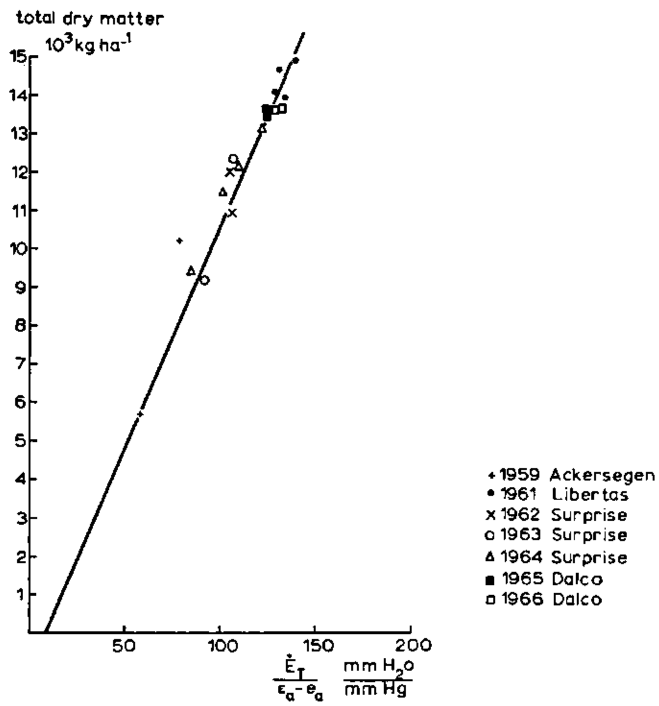

Fig. 55. Relationship between total dry matter production and the transpiration to vapour pressure deficit ratio (Rijtema & Endrödi, 1970).

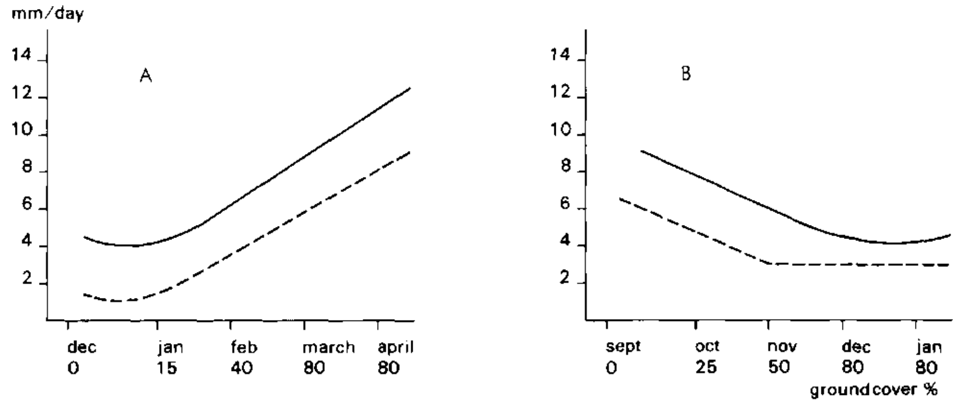

Fig. 56. Estimates of average daily water use of a spring (A - - -) and an autumn (B - - -) crop and the measured average Class-A pan evaporation (—) in Unayaza (Saudi Arabia).

demonstrated by Levy (1986). He found tuber yield losses of 10–30 % on a light loam soil during the bulking period when the irrigation amount (expressed as a percentage of Class-A pan evaporation) was about 2/3 of E_0 (6.0–6.5 mm per day) and tuber losses of 30–50 % when the irrigation amount was about 1/3 of E_0, compared with tuber yields obtained from irrigation amounts equal to E_0. Obviously a crop in full growth needs a quantity of water that approaches the value of E_0.

Based on the mean monthly Class-A pan evaporation values, the average daily amount of water needed by a well developed potato crop in the Unayaza region (Saudi Arabia) has been calculated for both spring and autumn crops (fig. 56). The total amount of water needed for the spring crop is 610 mm and 475 mm for the autumn crop. Some of the water is evaporated from the soil and foliage and not transpired by the crop. This is particularly the case for the autumn crop, nevertheless the amount of water transpired by the autumn crop is considerably less than that transpired by the spring crop due to the fact that evapotranspiration during the bulking period is much lower in the months November–January than in March and April.

The difference in water use by a spring and an autumn crop in Egypt is also shown in table 34. For crops with a fairly optimum supply of water, the water use was 565

Table 34. Effect of soil moisture depletion (irrigation interval) and thus water use on tuber yield in Egypt (cv. Alpha) (El Motazbelah et al., 1970; cited by Rijtema & Aboukhaled, 1973).

Depletion levels of soil moisture (%)[1]	Spring crop		Autumn crop	
	water use (mm)	tuber yield (t/ha)	water use (mm)	tuber yield (t/ha)
60	565	27.6	340	12.6
45	510	25.5	310	11.9
30	385	18.3	270	11.0

1. Percentage of soil moisture at field capacity.

mm and 340 mm respectively. Interesting to note is that a 2/3 reduction in the water supply in spring also reduced the tuber yield by 2/3, but in autumn, when the evaporation values in the bulking period are lower, a reduction in water by 20 % reduced the tuber yield by only 12 %. This again shows how critical water supply is to crops where evapotranspiration rates are high.

10.2.2 Amount of soil water available for crop growth

The amount of water available for crop growth depends on soil type, rooting depth and ground water. As ground water is usually not available for crop growth in most regions in the world, particularly not for shallow root crops like the potato, we will not discuss it here.

The available water holding capacity of a soil is the amount of water that it can store in the effective root zone for use by the crop. When a saturated soil is adequately drained, the moisture content of the soil is said to be at field capacity (i.e. a soil water tension of about 0.02 MPa or 20 centibar). A soil moisture content where plants cannot take up water anymore, is called the permanent wilting point (soil water tension is about 1.6 MPa). The amount of water held by the soil between the permanent wilting point and the field capacity is the available water holding capacity. This quantity depends on the soil type. However, stress occurs long before all the available water is taken up by the crop. There is a close correlation between soil water tension and leaf water tension, but this correlation is strongly influenced by the transpiration rate of the crop and thus by the daily evaporation values (E_o). The greater the evaporation, the smaller the percentage of available water that can be used before moisture stress occurs.

The cell elongation and transpiration rate of a potato crop already begins to reduce at a leaf water potential of -0.3 MPa; for cereals, grasses, clover and alfalfa this value is -1.0 MPa and for cotton -1.3 MPa. So the total available soil water that can be used before the first stress starts and is called the readily available soil water or the available non-stress soil water, differs widely for the various crops (table 35).

The data in table 35 which are based on observations in Egypt, show clearly that potatoes and pepper need to be irrigated at a much higher soil moisture content than wheat or cotton. The potato is obviously a drought-sensitive crop.

Table 35. Relationship between evapotranspiration (E_{pot}) and the percentage of available soil water which can be used before water stress develops (non-stress) soil water. The leaf water potential at which water stress starts is shown between brackets (Rijtema & Aboukhaled, 1973).

E_{pot}	Potatoes, pepper (- 0.35 MPa)	Cereals, grasses, clover, alfalfa (- 1.0 MPa)	Cotton (- 1.3 MPa)
1	55	83	90
3	33	67	76
5	23	51	62
7	19	41	50
9	16	33	42

Table 36. Estimates of available soil water in four soil types at different soil water tensions (MPa) and of available non-stress soil water for two depths of effective root zone and two soil water tensions (based on data from Doorenbos & Pruitt, 1975).

Soil type	Available soil water (mm per 10 cm soil layer) at different soil water tensions				Available non-stress soil water (mm per 10 cm soil layer) at 2 soil water tensions		Total available non-stress soil water (mm) at 2 depths of root zone and 2 soil water tensions			
							30 cm		50 cm	
	0.02	0.04	0.07	0.25	0.04[1]	0.07[2]	0.04	0.07	0.04	0.07
Medium fine sand	6	4	3	2	2	3	6	9	10	15
Loamy fine sand	14	12	9	5	2	5	6	9	10	25
Sandy loam	13	9	5	3	4	8	12	24	20	40
Silt loam	25	21	15	5	4	10	12	30	20	50

1. At high evaporation values, e.g. E_0 more than 5 mm per day, soil water tension should not exceed -0.04 MPa.
2. At low evaporation values, e.g. E_0 less than 4 mm per day soil water tension should not exceed -0.07 MPa.

How much non-stress soil water will be available for a potato crop has been calculated for 4 different soil types, 2 soil water tensions and 3 root-depth zones. The estimates are given in table 36.

From this table it can be concluded that for a potato crop on medium fine sand with a shallow rooting system (30 cm) the water that is taken up by the crop on days with high evaporation values (e.g. $E_0 = 6$ mm per day) should be replenished each day to prevent any stress. On the other hand, for a crop on a silt loam soil with a root zone of 50 cm deep, the soil water should be replenished every three days. This example demonstrates the importance of the root depth and soil type to production.

In the New Polders in the Netherlands root depths of 100 cm have been observed in silt loam soils. Under moderate evaporation rate conditions (E_0 3-4 mm per day) as occur in that region, 100 mm non-stress soil water is available for crop growth. In addition, in most cases in that region ground water can reach the root zone by capillary movement, therefore even a drought period of several weeks will not cause severe drought stress.

10.2.3 Water supply to replenish soil moisture used

A well-developed potato crop needs considerably more water than is available in the soil. In Egypt, a well-irrigated spring crop required 565 mm and 340 mm was needed for an autumn crop (table 34). In the dryer region of Unayaza it was estimated that 610 mm and 475 mm was needed for the spring and autumn crops respectively. In the Netherlands which has a much lower evapotranspiration rate but a longer growing season 300–400 mm water is needed in total. So the shortage of water must

Table 37. Estimate of the number of days between successive irrigations of a crop (> 80% ground cover) in relation to weather conditions, soil type and depth of the root zone. The amount of water required per irrigation is given between brackets (wind velocity 2 m; gentle breeze) (based on data from table 36).

Weather conditions during day time		Evaporation (mm/day)	Depth of root zone			
			30 cm Soil type		50 cm Soil type	
temperature (°C)	relative air humidity (%)		I	II	I	II
18-23	60-80	3	3(9)	10 (30)	8(25)	17 (50)[1]
23-27	30-50	6	1(6)	2 (12)	2(10)	3 (20)
> 27	< 30	8	< 1(6)	1½(12)	1(8)	2½(20)

Soil type I loamy fine sand; Soil type II silt loam (see table 36).
1. 50 mm water in one irrigation may be too much, depending on the irrigation system used.

be replenished by rainfall, ground water or irrigation, or by all three together.

In many climates the rainfall is insufficient, all the more so because the distribution of the rainfall often does not coincide with the distribution of water needed by the crop during its growing period. If the groundwater level is too deep for the roots, water must be replenished by irrigation.

If there is very little rainfall, the frequency of irrigation or the irrigation intervals can be estimated on the basis of the total non-stress available soil water (tables 36 and 37) and the daily evaporation rate (E_0).

It should be noted that the estimates given in tables 36 and 37 are based on the assumption that sufficient non-stress soil water is available for the crop.

At high evaporation rates it will be particularly difficult to irrigate as frequently as indicated. Depending on the cost of irrigation and the effect of stress on tuber yield and quality, it may be more economic to leave a longer period between successive irrigations. In cases of irregular rainfall this may even be recommendable, because heavy rainfall soon after irrigation may cause a great deal of damage to the crop. Therefore in periods with a likelihood of showers, the timing and amount of irrigation should be chosen very carefully.

There are three practical methods for determining the time of irrigation:
- estimate soil moisture content by hand
- measure soil moisture content with tensiometers
- estimate the daily water usage and the non-stress available soil water in the root zone.

With some experience it is possible to estimate the soil moisture content by hand. A sample of soil should be taken from a few centimetres below the seed tuber and squeezed by hand several times. The degree to which a ball can be formed will depend on soil type and soil moisture content (table 38).

Tensiometers can be helpful if they are used carefully. The ceramic tip must be in good contact with the soil and at least two pairs of tensiometers should be placed in

Table 38. Texture guide for total available soil moisture.

Total available soil moisture	Soil status of loamy sand and sandy loam
0-25%	Dry, loose, flows through fingers
25-50%	Appears to be dry, will not form a ball under pressure
50-75%	Tends to ball under pressure but will seldom hold together when bounced in the hand
75-100%	Forms a weak ball, breaks easily when bounced in the hand, will not stick
100%	Upon squeezing no free water appears on soil but wet outline of soil is left on hand, soil will stick to thumb when rolled between thumb and forefinger
Satured	Free water appears on soil when squeezed

the field. One tensiometer of each pair should be placed slightly under the seed tuber and the other about 5–10 cm above the depth of the effective root zone.

In places where rainfall is very rare the intervals between successive irrigations can be estimated based on the daily evaporation rates, the soil type and the depth of the root zone (table 37). These estimates should always be checked by estimating soil moisture content by hand.

All the factors which influence the irrigation frequency are summarized in figure 57.

At present there is still no method available for estimating the water status of the crop in practice. This would, of course, provide a much simpler solution of the problem.

How much water can be supplied per irrigation depends on the amount of water

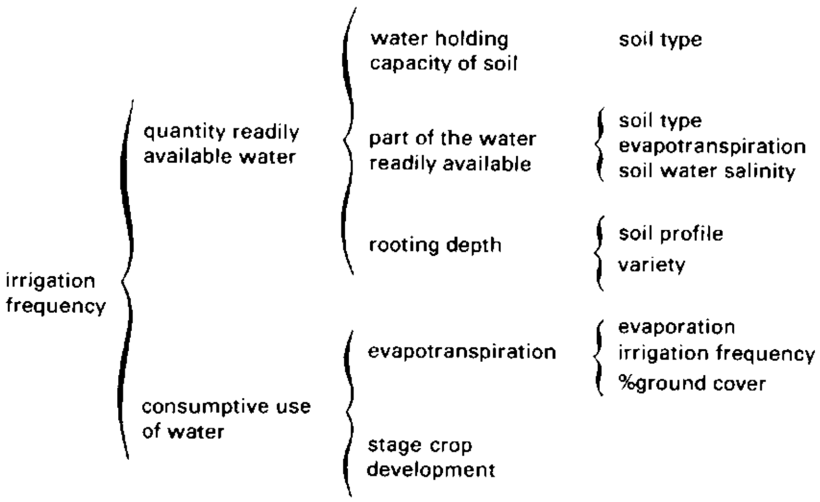

Fig. 57. Factors influencing irrigation frequency.

needed to replenish the soil water content to field capacity and on the irrigation system applied. Once more it should be stressed that too much water is often more harmful to crop growth and tuber quality than too little water.

10.3 Irrigation systems

There are three basic irrigation systems suitable for the potato crop: (1) furrow irrigation, (2) sprinkler irrigation, and (3) drip irrigation. Drip irrigation is not used on a large scale for the potato crop at the moment, although this system may be useful in regions with saline water. The advantages and disadvantages of the furrow and sprinkler irrigation systems will only be discussed briefly.

10.3.1 Furrow irrigation

Furrow irrigation is the oldest system and is still applied in many parts of the world. The advantages of furrow irrigation are:
- low investment
- no wetting of the foliage (favourable in preventing foliage diseases and when using saline water).

Disadvantages:
- high labour demand
- low application efficiency (run off, percolation, inadequate distribution). Only 50–70 % of the water applied will be used by the crop
- obstacle to mechanization.

10.3.2 Sprinkler irrigation

Sprinkler irrigation can be divided into:
- solid-set or movable pipes with small sprinklers
- sprinkler cannon or hose reel sprinkler
- center-pivot system
- moving linear sprinkler system.

The solid-set sprinkler system is fairly unusual due to its high cost. More commonly found is the system with movable pipes and small sprinklers. The investment costs are lower, but the system is more labour intensive. Both systems have the advantage that the amount of water that is applied per hour is small (usually 8–10 mm per hour), which prevents soil and crop damage and ensures that the application efficiency is high.

The sprinkler cannon is popular on mechanized farms with medium-sized potato acreages. Although the investment, expressed per hectare of potatoes, is rather high, expressed per unit they fall within the scope of this type of farm. The main disadvantage of this system is that it is very wind sensitive and can cause crop and soil damage, due to a high intensity of irrigation. In the newer systems the large sprinkler or cannon is replaced by a line of smaller sprinklers, which give better results.

The center-pivot systems and the moving linear sprinkler systems are only used on large modern potato farms. The investment required is high but the labour demand is very low. Moreover, fertilizers, herbicides, fungicides and insecticides can be applied with this system. The center-pivot system has the disadvantage that the irrigation intensity is high, particularly at the end of the lateral. This can partly be overcome with small sized droplets. However, this reduces application efficiency due to an increase in evaporation and greater sensitivity to the wind. This system is used mainly on light soil, with short intervals between each irrigation.

11 Specific weather conditions affecting yield and quality

Extreme weather conditions affect yield and quality. To estimate losses, it is not only important to know the length of the period during which these conditions occurred, but also the growth stage of the crop at the time.

11.1 Hail and night frost

Night frost and hail both affect potato yields. The reduction in yield will depend on the severity of the damage and the stage of growth when it occurred. Young plants may recover after damage and older plants may not. In a simulated hail damage experiment, Beresford (1967) demonstrated the effects of such damage at different stages of growth (table 39).

Yield reduction is greater if the crop is attacked just after flowering rather than before, provided the available growing period is long. Assuming that the crop will recover, an early attack by night frost is less harmful than an attack at a later stage.

11.2 High temperatures

The effect of high temperatures on emergence (sections 3.4.4 and 8.2), seed quality, and photosynthesis (section 4.2.1.2) has been described. Other phenomena in potatoes caused by high temperatures are: second growth, black heart and heat necrosis.

11.2.1 Second growth

Several types of second growth have already been described in figure 58.

- elongated tubers (A)
- bottlenecks (A)

Table 39. Yield of tubers (tonnes/hectare) as affected by severity of hail damage at each of three stages of vine growth (Beresford, 1967).

Stage of growth when damaged	Control	Severity of hail damage				
		25%	50%	75%	100%	average
50% bloom	36.6	35.6	33.0	31.0	19.1	31.1
Full bloom	37.8	33.6	31.0	28.1	12.3	28.6
50% past bloom	36.8	30.2	29.4	21.6	14.6	26.4
	37.2	33.2	31.2	27	16.3	

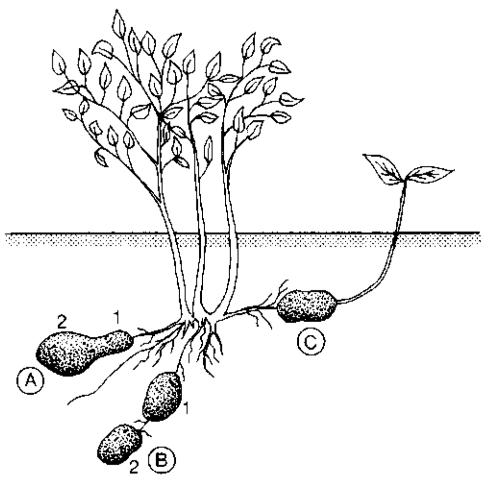

Fig. 58. Forms of second growth (Lugt, 1960).

- chain-tuberization or secondary tuber formation (B)
- sprouted tubers (C)
- knobby tubers.

The first three types have primary (1) and a secondary (2) tuber or part of a tuber.

Second growth is induced by high temperatures. Bodlaender et al. (1964) induced second growth at 22–27 °C. High soil temperatures had more effect than high foliage temperatures. Different varieties react differently at various temperatures. Any conditions (e.g. long days, high nitrogen supply, etc.) which delay tuber formation and promote stem and stolon elongation will stimulate the induction of second growth in potato tubers.

Drought may not stimulate second growth directly, but rather indirectly, since under dry soil conditions, leaf temperatures are often higher and nitrogen uptake is hampered.

Once second growth is induced, the primary tubers stop growing, while the assimilates produced by the haulm contribute to the growth of the secondary part of the tubers or the growth of secondary tubers (fig. 59). If the primary and secondary tubers are still connected and the haulms of the plants are destroyed, the secondary tubers may continue growing, using carbohydrates from the primary tubers. The starch from the primary tubers first disappears at the heal end (producing glassy tubers, jelly-end rot). The cooking quality of these glassy tubers is poor but such primary tubers may still be suitable for seed if not too much carbohydrate has been extracted.

11.2.2 Internal brown spot

High soil temperatures can cause internal brown spot (also called chocolate disease, internal necrosis or internal rust spot) especially on sandy soils. Some varieties are very susceptible to this disorder (e.g. Arran Banner). Internal brown spot is characterized by irregular, dry brown spots or blotches scattered throughout the flesh. Good

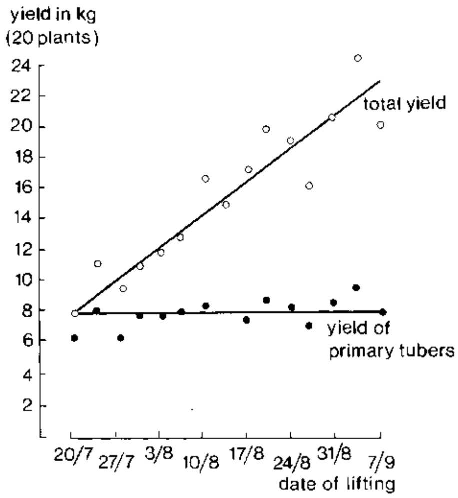

Fig. 59. Relation between date of lifting, total yield and yield of the primary tubers (Lugt, 1960).

cultural practices (proper irrigation and large ridges) reduce the severity of brown spot. In areas where it is a major problem it is recommended to avoid planting susceptible varieties.

11.2.3 Black heart

Black heart is a physiological disorder, which develop in tubers kept at high temperatures (e.g. 35-40 °C). High respiration may lead to a lack of oxygen in the tuber. Such conditions can occur during storage and transport. It may also occur when tubers are exposed to bright sunlight during harvest or when soil temperatures rise abnormally during the growing season or even in the seed tuber after planting.

12 Tuber quality

The composition and physical condition of the tubers determine for what purpose the potatoes can be used. Important tuber characteristics are: dry matter content, reducing sugar content, discolouration after peeling, susceptibility to black spot and discolouration after cooking. These topics were extensively discussed by Hughes (1974) and later by van Es & Hartmans (1987a and b). In this chapter some of the most important aspects will be discussed.

12.1 Dry matter content

Mealiness and disintegration of boiled tubers are associated with the dry matter content. This is an important characteristic of ware potatoes intended for the fresh market. As is well known, the canning industry can only use tubers with a low percentage of dry matter. For most processing purposes a high percentage of dry matter is desirable. During processing, tubers are dehydrated to a greater or lesser extent. The higher the dry matter content, the less water has to be evaporated, consequently the output from tubers with a high dry matter content is higher than that from those with a low dry matter content. For chips and french fries (pommes frites) this also means less oil uptake.

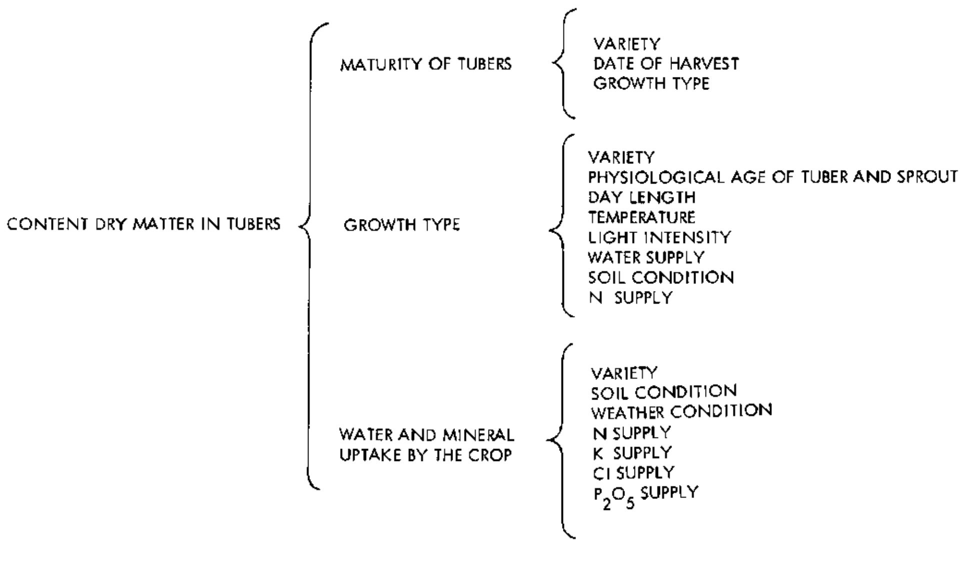

Fig. 60. Simplified version of a survey of factors which affect percentage of dry matter in tubers.

Almost all the factors which influence the total quantity of dry matter stored in tubers also affect tuber yield. The ratio of total tuber dry matter to tuber weight is the percentage of dry matter in the tubers. If a given factor stimulates total tuber dry matter more than total tuber weight the percentage of dry matter will increase. If the reverse occurs then the percentage of dry matter decreases. The effect of various factors upon dry matter content is very complex. It may be that under certain conditions a factor has a positive effect and under other conditions (not always noticeable) it has a negative effect. To keep this discussion short and to make it sufficiently clear, we must simplify the problem. Figure 60 shows the various factors that may have an effect on the dry matter content.

Dry matter content is influenced by maturity and growth type as well as water and mineral uptake by the crop. The effect of variety on percentage of dry matter results mainly from differences due to these crop characteristics. The effect of degree of maturity of tubers on dry matter content is shown in figure 61. Dry matter content increases as the growing season progresses but it tends to decrease at the end of the season.

The effect of growth type and water and mineral uptake on the percentage of dry matter of tubers is very complex. Generally the factors which stimulate haulm growth tend to decrease dry matter content, and the factors which stimulate tuber growth increase dry matter content. High temperature decreases the percentage. That is why dry matter content of tubers is usually rather low in hot climates, which is a disadvantage for processing.

To obtain tubers with a high dry matter content a variety should be selected which is known for this characteristic, and it should be supplied with sufficient nutrients and water so that at harvest almost all the leaves are yellow or brown without any incidence of pests or diseases. The relationship between tuber size and dry matter

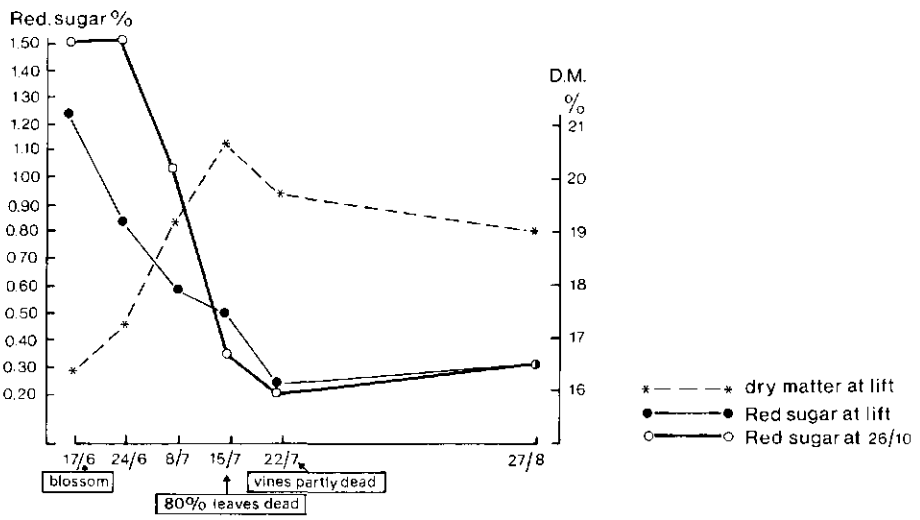

Fig. 61. Reducing sugar and dry matter content in tubers during growth (derived from data from Appleman & Miller, 1926).

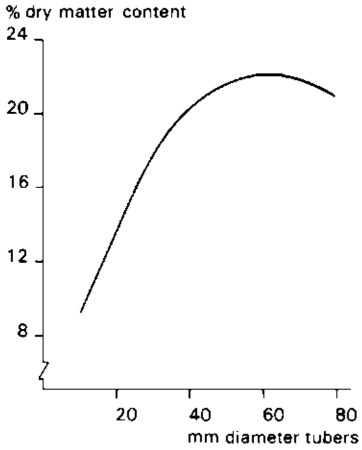

Fig. 62. Relation between tuber size and dry matter content of Pentland Crown potatoes (Wilcockson, 1986).

content will not be discussed in detail here (fig. 62). Small tubers are usually initiated about at the same time as large tubers but as they receive fewer assimilates the dry matter content remains low.

12.1.1 Variation in dry matter content between tubers of the same batch

Processing often means dehydration. After processing tubers with different dry matter contents, different amounts of water remain in the tuber pieces. This is a disadvantage for both chips and frites. A wide variation in dry matter content in the same batch of potatoes is also undesirable for the fresh market.

Variation in the dry matter content is partly due to differences in the field, e.g. soil, fertilization, moisture content, etc., and partly due to differences in the dry matter content of tubers from the same plant. This may be caused by differences in the time of tuber initiation and by differences in the growth of the plants or stems due to a variation in conditions at the onset of growth (sprout development, tuber size, depth of planting, etc.) or to a variation in plant spacing. Time of tuber initiation is a factor which determines the degree of maturity of the tubers at harvest and consequently the dry matter content.

Krijthe (1962b) showed that a potato plant forms many very small tubers, but that only relatively few of these develop into normal sized tubers, the rest remaining small or even disappearing. According to Krijthe, under normal conditions, all tubers start to grow during the same 7-10 days. There are, however, factors which may stimulate the plant to recommence tuber initiation. These are, in the main, high temperature, large amounts of available nitrogen and low soil humidity followed by high humidity. This phenomenon is a form of second growth not unusual in the Netherlands. Under such conditions, the period of tuber initiation may be very long and lead to differences in maturity of the tubers and consequently to differences in dry matter content.

Second growth may also influence variation in dry matter content in another way.

Tubers may form new secondary tubers and these can remove starch from the primary tubers when the haulms die off or are destroyed, with the result that the primary tubers become glassy (section 11.2.1).

Another cause of variation in dry matter content in a sample is the variation in the size of the tubers. When a plant is immature the smaller tubers are normally higher in dry matter content than the larger ones. During the final weeks of the growing season the dry matter content of the larger tubers increases more than that of the smaller ones, so that at maturity, the smaller tubers often have a lower dry matter content than the larger ones (Meijers & van Veldhuisen, 1970; Wilcockson, 1986; fig. 62).

Reestman (1970) found that most virus infected tubers have a lower dry matter content than healthy tubers.

As far as farming practice is concerned the following may be said:

- Fields that are homogeneous in soil and fertility produce crops with less variation in dry matter content than soil which is very heterogeneous in these respects.
- Regular emergence (which means well prepared seed and seed bed) and regular plant density, promote even growth of all the plants and thus shorten the period of tuber initiation.
- New tuber initiation after the main period is or can be prevented by a moderate application of nitrogen and an adequate water supply.

12.2 Reducing sugar content

Reducing sugar is a nightmare for the commercial processor manufacturing chips; and to a lesser extent in the production of french fries, granules and flakes which also requires potatoes with a low percentage of reducing sugar (i.e. glucose and fructose). On frying, the potatoes darken due to the reaction between the reducing sugars and amino acids; this is known as the Maillard reaction. The reducing sugar content of the tuber largely determines the colour of the fried product.

Reducing sugar content depends mainly on:

- variety
- degree of maturity of the tubers
- growing conditions
- storage temperature
- physiological development of the tuber.

12.2.1 Variety

Varieties can respond differently to external circumstances. Several factors affect reducing sugar content and the reaction of different varieties can vary. This means that some varieties are consistently high in reducing sugars and others low. Record and Saturna are varieties with tubers of relatively low reducing sugar content.

12.2.2 Degree of maturity of the tubers

The reducing sugar content decreases with the maturity of the tubers. This has very clearly been shown by Burton & Wilson (1970) with the variety Record grown in

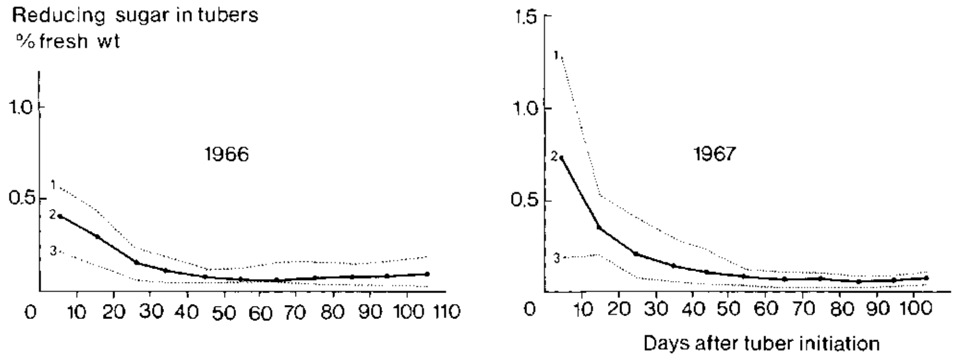

Fig. 63. Reducing sugar content of tubers plotted against time elapsed after tuber initiation (1, 2, 3 correspond with maximum, average and minimum respectively for all 5 centres in; the UK) (Burton & Wilson, 1970).

different parts of Great Britain (fig. 63). The data of Appleman & Miller (1926) (fig. 61) show that the stage of high dry matter content is already reached before all the leaves are dead, but that the lowest reducing sugar content is reached when the haulm is completely dead. All factors that delay maturity can increase the reducing sugar content in the harvested tubers.

12.2.3 Growing conditions

To obtain tubers with a low reducing sugar content it is important to strive for regular, even growth, not too abundant haulm growth and a natural haulm maturity. Long days and very high temperatures can stimulate haulm growth so much, that the ripening of the tubers is delayed too long.

Fontenot et al. (1965) found that with 10, 14 and 18 hours day length the chip colour became progressively darker. This means an increase in reducing sugar content with an increase in day length. This seems in agreement with the experience that it is more difficult to grow potatoes for chips in northern than in southern regions of Europe. The work of Burton & Wilson (1970) mentioned above is interesting in this respect. They found a positive correlation between the reducing sugar content of the tubers and the distance of the place where they were grown north from a point in the south of England. They do not give an explanation of this phenomenon.

It could be difference in day length, but it could also possibly be rainfall and light intensity, since it is assumed that tubers grown in warm dry summers have a lower reducing sugar content than those grown in cold wet summers. However, very high temperatures prevent the haulm reaching a natural maturity. Moreover, high temperatures reduce the dry matter content of tubers, which is unfavourable to processing.

Another aspect is rainfall. High rainfall, especially late in the season is unfavourable. This means that the water supply should be adapted to crop growth, if possible.

A mineral supply that stimulates regular growth but avoids abundant haulm growth is required for the production of tubers with a low reducing sugar content. This means that if nitrogen application does not result in the harvesting of immature tubers late in the season (low temperatures), it will not have any marked effect on the reducing sugar content. If, on the other hand, weather conditions are such that a heavy nitrogen application produces abundant haulm growth and thus a considerable delay in the ripening of the tubers, these heavy nitrogen dressings may increase the reducing sugar content especially if the tubers are harvested when immature (e.g. because of inadequate blight control) and the soil temperature is low at the time.

Very little is known about the effect of phosphorus on the reducing sugar content. It seems that under average farming conditions a normal phosphate application has no adverse effect. It appears that potassium often reduces sugar content, but as it also tends to decrease dry matter content, growers must aim for a reasonable compromise.

12.2.4 Storage temperature

Storage temperature together with variety has the most marked effect on the reducing sugar content. The conversion of sugar to starch and of starch to sugar is temperature sensitive, which is also the case in the conversion of sucrose to reducing sugars and of reducing sugars to sucrose, although they react differently to low temperatures, as shown in figure 64. An increase in temperature from 2 to 4 °C reduces the sucrose ($C_{12}H_{22}O_{11}$) content considerably more than the reducing sugar ($C_6H_{12}O_6$) content. This explains why potatoes for the fresh market can become sweet when stored at 2 °C and not or hardly at all when stored at 4 °C.

For a large reduction in reducing sugar content, the storage temperature should be higher. How much higher depends on the variety and reconditioning possibilities. The low-temperature sweetening, as it is called, is largely reversible by raising the temperature to 15–20 °C. Some of the sugar is respired and most of it is converted

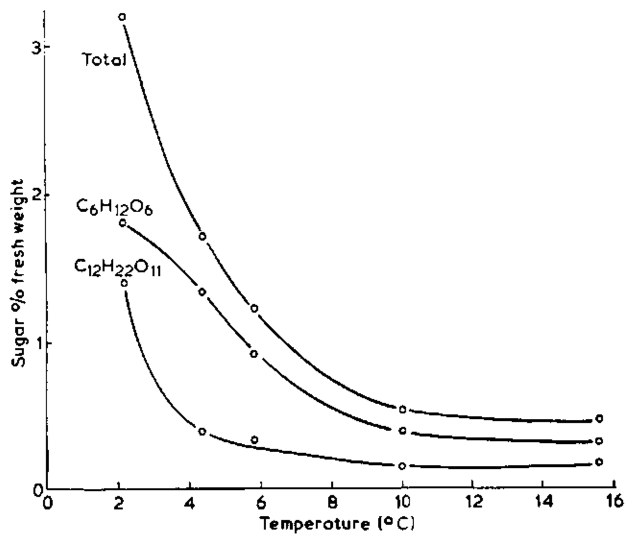

Fig. 64. Low temperature sweetening: sugar content of potato tubers (cv. Majestic) after storage for 4 weeks (17th Dec.–14th Jan.) at different temperatures (Burton, 1965).

to starch. This method is sometimes used by the processing industry, where it is called the 'reconditioning of cold stored potatoes'.

Two low temperature sensitive enzymes, viz. phosphofructokinase and phospho-fructo-phosphotransverase, play an important role in the accumulation of reducing sugar. The latter is supposed to be a key-enzyme in the process (van Es & Hartmans, 1987b). Varietal differences in low-temperature sweetening may be explained by differences between varieties in enzyme activity at low temperature. The Bintje variety accumulates much more reducing sugars at low temperatures than Saturna variety, whilst at higher temperatures the differences between the varieties are much less (fig. 65). Obviously the processing industry is interested in varieties which do not accumulate much reducing sugar at low temperatures.

Even when the temperature is increased to 28 °C the reducing sugar content drops (fig. 66). Iritani & Weller (1976) found that exposure of the tubers to a higher or lower temperature than 9 to 10 °C during a 14-day period preceding final storage at 5.6 °C increased the reducing sugar content at the end of a 6 month storage period.

The idea that the sucrose contents of tubers at lifting could be used as a quality

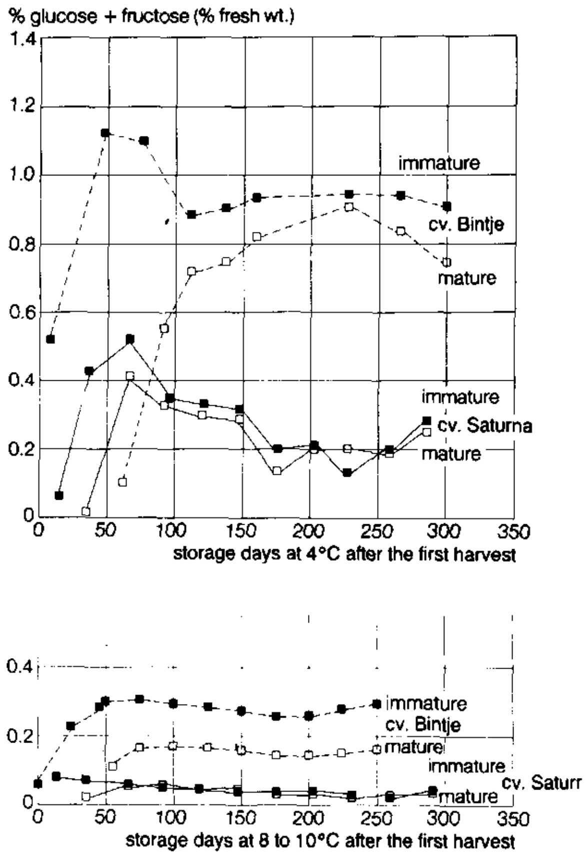

Fig. 65. Reducing sugar content in immature and mature tubers of the Bintje and Saturna varieties stored at 4 °C and at 8–10 °C (van Es & Hartmans, 1987b).

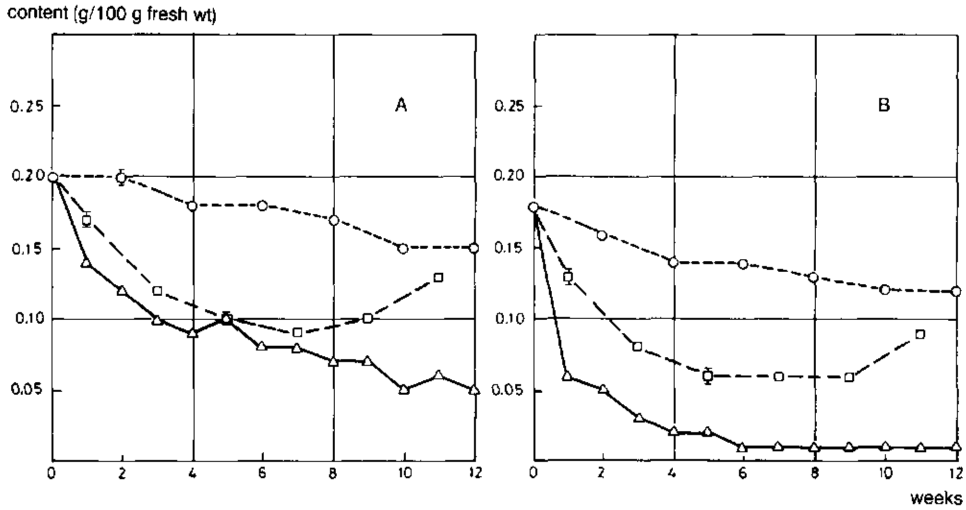

Fig. 66. Changes in glucose content (A) and fructose content (B) in potato tubers stored for 12 weeks at temperatures of 7 °C (○), 16 °C (□) and 28 °C (△) (Linnemann et al., 1985).

criterion in selecting batches of potatoes suitable for processing after a period of storage has been considered (Sowokinos, 1977). However,this idea has not proved to be suitable in Europe.

Although the brown colour of fried products is not exclusively caused by reducing sugars, it is generally accepted that the reducing sugar content should not exceed 0.2 % (of fresh weight) for chipping potatoes or 0.4 % for potatoes used for french fries, granules or flakes. To meet this requirement the grower should combine a well-chosen variety with a well planned method of production and storage (section 15.2.6).

12.2.5 Physiological development of tubers

Immature tubers contain more reducing sugar than mature tubers. During storage the sugar content tends to increase from the moment that the sprouts begin to grow, but growth is suppressed by sprout inhibitors or by de-sprouting. This increase in sugars will be respired again during storage, so it is reversible.

Quite different from this low-temperature sweetening and the sugar formation caused by the suppression of sprouting is the senescent sweetening which occurs when tubers are stored for a long time (fig. 67). This sugar accumulation is irreversible, so that reconditioning cannot overcome this problem.

12.3 Discolouration after peeling and black spot

Discolouration after peeling or bruising is caused by the formation of melanine from tyrosine; a reaction catalysed by the enzyme phenolase. Discolouration after peeling is mainly determined by the tyrosine content and the phenolase activity, while according to Vertregt (1968) black spot susceptibility is mainly determined by the

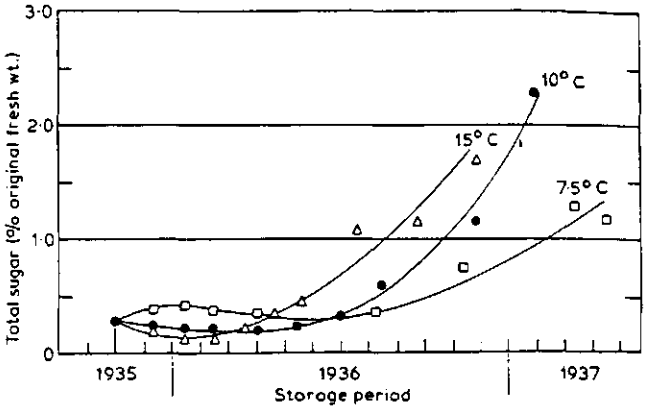

Fig. 67. Senescent sweetening of potato tubers (cv. King Edward) after prolonged storage at 7.5 °C and less prolonged storage at 10 °C and 15 °C (Burton, 1966; adapted from Barker, 1938).

susceptibility of the cells to damage.

It is generally accepted that potassium decreases tyrosine content but that sometimes it may be increased by nitrogen. Rainfall may also increase the tyrosine content. Enzymic greying is also dependent on variety. Some are much less susceptible to it than others.

Black spot manifests itself as blue-grey patches of various sizes under the skin of the tubers. It is caused by impact and is also known as blue bruise and blue spot.

In wounded cells the colourless phenolic amino acid, tyrosine is converted by enzymic hydrolysation and oxidation, by a series of reactions, into black coloured melanine. This discolouration takes about 2 to 3 days which means that the consequences of any impact may not be visible for at least 2 days after the fact and then only after peeling as it is invisible in the unpeeled tuber. Differences in susceptibility to black spot can partly be explained by differences in cell wall damage during handling. It appears that susceptibility relates to:
- storage and tuber temperature
- dry matter content
- cell turgidity.

The incidence of black spot depends on the susceptibility of the tubers to damage and the roughness of handling.

The effect of both storage temperature and tuber temperature together with storage duration is clearly shown in figure 68. Susceptibility to black spot is related to the dry matter content of the tubers in a variety. Tubers of the Bintje variety are not usually susceptible to black spot when the dry matter content is less than 20 %. All factors which reduce dry matter content will also decrease black spot susceptibility e.g. high rates of potassium and nitrogen application or immature harvest.

Weight loss due to evaporation normally increases the susceptibility of tubers to blue discolouration. However, it is possible that, at harvest, tubers show such a high degree of turgidity that they are very prone to black spot. Initial evaporation will then

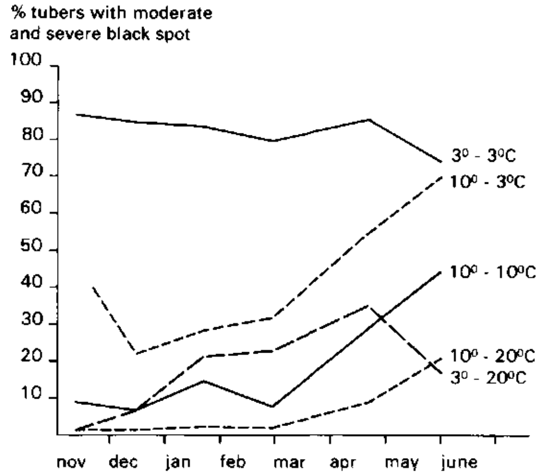

Fig. 68. Effect of storage temperature (first number) and temperature of tubers when assessing black spot-susceptibility (second number) during storage period of cv. Bintje (based on data from Meijers, 1987).

reduce their susceptibility to black spot. Very soft tubers are also usually less susceptible.

12.4 Discolouration after cooking

Grey discolouration after cooking is a common fault. This non- enzymic greying is caused by a grey pigment which largely consists of a complex of ferrous iron and chlorogenic acid. A colourless complex of ferrous iron and chlorogenic acid is formed first, which on exposure to air, is oxidized to a coloured ferric complex. This discolouration is influenced by:
- the pH of the tuber
- the ratio of citric acid to chlorogenic acid.

12.4.1 pH

Hughes and Swain changed the discolouration from grey-green at pH 5.5 to grey-blue to dark grey with a reddish tinge at pH 8 (Burton, 1966). This means that an increase in pH stimulates discolouration. Discolouration is normally greater at the heel end of a tuber than at the rose end; the pH is also higher at the heel end.

Irradiation of tubers to inhibit germination may also stimulate discolouration. This may be to due to a slight increase in pH caused by the radiation.

12.4.2 Ratio of citric acid to chlorogenic acid

Citric acid can bind the iron in the tuber so that it is no longer available to react with the chlorogenic acid. It has been proved by several researchers that this ratio plays a major part in determining discolouration. As the pH is inversely proportional to the citric acid content, it is evident that the effects of pH and citric acid on discolouration are difficult to distinguish.

According to Burton (1966), Hughes and Swain proved that the difference in discolouration between the heel and the rose end of the tuber is due more to differences in the ratio of citric acid to chlorogenic acid than to differences in pH.

12.4.3 Factors influencing discolouration

From the foregoing, it is clear that the amount of iron and chlorogenic acid which is available to form a coloured complex determines the greying after cooking and that its nature and colour will depend on the pH.

Any factor which influences these three properties will be liable to affect the propensity to greying. As citric acid affects not only the pH but also the amount of iron available to form a complex with chlorogenic acid, it is clear that the factors affecting citric acid content may be expected to affect greying (Burton, 1966).

Researchers have often found that potassium increases and chloride decreases the citric acid content. Nitrogen increases and potassium decreases the chlorogenic acid content. The ratio of citric acid to chlorogenic acid is lower in cool, wet summers than in warm, dry summers. Soil conditions also affect discolouration. Potatoes from peat soils are normally more prone to this fault than potatoes from silt or loam soils.

The difference between varieties is striking and can be explained by the foregoing. Bintje is an example of a variety which does not discolour even if a high level of nitrogen or even chloride has been applied to the crop. Other varieties liable to discolouration after cooking should be fertilized correctly with this in mind.

12.5 Glycoalkaloids

Glycoalkaloids are potentially toxic compounds found in plants of the Solanaceae family. They are found in all parts of the potato plant with the highest concentrations in the flowers and sprouts (table 40). At least 95 % of the solanidine glycosides (SG) found in commercial varieties consist of α-solanine and α-chaconine compounds derived from the aglycone solanidine. Other types of glycoalkaloids are found in wild, tuber-bearing *Solanum* spp. such as β-chaconine, solamarine, demissine and toma-

Table 40. Miscellaneous values for glycoalkaloid content in various parts of the potato plant and tuber.

	Fresh weight (mg/kg)
Tubers	20- 200
Peel (ca. 3 mm thick)	20-1000
Light sprouts	600-4000
Dark sprouts	1000-5000
Leaves	300-3000
Stems	30- 100
Flowers	3000-5000
Berries	200-1500

tine (Gregory, 1984).

At low concentrations solanidine glycosides enhance potato flavour but concentrations exceeding about 150 mg/kg tuber fresh weight (tfw) cause a bitter taste (Burton, 1974). Moreover, the consumption of potatoes with a high level of SG can cause gastroenteritis and even death. There is no generally accepted opinion about the safe upper limit but it is generally assumed that at consumption SG should not exceed about 150 mg/kg tuber fresh weight.

Boiling, microwave cooking or frying tubers has little effect on the SG content, because they can withstand temperatures of around 280 °C. As the SG content of the peel is higher than that of the tuber flesh, peeling of tubers decreases the SG content, although a peeled tuber is no guarantee of a low SG content.

Pigs or other animals should not be fed the skin and sprouts of old tubers. Similarly, the foliage of a green potato crop is poisonous to animals.

What are the factors which influence the SG content of a tuber?

- variety
- maturity
- growing conditions
- damage (caused by mechanical impacts and by diseases and pests)
- storage conditions and duration of the storage period
- exposure to light.

12.5.1 Variety

There is broad divergence in the SG content among genotypes. In Bintje tubers, for example, it is low (20-40 mg/kg tfw) while it is usually high in the tubers of the Astarte variety (200 mg/kg tfw). This variety is, therefore, only recommended for starch production in the Netherlands and not for human consumption. This is because starch is free of SG.

In recent years, breeders have made much use of *Solanum* spp. other than *tuberosum*. It appears that the SG content of tubers from some tuber-bearing *Solanum* spp. can be very high. Gregory (1984) found 1260, 290 and 468 mg/kg tfw of SG in clones of *S. acaule, curtilobum* and *juzepczukii* respectively. Fortunately, there appears to be little, if any, evidence of a causal relationship between SG in potatoes and varietal resistance to various major fungal diseases including early and late blight and common scab.

However, glycoalkaloids have been associated with resistance to Colorado potato beetle and potato leafhopper (Tingey, 1984). It is therefore essential that breeders using wild species test their material for glycoalkaloid content, all the more so as there is a correlation between the SG content in leaves and in tubers. Although rapid methods for determining SG content have been developed, it is important to understand that new types of glycoalkaloids could occur in varieties derived from wild species with unusual forms of glycoalkaloids. While glycoalkaloid levels and types in present commercial varieties offer little cause for concern, additional research and some caution in breeding with wild species will help to ensure the safety of future varieties (Sinden et al., 1984).

Table 41. Extent to which certain conditions and circumstances can affect the increase in SG content of tubers. This increase relates to the content of undamaged mature tubers grown under normal conditions (van Gelder, 1985).

	Increase (times)
Immature tubers	4
Small tubers	2
Exposure to sunlight immediately after harvest	10
Short storage in light	2-3
Storage in the dark (8 months)	1-2
Damage	2-3
Growing conditions	2-3

12.5.2 Conditions and circumstances influencing the SG content of tubers

An indication of the effects of conditions and circumstances which are known to influence SG content, is given in table 41. Not much is known about the effect of soil type, fertilization, climate or other growth factors on SG. Furthermore, the results are not always consistent. It is likely that various kinds of stress tend to increase glycoalkaloids.

The effect of even a short exposure to sunlight on tubers, particularly immature tubers, has a very dramatic effect. Special care should be taken in the handling and marketing of early potatoes. In general, potatoes should not be exposed to light for several days. The period between harvest or storage and consumption should be short, especially for varieties which show a rather high content at harvest when grown under normal condition.

It is recommended that at harvest ware potatoes grown under normal conditions should contain no more than about 100 mg/kg tfw SG in the tubers. Breeders should therefore include this criterion when drawing up their selection programme.

13 Disease and pest control systems

13.1 Disease and its control

This aspect of potato crop management concentrates on:
- integrated control of disease
- reduction of crop losses due to disease
- preventing the introduction of diseases into areas or countries which are free of them at present.

13.1.1 Integrated control of diseases

There are specific methods of control for each disease. In commercial potato production several diseases are usually controlled at the same time rather than single diseases. The methods applied to control some of the major diseases often include the control of minor diseases that would be of too little importance to warrant separate control measures. In practice, groups of diseases are controlled and it is important to know the characteristics of each disease, including its specific methods of control, so that in cases when it becomes more relevant to concentrate on a particular disease, the total control scheme can be adjusted accordingly.

With our present methods and schemes most diseases are only controlled to a certain degree. Complete control would be impossible, or if possible, too expensive. The degree of infection of a particular disease that can be tolerated depends on the threat posed by the disease, the losses caused (quantitative and qualitative) and the purpose of the crop (fresh consumption, industrial use or seed).

13.1.2 Reduction of crop losses

Disease may cause crop losses due to:
- seed decay or attack on the sprouts leading to a poor stand
- attack on the leaves by fungal diseases causing a reduction in the growing period with consequent low yields (mainly a reduction in cumulative light interception)
- reduced haulm growth and a decreased assimilation caused by virus diseases (mainly a reduction in light interception)
- wilting plants due to bacterial or fungal infection also resulting in a reduction in the growing period with consequent low yields (both a reduction in cumulative light interception and a reduction in the utilization coefficient of intercepted light)
- lesions in the tubers
- tuber rotting during the growing season or during storage
- attack on the root system

- skin blemishes caused by fungal diseases resulting in lower prices
- misshapen and small tubers.

This list can be used to evaluate losses caused by the various diseases and to decide to what extent any particular disease should be controlled.

Besides the losses in the current crop, the consequences of disease for the following crops should also be taken into account.

13.1.3 Preventing the introduction of diseases

Diseases can be spread by seed, soil, sacks and implements. Seed is generally the main source of infection and should be avoided or restricted. It should be avoided for those diseases which:

- cause extensive crop losses
- are difficult to control
- survive for a long time in the soil
- cause damage not only to potato crops but to other crops as well.

Spread should be restricted of those diseases which are difficult to control and where a high inoculum may produce significant crop losses. For diseases that are commonly found in potato fields (e.g. *Rhizoctonia*, common scab) no particular measures are usually taken with regard to the spread of the disease. Realistic measures have to be taken regarding the spread of each disease. Regulations which are too restricting make the development of a viable potato programme impossible, while inadequate precautions may cause major problems in the long run.

13.2 General methods of disease and pest control

Various methods are available for the control of diseases and pests. As most of these will not be sufficient on their own to provide adequate control it should be recognized that, to produce a good potato crop, combinations of various control methods will have to be applied.

The methods available are:

- cultural practices: (1) soil tillage, planting and ridging procedures, (2) seed preparation, (3) water supply, drainage, irrigation, (4) roguing and haulm destruction, (5) harvesting, handling and storage methods
- use of clean seed
- tuber disinfection
- soil disinfection
- foliar application of fungicides
- insect control
- rotation
- phytosanitation

13.2.1 Cultural practices

Good cultural practices normally form the basis of all efforts to control diseases. Most of those which are advised in connection with disease control, contribute in any case to higher yields for other reasons.

13.2.1.1 Soil tillage, planting and ridging methods

Soil tillage is not done just to improve the physical condition of the soil for plant growth but also to control weeds and to promote the destruction of anything (e.g. ground keeper tubers, weeds, etc.) carrying potato pathogens. Rapid emergence and prevention of seed decay are important in reducing crop losses and attack on emerging plants by pathogens. Soil tillage, seedbed preparation, planting and ridging should be done in such a way that emergence is not delayed (chapter 8).

After planting, the seed should be covered with a moist layer of soil so the tubers do not dry up. The soil temperature near the tubers should not be too low or too high. In cool wet climates, planting should be shallow and the final ridge should not be made before the plants emerge, while in dry, hot regions planting should be deeper and the tubers should be covered with more soil. To prevent the moist soil from drying out at the time of seedbed preparation, the intervals between this operation, planting and first ridging should be kept as short as possible.

Planting time should be adjusted according to soil and weather conditions. Soil which is too wet, too cold or too hot is a good reason for delaying both seedbed preparation and planting. Large ridges are required to cover the newly formed tubers with sufficient soil to prevent attack by insects (e.g. tubermoth), greening of tubers, blight attack and tuber temperatures which are too high. Eventually a mulch can be used.

13.2.1.2 Seed preparation

Before planting, various seed treatments are applied e.g. pre-sprouting and cutting (chapter 7).

Pre-sprouting If rapid emergence is required (e.g. risk of *Rhizoctonia* attack) it is advisable to allow the seed to sprout before it is planted. At least the eyes should be open, but it is even better to have sprouts 1–2 cm in length. The sprouts should be strong enough to be able to withstand damage at planting and so avoid attack by pathogens. Strong green sprouts develop in light and moderate temperatures. Pre-sprouting is specifically advised when seed is physiologically old.

Cutting Cutting seed is normal practice in many areas and there are many reasons for this (section 7.6). There is one major disadvantage to cutting, which is the risk of spreading disease and promoting seed piece decay. To reduce infection and decay the following points should be taken into consideration (the first four items are essential):
- old seed should not be cut
- if seedbed conditions are expected to be unfavourable (e.g. high temperature) seed should not be cut
- seed carrying pathogens should not be cut
- the cut surface should not be allowed to dry out
- a sharp, disinfected knife should be used
- tubers should be disinfected before cutting (see: disinfection of tubers)
- the fresh cut surface should immediately be dusted with 15 % carbamates at least

(e.g. Dithane M45). Finely ground rice hull, ash, kaoline or talcum can be used as a filler (approx. four parts filler to one part commercial chemical)
- or alternatively, the fresh cut surface should be dusted with 2 % thiabendazole (this treatment has shown promising results)
- dipping in a solution of 500–1000 ppm (mg/l) sodium hypochlorite may reduce decay caused by bacteria.

13.2.1.3 Water supply: drainage and irrigation

Many pathogens can enter the potato tubers easily if the soil is very wet, as the lenticels are then open. Roots and underground stems are also easily attacked when the soil is wet. The soil should be well drained and, during tillage compaction should be avoided so that surplus water can infiltrate easily. 'Over' irrigation should be avoided as seed pieces are very susceptible to wet conditions when just planted. It is better to plant potatoes in pre-irrigated furrows or seedbed instead of in dry soil and then to irrigate immediately afterwards. High soil temperatures (above 30 °C) can be also detrimental for a rapid emergence. Wetting the soil surface or using a mulch will decrease soil temperatur and so stimulating emergence.

Irrigation should be continued throughout the growing season, not allowing the soil to become too wet or too dry. If the soil is too dry, especially at the end of the growing season or at harvest, not only does the soil crack allowing insects to attack the tubers, but also harvesting the tubers from dry soil increases tuber damage.

13.2.1.4 Roguing and haulm destruction

Roguing is done:
- to remove sources of infection and prevent the spread of disease (e.g. viruses)
- to ensure that the number of rotten tubers entering the store will be kept to a minimum (e.g. bacterial diseases)
- to avoid a rapid build up of pathogens in the soil (e.g. *Pseudomonas solanacearum*).

Roguing is mainly restricted to seed crops and neighbouring potato fields to prevent the spread of disease. It is clear that roguing must be carried out as soon as disease symptoms are visible as:
- Plants are then still small and less plant material will have to be removed from the field.
- Sources of infection are eliminated before the disease spreads.

Prior to roguing, seed crops are sprayed to kill virus-carrying insects (e.g. aphids). Under high degeneration conditions (section 16.1.1) roguing is of doubtful benefit in a field where more than about 2 % of the plants are virus infected.

Haulm killing is carried out:
- to prevent the spread of diseases caused by fungi (e.g. *Phytophthora infestans, Alternaria solani*) (In certain cases only small patches in a field are heavily attacked.)
- to stop spore production by fungi that can attack tubers (e.g. *Phytophthora infestans*)
- to stop spread of virus to the tubers and to prevent virus infection if the transmitting aphid population becomes large
- to enable crops to be harvested before excessively wet soil induces tuber rotting

- to enable crops to be harvested before the soil temperature becomes too high or too low.

13.2.1.5 Harvest, handling and storage methods

Attack by diseases and pests may increase when tubers remain in the soil for too long, especially if the soil conditions are wet or hot. To restrict the spread and development of tuber diseases the following measures should be considered:
- start harvesting before soil and weather conditions become unfavourable (i.e. too wet, dry, hot, cold)
- if immature crops have to be harvested destroy the haulms (mechanically or chemically)
- the time between haulm destruction and harvesting should be kept to a minimum, but must be long enough for the skin to set well
- avoid damage as much as possible during harvesting and handling
- discard diseased tubers
- grading and sorting should not be carried out before the skin of the tubers has hardened
- dry wet potatoes as soon as possible (by good ventilation)
- protect potatoes from rain after harvesting
- do not store potatoes wetted by rain after harvesting
- first store potatoes for two weeks at a temperature of approx. 15 °C before lowering the temperature
- potatoes should be stored so that the tubers are adequately ventilated.

13.2.2 Use of clean seed

Seed should be free from diseases and pests which can survive in soil for a long time and that are difficult (or expensive) to control (e.g. *Pseudomonas, Synchrytium, Globodera*). Health requirements for other diseases should be very strict, although some can be tolerated (e.g. *Phoma, Phytophthora*, etc.). The tolerances for seed to be used in seed production are lower than for seed used in the production of eating potatoes.

13.2.3 Tuber disinfection

Disinfection of seed is common practice in potato production. Seed treatment with chemicals can never replace high quality seed or proper handling and storage of seed.

13.2.3.1 Pre-storage treatment

Treatment of the tubers before storage with either a dustor a spray containing fungicides (e.g. 1 litre water containing 30–40 g thiabendazole per tonne) reduces losses due to *Fusarium, Phoma* and *Helminthosporium*, for example. The application is made while loading the storage space and care has to be taken that the liquid is evenly distributed. The potatoes should not be allowed to get too wet. They require proper ventilation afterwards.

13.2.3.2 Wet treatment of tubers

Disinfecting tubers by dipping them in chemical solutions is a method commonly applied in seed programmes. Mercury compounds have been widely used since the chemical not only kills various fungi found on the tuber surface (e.g. *Rhizoctonia, Alternaria, Phoma, Verticillium*, etc.) but also the bacteria in the solution. Although mercury compounds are effective, they cause too much environmental pollution, and their use has now been abandoned in most countries.

Dipping tubers in a thiabendazole solution is still done in some places. It is an effective method of treatment for controlling several fungal diseases, but there is the risk with this method that bacterial diseases are spread when the seed treated contains tubers that are contaminated with bacteria. Sodium hypochlorite (500–1000 ppm (mg/l)) can be added to the solution to reduce the spread of bacteria.

In some seed programmes, where *Globodera* sp. is a problem the seed is washed with water. With this method too there is the risk of spreading bacterial diseases and sodium hypoclorite is used here as well to reduce this risk.

The safest method of dipping is to place the seed tubers in chitting trays and then to submerge the tray of tubers in the solution. This has the advantage that there is no damage and the risk of spreading bacteria is limited. Although less effective, dusting is often a better solution (section 13.2.3.4).

13.2.3.3 Fumigation of tubers

Smoke generators containing trioxymethylene produce formaldehyde when heated. Sclerotia of*Rhizoctonia* and other fungal diseases are killed when tubers are exposed to this formaldehyde in an airtight room. In practice it is often difficult to ensure that the smoke is distributed well enough to expose the tubers evenly.

2-Amino-butane at a dose of 200 mg per kg potatoes is effective in controlling several fungal diseases (e.g. *Phoma*).

13.2.3.4 Dusting tubers at the time of planting

The main reason for dusting seed potatoes is to reduce *Rhizoctonia* problems. Some of the chemicals used are mancozeb, solacol, moncerene and thiabendazole. Mancozeb has a wide range while solacol and moncerene are fairly specific to *Rhizoctonia*. Thiabendazole has a wider spectrum but is not always effective in controlling *Rhizoctonia*.

In several experiments solacol and moncerene have shown better control of *Rhizoctonia* than mancozeb, but since these chemicals are specifically intended to treat the disease there is the risk that resistant strains of the fungus could develop. In other countries, not much difference has been observed between mancozeb and the more specific chemicals for dealing with *Rhizoctonia*. In such cases it may be advisable to use mancozeb, which has a wider spectum.

13.2.4 Soil treatment

Various chemicals are applied to the soil to control nematodes, fungi and insects.
- Talcofosmethyl (Rhizolex 50 % a.i.) at a rate of 20–30 kg per ha or 15–20 kg pencycuron (Moncerene 25 % a.i.) are sprayed as wetted powder before planting and incorporated in the soil at planting. If applied in the furrow at planting, half the dosage is used. Chemicals are effective in controlling *Rhizoctonia* if the soil is the main infection source, but its use is expensive.
- Quintazen (PCNB) applied as a powder or spray and mixed with the soil can contribute to the control of *Rhizoctonia* and common scab. However, the chemical can reduce yield and may cause an impaired flavour. Its use is restricted to seed potatoes.
- Dichloropropane (150–250 l/ha) and metamnatrium (300–400 l) are used to control potato cyst nematodes. These chemicals can reduce the *Globodera* sp. population by 80 % if applied properly. The use of these chemicals is only justified if good methods of application are available. They are also used to control *Verticillium dahliae*.
- Aldicarp, carbofuran, ethoprophos and oxamyl applied as granulates to the soil reduce crop losses caused by soil nematodes and reduce their multiplication. They are systemic nematicides but also act as insecticides. Aldicarp en ethoprophos are effective in the control of nematodes. Carbofuran is effective in controlling soil insects while aldicarp and oxamyl are used to control aphids and other insects. The chemicals must be applied with great care.
- Chlorinated hydrocarbons such as Dieldrin, though abandoned in many countries, are still being used in countries where soil insects are a major problem and no other solutions are available.
- Systemic insecticides (e.g. disyston) applied as granulates in the furrows at planting may control aphids for a period of 8–12 weeks.

Although there are certain advantages in applying chemicals to the soil, there are also a number of disadvantages, such as:
- The chemicals are only effective if applied properly.
- Some of the chemicals have to be applied before any real problem arises, while it is not certain that there would be any crop damage without the chemicals.
- Some chemicals have a long residual effect.
- Not only the target insect is killed but its natural enemies as well.

13.2.5 Foliar application of fungicides

Diseases which attack the foliage (e.g. *Phytophthora, Alternaria, Cercospora*) can be controlled by spraying crops with copper compounds, dithio-carbamates, fentin compounds and maneb/fentin compounds. The fungicides mentioned here do not have a curative effect but are only protective. Obviously, the fungicide has to be present on the foliage by the time conditions are favourable for infection.

To prevent sources of infection developing, a spraying schedule must be started early in the growing season (before the first attack is expected). The frequency of spraying depends on the local conditions (intervals of between 3 and 20 days). The spraying schedule should be based on the control of the major diseases (e.g. *Phytophthora, Alternaria*). Good control of these also guarantees control of the minor fungal diseases of the foliage.

Chemicals which not only prevent infection but also the growth and sporulation of the penetrating mycelium are a recent development. Strains of *Phytophthora* resistant to Ridomil, the most commonly used chemical treatment, were found soon after its introduction. To hamper the development of resistant strains, maneb has been incorporated into the compound and furthermore growers are strongly recommended to use Ridomil only in emergency cases.

13.2.6 Rotation

Rotation is a common practice to avoid a build up of pathogens. It is also used to reduce the level of soil infestation once the soil has been contaminated. As some diseases and pests (e.g. *Pseudomonas, Synchrytium, Globodera*) can survive in soil for a long time, crop rotation should also be practiced on fields which have always been free of these troubles. This is to avoid the build up of diseases and pests to a level at which crop losses occur. Rotations should not include crops that are hosts for these diseases and pests, furthermore, the growth of volunteer potatoes should be prevented. Theoretically longer rotations are desirable, in practice, however, it is usually advised to grow potatoes only once in every four years.

13.2.7 Isolation

Neighbouring fields may also be sources of infection (e.g. late blight, viruses, insects). To prevent further spread it is advisable to destroy the haulm of crops infected with late blight.

In some cases it is useful to control insects (including aphids) in neighbouring potato crops; where this is done, virus diseased plants in these crops should also be rogued.

13.3 Control of virus diseases

The reduction in yield due to virus diseases has been described in chapter 7. The reduction due to primary infections (i.e. infections that take place during the growing season) is much lower than that due to secondary infections (i.e. in plants grown from seed infected by a virus). It is doubtful whether it is worth taking measures to reduce the spread of virus diseases in ware potato crops purely to maintain the level of yield.

The major methods of controlling virus diseases are included in seed programmes used by farmers wishing to produce their own disease-free seed (chapter 16). The basic element of seed programmes is positive or negative selection aimed at reducing the spread of virus diseases. Virus diseases are grouped according to their mode of transmission (i.e. contact, aphids, nematodes, fungi). Aphids are the main transmitters of viruses. They transmit them either persistently or non-persistently.

A persistently transmitted virus (e.g. potato leaf roll virus) can only be transmitted after the virus has circulated through the aphid, which takes several hours. A non-persistently transmitted virus (e.g. PVY) is transmitted directly after acquisition by the aphid but the aphid is only able to transmit it for a short time. Persistently transmitted viruses can be transmitted over relatively longer distances than non-

Table 42. Efficacy of insecticides in control of potato insect pest.

Chemical name	Trade name	Quantity per ha	%AI	Foliar application				Soil application							
				Aphids	Tuber moth	Beetles	Leaf hoppers	Cutworms	Mole cricket	Aphids	Beetles	Wire worms	White grubs	Tuber moth	Leaf hoppers
Acephate	Orthene	0.5- 1kg	80	G	G	–	–	–	–	–	–	–	–	–	–
Aldicarb	Temik	10 -25kg	10	★	★	★	★	–	–	G	G	G	G	–	G
Aldrin	many	0.5- 1.5l	25	–	–	G	–	G	–	–	–	G	G	–	–
Azinphos methyl	Gusathin	1 - 1.5l	25	–	G	–	–	–	–	–	–	–	–	–	–
Carbaryl	many	1 - 1.5kg	50	–	G	G	G	–	–	–	–	–	–	G	–
Carbofuran	Furadan	10 -25kg	5	★	★	★	★	–	–	–	G	G	G	–	–
Chlorfenvinphos	Birlane	0.5- 1kg	25	–	G	G	–	–	–	–	–	–	–	–	–
Dieldrin	many	2 - 2kg	50	–	–	G	G	G		–	G	G	G	–	–
Dimethoate	Rogor	1 - 1.5kg	20	G	–	–	–	–	–	–	–	–	–	–	–
Endosulfan	Thiodan	1 - 2l	50	G	G	G	–	G	–	–	–	–	–	–	–
Lindane (gamora BMC)	many	0.5- 1.5l	21	–	–	G	G	G	G	–	G	G	G	–	–
Malathion	many	1.5- 3kg	25	G	–	–	G	–	–	–	–	–	–	–	–
Oxydemeton-methyl	Metasystox R	1l	25	G	–	–	–	–	–	–	–	–	–	–	–
Parathion	many	1 - 5l	25	G	G	G	G	G	G	–	G	G	G	–	–
Permethrin	Ambush	0.5- 1l	25	–	G	G	–	–	–	–	–	–	–	–	–
Pirimicarb	Pirimor	0.5- 1kg	50	G	–	–	–	–	–	–	–	–	–	–	–

G = good, – = fair to poor, ★ = not used.

persistently transmitted ones. The spread of persistently transmitted viruses within a field can be controlled fairly effectively by destroying the aphids but infection from outside will still continue unless the neighbouring fields are also sprayed with aphicides (see also section 16.5.1).

13.4 Insect control

Insects can cause direct or indirect damage to crops. Indirect damage is caused by the fact that insects (mainly aphids) are vectors of viruses (chapter 16). In ware potato production, insect control concentrates mainly on the prevention of direct damage while in seed production both direct and indirect damage should be prevented.

Measures to control direct damage include the use of insecticides (table 42). There are many arguments against their use (e.g. build up of resistance, danger to human beings, environmental pollution, etc.) and sometimes a certain level of attack (especially of the foliage) has to be accepted. In addition to extremely important cultural practices (i.e. crop rotation, proper soil tillage, soil drainage and a good ridging system), the following methods of control are available:

- foliar application of insecticides
- soil application of insecticides to growing crops
- application of chemicals to the soil at emergence
- chemicals applied and mixed with the soil before planting
- treatment of tubers in store.

Most pests can be controlled at the time they appear but in the event of white grubs and wire worms, control has to be carried out in advance wherever attack may be expected. For some pests (e.g. *Phythorimaea operculella*) more than one control method has to be applied.

There is now a general trend towards reducing the use of chemicals which may have an adverse effect on the environment or on the food value of the crop. To promote this development the integrated production system was launched, which is defined by Schöber & Keller (1984) as 'production of healthy seed, food and stock feed, maintaining the production capacity of the soil and taking into account ecological, economical and social aspects, allowing long term field production'.

14 Harvest

14.1 Time of harvest

To determine the time to harvest the following should be taken into consideration:
- actual yield of the crop and its attainable yield
- actual prices and expected prices
- influence of harvest time on the quality of the crop
- present and expected field and weather conditions
- when the field has to be available for the next crop.

The yield and yield reduction (in tonnes/ha) of the two crops in figure 31, harvested on different dates, are shown in table 43. The fact a crop yields less may be compensated for by the higher prices obtained.

Apart from yield, the quality of the crop is also influenced by lifting at an immature stage. The skin of an immature tuber is weaker and the walls of the cells just below the epidermis are much thinner than in mature tubers. This is the reason why skin damage and skinning or feathering easily occur with immature potatoes.

The early harvest of a crop may influence its quality. During the growing period the dry matter content of the tubers often increases gradually, while both the total and reducing sugar content decrease (sections 12.1 and 12.2).

Table 43. Yield and yield reduction on different harvest dates for two types of crops (see figure 31).

Harvesting date	Short cycle crop			Long cycle crop		
	yield (t/ha)	yield reduction as compared with attainable yield (t/ha)	yield reduction as compared with next harvest (t/ha)	yield (t/ha)	yield reduction as compared with attainable yield (t/ha)	yield reduction as compared with next harvest (t/ha)
August 1	26	11.5	5	19	27	7
August 10	31	6.5	4	26	20	7
August 20	35	2.5	2	33	13	6
Sept. 1	37	0.5	0.5	39	7	4
Sept. 10	37.5	-	-	43	3	3
Sept. 20	37.5	-	-	46	-	-

On account of this, tubers harvested while still immature tend to have a low dry matter content, while the reducing and non-reducing sugar content is high. Seed potatoes are often harvested early to avoid virus infection, which may occur during the latter part of the growing season. Late blight attack on the haulm may also be a reason for early lifting. Harvesting an immature crop often leads to more skin damage and results in the tubers being more easily infected by fungal and bacterial pathogens (e.g. *Fusarium*).

14.2 Haulm destruction

It is almost common practice to cut, pull out, burn or destroy haulms with chemicals before harvesting. In combination with chemical destruction haulms are often beaten. The haulm is destroyed to facilitate harvest and to allow the skin of the tubers to harden.

Especially if the potatoes are to be harvested mechanically, the haulm has to be destroyed 10 to 20 days before harvest, depending on the maturity of the crop, the harvester used and the likely soil conditions at harvest time. Table 44 shows the effect of date of haulm destruction and date of harvesting on the skinning of potatoes (Terman et al., 1952).

To reduce skinning in a young immature crop a longer time interval is needed between haulm destruction and harvesting than for an old, almost mature crop. There is also a varietal influence on skinning. The normal process of maturation in itself also has an obvious influence on the reduction of skinning.

Haulm destruction, especially when the potatoes are not yet mature, greatly affects the release of the tubers from the vines at harvest. An interval of 10–20 days between haulm destruction and harvesting is usually sufficient to ensure easy release. As tubers can be attacked by micro-organisms (e.g. *Rhizoctonia solani*) and pests during that period, the time interval between haulm destruction and harvesting should not be too long. The result of an experiment in which an increase in *Rhizoctonia* infestation was demonstrated as a result, is shown in table 45.

Table 44. The influence of harvesting and haulm destruction dates of various varieties on skin damage (Terman et al., 1952).

Varity	Skinning index of tubers for various destruction and harvesting dates					
	August 14		August 24		September 3	
	10 days later	20 days later	10 days later	20 days later	10 days later	20 days later
Chippewa	44	38	42	29	32	32
Kennebec	54	52	55	33	38	40
Kathadin	54	36	40	31	39	34
Green Mountain	43	35	49	36	45	35

(A skinning index is the weighted average percentage of the feathered surface of tuber samples)

Table 45. Effect of methods of haulm destruction and time between haulm destruction and tuber harvest on tuber infestation by *Rhizoctonia sclerotia* (de Bruin, personal communication).

Method of haulm destruction	Number of days between destruction and harvesting	Percentage of tubers infected by *Rhizoctonia*			
		free	slight	moderate	serious
Chemical destruction	4	87.8	11.0	1.3	0.0
	8	84.4	14.0	1.3	0.0
	11	72.0	17.4	9.3	1.3
	15	71.7	14.0	11.3	3.0
Haulm pulling	4	84.3	15.0	0.7	0.0
	8	90.0	9.0	1.0	0.0
	11	84.0	14.7	1.3	0.0
	15	93.0	6.3	0.7	0.0

14.2.1 Methods of haulm destruction

Pulling is one of the best methods of haulm destruction as no dangerous chemicals are applied, mechanical harvesting is easier (release of the tubers), and the risk of *Rhizoctonia* infestation of the tubers is reduced. The method also has its disadvantages: the soil covering the tubers is often partly removed (greening may occur) and the labour investment is high.

The capacity of haulm pulling machines has increased considerably in recent years and there is little doubt that such equipment will be used much more extensively in the near future.

Haulm cutting or haulm beating is also practiced, particularly for early potatoes, and where potatoes are not lifted with complete harvesters. Chemicals are commonly used for destroying haulm. If the haulm growth is abundant and the crop is not yet mature, spraying is often done in combination with haulm beating. Chemical haulm destruction is cheap and easily carried out, its disadvantages are that the chemicals are often poisonous and/or corrosive, furthermore, some chemicals may affect the growth of the following crop.

To avoid blight attack on the tubers, the haulms are often destroyed just when they are likely to become infected with *Phytophthora infestans*. (In the Netherlands it is advised to kill the haulms if 5–10 infected leaves occur on 20 plants.)

The use of chemicals is much more effective than haulm pulling with regard to control of attack on the tuber by fungi that occur on the haulm. With chemical haulm destruction, not only are the haulms destroyed but the weeds as well. The best results are obtained if the relative humidity is high at the time of spraying. A large amount of water is required, a minimum of 500 l of water per hectare if the haulms are beaten, and 800–1000 l if they are not.

– DNOC in oil. This chemical is very poisonous to humans, especially when applied at high temperatures. The haulms are destroyed quickly but less effectively than with arsenites. There is no effect on the following crop. Depending on the brand and on

the degree of crop maturity, 20–35 l/ha are applied. DNOC has been abandoned in many countries.
- DNBP in oil (Dinoseb). See: DNOC in oil.
- Diquat (Reglone). This chemical is less poisonous than the others mentioned. In crops with a luxuriant haulm growth spraying will not always be sufficient. The chemical is not dangerous to the following crop. 5 l/ha are applied.
- Sodium chlorate. 15–25 kg/ha is applied in a reasonable volume of water. It acts rather slowly and is not very effective on stems. Where rainfall is low higher doses may be harmful to succeeding crops sown soon after the potato harvest.

14.2.2 Stem end and vascular ring necrosis

After chemical haulm destruction and, to a lesser extent, after haulm pulling, stem end and vascular ring discolouration may occur due to necrosis.

The stem end attachment is often slightly sunken and only the vascular ring near the stem end will appear faintly yellow to dark brown. In severe cases, the whole vascular ring is discoloured and the tuber starts rotting from the stem end (a dry rot) during storage. The risk of this disorder occurring is particularly great if the chemicals are applied at high temperatures while the plants are under high water stress. To avoid this it is advisable not to spray the crops during the daytime, when the water stress in the plants is highest, but to wait until late evening or early morning. It is even better not to spray until the soil is thoroughly wet from rain or irrigation.

14.3 Harvesting operations, transport and storage

Harvesting potatoes includes the following operations:
- lifting
- collecting the tubers
- separating tubers and soil/clods/stones
- transport.

The aim of each harvesting system is to take the tubers from the soil to the store or to the market as cheaply as possible, keeping losses (e.g. of quality) to a minimum.

The harvesting system used depends on:
- the economic situation (i.e. machinery costs – labour costs)
- the quantity of potatoes to be harvested and the time available
- the size, shape and situation of the potato field
- the soil and weather conditions
- the use to be made of the potatoes (immediate consumption, storage).

Various types of potato diggers (e.g. ploughs, spinners, elevator diggers) as well as complete harvesters are used for harvesting. Potato diggers lift the potatoes from the soil for hand-picking. A complete harvester lifts the potatoes and delivers, them free from soil, stones and haulm, directly onto a trailer or bulk container, or into bags, with a minimum of manual labour. These are widely used for large fields where soil tillage and planting methods have been used which ensure that there are few clods in the ridges. In other fields a potato digger must be used.

14.3.1 Time between lifting and collection

If potatoes have to be harvested from wet fields, it may be advantageous to allow the tubers to dry for some time between lifting and collecting (rain is critical as it affects the keeping quality of the harvested tubers). During this time the skin hardens and the adhering soil dries. The tubers should, however, only be exposed to the air for a short time. Exposing them to bright sunshine may cause sunburn, especially if the skin is still thin and young.

Black heart, due to lack of oxygen in the tuber, may also occur, especially when temperatures are high and the soil is dry.

14.3.2 Damage during transport and grading

With complete harvesters, potatoes are often loaded, transported and stored in bulk. Grading should not be started before wound healing and skin hardening has taken place. Some potato harvesters deliver the potatoes in bags. To facilitate handling, these should not be too large or alternatively, large bags should not be filled completely.

After the potatoes have been lifted by a digger, the tubers are often collected in baskets or crates. Those in crates are usually less bruised.

15 Storage principles

15.1 Methods and duration of storage

If there are only one or two harvests a year, potatoes often have to be stored, to ensure a more regular supply and to obtain higher market prices. To ensure that seed of the correct physiological stage is available at the required planting time, adequate storage methods for seed are essential.

As long term storage facilities are expensive and storage losses are unavoidable, it has to be determined for each case individually whether either adaptation of the growing periods or investment in storage is the best solution for a more regular supply of potatoes. It is also important to determine which storage method is the most appropriate. The method used depends on:

- the purpose of the crop (e.g. fresh consumption, processing, seed, etc.)
- the duration of the storage period
- the outside temperatures during the storage season (average T, average T_{max}, average T_{min})
- the quantity of potatoes to be stored
- the methods of handling.

The 'storage life' of a potato largely depends on the storage temperature, the quality of the crop and the variety. An estimate of the 'storage life' at various temperatures

Table 46. Estimated 'storage life' of potatoes (months).

	Purpose of the crop			
	consumption		seed	
Light conditions	dark		dark	diffuse light
Sprout inhibitors	–	IPC-Cl IPC	–	–
Storage temperature				
4 °C	10	10	10	11
10 °C	5	8	6	9
15 °C	4	6	5	8
20 °C	3	4	4	6
25 °C	2	2	3	5
30 °C	1	1	2	3
35 °C	0.5	0.5	1	2

is given in table 46. The data given in this table can only serve as a guideline, not only because not all potatoes have the same 'storage life' but also because the evaluation of quality at the end of the storage season is purely subjective.

15.2 Storage losses and storage requirements

Losses are unavoidable during storage and changes in physiological condition as well as chemical composition will occur. These losses will be due to evaporation, respiration, sprouting, infection by fungi and bacteria and infestation by insects. Storage conditions should be such that:
- losses due to evaporation, respiration, sprouting, infection by fungi and bacteria and infestation by insects are kept to a minimum
- tubers are brought to or kept at the right physiological stage
- the chemical composition of the tubers is maintained at or brought to the desired quality.

15.2.1 Evaporation losses

The potato tuber consists of 80 % water. The main weight loss during storage is water loss, which also reduces quality. Water evaporates through the skin, wounds and sprouts. Much more water can disappear through wounds and sprouts than through mature skin. The ratio of the amount of water loss per unit of area of the skin, wounds and sprouts is 1 : 300 : 100 respectively. Therefore evaporation is relatively high if potatoes are damaged or have a weak, injured skin and are not cured. Tubers sprouting also leads to high evaporation losses.

In the evaporation process water from the tuber is taken up by the air surrounding the tuber. In a stack of potatoes circulation of air or ventilation is essential to keep the surface of the potatoes dry, to remove heat and to supply oxygen. As a result there will always be water losses (e.g. 1.5 % of the fresh weight during the first month of storage and 0.5 % for each additional month is possible).

The losses caused by evaporation largely depend on the ventilation rate, the duration of ventilation and the relative humidity (RH) or vapour pressure deficit (VPD) of the air used for ventilation. Table 47 shows the effects of different ventilation

Table 47. Estimated evaporation of potatoes ventilated at different rates (% of original weight per week per mm initial VPD) (Burton, 1963).

Potatoes		Ventilation rates (m^3 per hour per 1000 kg potatoes)				
		10	20	50	100	200
Freshly harvested		0.17	0.34	0.7	0.7	0.7
Unsprouted, after some weeks in store		0.17	0.2	0.2	0.2	0.2
Sprouted with	1%	0.17	0.3	0.3	0.3	0.3
by weight of	2%	0.17	0.34	0.4	0.4	0.4
sprouts	4%	0.17	0.34	0.6	0.6	0.6
	8%	0.17	0.34	0.84	1.0	1.0

rates on water loss.

From the data given it may be concluded that:

- Evaporation losses per time unit are low and are at the same level for freshly harvested, unsprouted and sprouted potatoes when the ventilation rate does not exceed 10 m^3 air per hour per 1000 kg of potatoes.
- At higher ventilation rates the evaporation losses per time unit are higher for freshly harvested or sprouted potatoes than for unsprouted potatoes with a firm and cured skin.
- Increasing the ventilation rate from 20 m^3 to 200 m^3 of air per hour per 1000 kg of unsprouted mature potatoes does not result in higher evaporation losses per time unit.

15.2.2 Respiration losses

A potato tuber is a living organism and therefore it respires. In respiration, oxygen is absorbed from the surrounding air and together with carbohydrates (sugar) from the tuber, converted into carbon dioxide and water. The carbon dioxide is expelled into the surrounding air. Heat is produced in this process. The respiration rate and thus the production of CO_2 and heat depends mainly on the temperature of the tubers (fig. 69). Other factors which affect the respiration rate are the maturity of the tuber, the presence of wounds and the sugar content. Tubers that are immature, damaged or starting to sprout have a higher respiration rate than the figures given in figure 69. The heat production of mature tubers at 5–10 °C a few weeks after harvest is about 40 J/kg per hour, at 20 °C this rises to 100 J/kg per hour.

The respiration of immature tubers soon after harvest is much higher than that of mature tubers. The heat production of freshly harvested immature tubers can be more than 400 J/kg per hour at 20 °C. After some time (e.g. 2 weeks) the level of respiration of these immature tubers will become normal and heat production as shown in figure 69 will be reached.

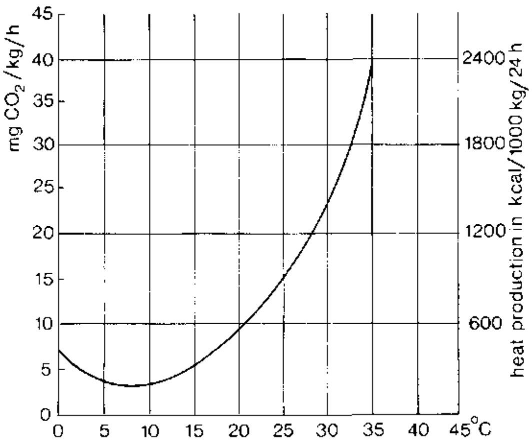

Fig. 69. Respiration and heat production of mature undamaged tubers at various temperatures (partly after Ophuis & Kroesbergen, 1955) 1 kcal = 4.1868 kJ.

The heat produced in a stack of potatoes by the respiration process should be removed by ventilation. When more heat is produced than is being removed, overheating will occur. This is the case when the ambient air temperature is relatively high, the respiration of the potatoes is high and the ventilation in the stack is poor.

It has been estimated (Burton, 1978b) that overheating can occur in naturally ventilated stacks, 1.80 m high with an ambient temperature of 25 °C and in stacks 3.50 m high with an ambient temperature of 20 °C. With freshly harvested immature potatoes overheating may occur in stacks of 1.80 m and 3.50 m high when even the ambient temperature is 20 °C and 14 °C respectively. It is evident that the losses will be least at a storage temperature of 4–8 °C.

To avoid oxygen starvation of the tubers (black heart), the CO_2 produced should be removed and replaced by oxygen. So the air surrounding the potato tubers should be replaced by fresh air from time to time. At least 4–5 m^3 of fresh air is required every 24 hours per 1000 kg of potatoes to supply sufficient oxygen for the respiration process.

15.2.3 Sprout growth losses

Sprout growth causes excessive losses due to evaporation, increased respiration and transfer of carbohydrates from the tubers to the sprouts. During the first 1–3 months, when the tubers are still dormant, no sprout growth will occur. Although the temperature has no major effect on the length of the dormancy period, it certainly does have an effect on the sprout growth. With increasing temperatures sprout growth accelerates. Moisture also stimulates sprout growth. At temperatures of 2–4 °C hardly any sprout growth occurs and if potatoes are to be stored for a longer period of time (e.g. 8 months) a storage temperature of 3–4 °C is required if sprout inhibitors are not used. The sprout inhibitor used at present (IPC – CL IPC) has little effect when temperatures are higher than 18 °C.

Light clearly reduces the growth of sprouts. When storing seed potatoes efficient use can be made of diffuse light (table 46).

15.2.4 Losses caused by fungi, bacteria and insects

During storage diseases and pests can cause major losses. This is particularly the case when the batch of potatoes brought into storage is partly infested and when tubers are damaged or have a weak skin. Depending on the susceptibility of the potatoes (due to variety, growing conditions) a disease or pest will develop and spread. Only sound tubers with a good skin can be stored successfully.

Not only organisms that cause soft rots (e.g *Erwinia* sp. *Pseudomonas solanacearum, Corynebacterium sepedonicum, Pythium* sp., *Phytophthora infestans* and *erythroceptica*) but also dry rot causing organisms (e.g. *Fusarium* sp., *Macrophominia* sp., *Phoma* sp.) may spread and cause serious losses. Other skin diseases, not causing rot (e.g. *Rhizoctonia, Oospora pustulans, Helminthosporium solani*) may spread during storage and affect quality.

In almost all cases the losses caused by fungi and bacteria can be reduced by providing good ventilation and reducing temperature to the lowest possible level, but no lower than 3–4 °C. Wet potatoes should be dried immediately and freshly harvested potatoes wetted by rain should not be stored at all. Insect damage caused by tubermoth can be quite serious. Low storage temperatures reduce such losses. Tubermoth becomes inactivate at temperatures lower than 10 °C and killed at temperatures lower than 4 °C.

15.2.5 Physiological stage

Potatoes for human consumption should preferably have little or no sprout growth at the end of the storage season. For long-term storage, low temperatures are required (e.g. 4–6 °C) whereas for short-term storage higher temperatures can be tolerated.

Seed potatoes should be stored so that tubers sprout and emerge quickly at planting time. Storage temperature, being the main factor influencing the physiological stage of the potato, should be adapted to the duration of the storage period. If the storage period (time between harvesting and planting) is 2–3 months, the storage temperature should be higher. If stored in light, tubers stay physiologically young longer than when stored in the dark. For long-term storage, seed is either stored at 3–4 °C or, in 'diffuse light' when stored at higher temperatures.

15.2.6 Chemical composition

During storage, starch is converted into sugar and vice versa. Conversions are processes controlled by enzymes, which are greatly affected by temperature. Sugars are also used in the respiration process. This reaction is controlled by temperature.

Table 48 gives an example which shows the sugar balance in potato tubers. Sugar accumulates in tubers stored at low temperatures. If stored at 2–3 °C tubers may develop a sweet taste. At higher temperatures less sugar is accumulated but at 5–6 °C it is still too high for potatoes to be used for processing. French-fries and chips (or crisps) made from potatoes with a high sugar content are too dark in colour. For this reason potatoes which are going to be used for producing french fries or chips are stored at temperatures no lower than 5–7 °C and 7–9 °C respectively.

For short-term storage higher temperatures are often used. A high potato sugar content can be reduced by storing the tubers for a while (1–2 weeks) at a high temperature (15–20 °C) (section 12.2.4). The accumulated sugar is then used for respiration (i.e. reconditioning). Reconditioning does not, however, always give good

Table 48. Chemical changes in the tuber (Müller-Thurgau, 1882).

	Sugar balance (mg/hour per kg potatoes)					
Temperature (°C)	0	3	6	10	15	20
Sugar used in respiration	2.3	2,8	3,5	4.5	6.5	9.5
Sugar converted into starch	1.7	20.8	25.8	31.3	32.5	34.5
Sugar balance	- 4.0	-23.6	-29.3	-35.8	-39.0	- 44.0
Sugar from starch	+32.0	+32.6	+33.6	+35.8	+39.3	+44.0
Sugar accumulation	+28.0	+ 9.0	+ 4.3	0	0.3	0

results (section 12.2.5).

Storage temperature is also important in connection with susceptibility to black spot and bruising. Potatoes stored at low temperatures are more susceptible than those stored at high temperatures. For this reason cold stored potatoes have to be heated to 15–18 °C before handling (section 12.3).

15.3 'Aspects' affecting the keeping quality of tubers

In fact there are only a limited number of 'aspects' which affect the keeping quality of the stored tubers. These are:
- good tuber quality and skin
- proper ventilation
- low temperature
- low moisture and humidity
- light
- chemicals.

15.3.1 Tuber quality and skin

The most important aspect of storage takes place before the actual storage period starts. Storage will only be successful if the tubers entering storage are sound and have a good skin which is not damaged. The quality of the tuber is greatly influenced by the cultural practices and the pest and disease control measures applied during the growing season. Immature potatoes are more difficult to store than mature tubers, as they have a low dry matter content and a weak skin.

As a rule only mature tubers should be stored. If there are reasons for harvesting and storing immature potatoes, it is advisable to destroy the haulms prior to lifting the tubers. This haulm destruction stimulates the maturing of the skin (table 44). Before the potatoes go into storage the rotten and infected tubers have to be removed, as they could become sources of infection. In some cases it has proven to be a good procedure to store the tubers temporarily in heap for about 1 week, before sorting and storing them permanently. During this temporary storage, curing takes place and disease symptoms become more visible, which facilitates the removal of the infected tubers.

Potatoes stored in cold stores (e.g. at 4 °C) require a temperature of 15 °C during the first few weeks for the skin to cure, before the temperature is lowered.

There is a wide difference in keeping quality between varieties and batches of tubers. Varieties and batches with the best keeping quality should be selected for storage, while those with less keeping quality should be marketed earlier.

15.3.2 Ventilation

During storage ventilation is needed to remove heat, water and CO_2 and to supply O_2. Ventilation can be convective (or natural) ventilation, or forced ventilation.

Potatoes bulked in a heap produce heat due to the respiration process. The heat raises the temperature of both the potatoes and the air between them, resulting in convective currents developing within the heap. Warm air räises from the stack and

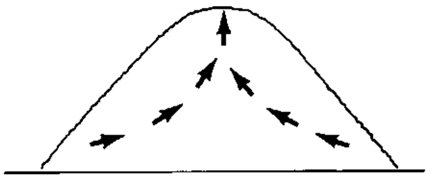

Fig. 70. Potato pile with convective ventilation.

cooler ambient air flows in to replace the heated air (fig. 70). This creates a natural convective transfer of heat away from the stack.

As the amount of air that flows through the stack is limited (often no more than 12 m^3 air per hour per 1000 kg of potatoes) the cooling efficiency is not very good. The air is gradually heated by the potatoes and as a consequence the temperature at the top of the heap is higher than that at the bottom. The difference in temperature between the top and the bottom of the heap of potatoes is about 1.5–2 °C for each metre of piling height, when only convection ventilation occurs.

When the piling height is not too high (e.g. 1 m) the temperature of the potatoes is close to the average temperature of the ambient air. This is the situation when the potatoes are sound and there is not too much air resistance (e.g. due to soil) in the stack. Potatoes may be stored either in bulk or in bags. There is more resistance to air flow in a pile of bags than in a heap of bulked potatoes. The acceptable size of a heap or pile depends on:

- the quality of the potatoes
- the ambient air temperature in the storage environment
- the resistance to air in the pile (due to tuber size, dirt and soil).

Potatoes can be bulked on a slatted floor or on slatted airducts (fig. 71) to a height of 1½–2 m, provided the tubers are sound, the ambient air temperature in the storage environment is low (e.g. 4–15 °C) and the duration of the storage period does not exceed the length of the dormant period. Where the temperature of the surrounding air is high, freshly harvested potatoes particularly, should not be bulked higher than 50–100 cm to prevent overheating (section 15.2.2).

Potatoes stored in bags should be piled in single or double rows with a space between the rows. The bags should never be piled too high. In many cases (because of the high temperature of the surrounding air) the bags should not be piled at all but placed upright in single or double rows on the floor.

If it is necessary to cover the pile to protect the tubers from light, high or low temperatures or rain, material with little air resistance (e.g. straw is better than hay)

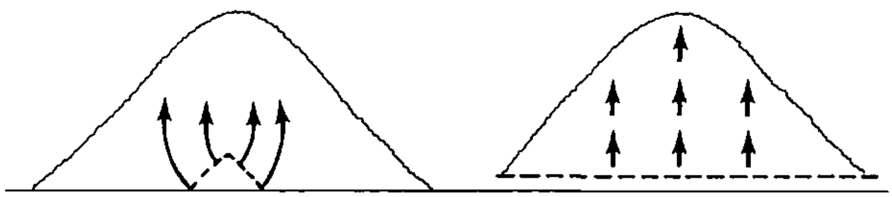

Fig. 71. Potato piles with provisions for improving convective ventilation.

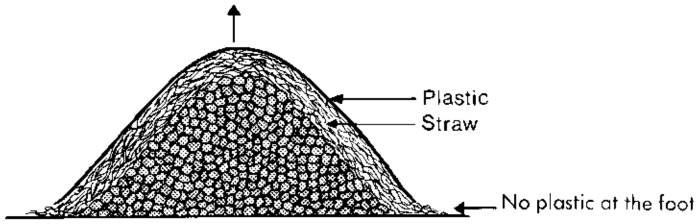

Fig. 72. Potato pile covered with straw and plastic.

should be used. If plastic sheeting is used (to protect outdoor piles from rain) the pile should never be completely covered (fig. 72). It is much better to cover the foot of the pile with straw. This is to allow some ventilation. Additional openings (chimneys) on top of the pile improve ventilation and are often used when piles are large.

As convective ventilation has its limitations with regard to cooling, it is often necessary to sub-divide large batches into smaller units, but then a relatively large floor space is required.

Forced draught ventilation produces movement of the air by a fan and the air stream is led through the heap or pile so that, as far as possible, the same amount of air passes each tuber (fig. 73).

With forced ventilation the ventilation rate is much higher than with convective ventilation. As a result heat can be removed more efficiently with forced ventilation than with convective ventilation. With a well designed forced ventilation system it is possible to achieve a situation where the temperature difference in a stack 3.50–4 m high between the bottom layer and the top layer is no more than 1.5 °C.

The capacity of the fan and the lay-out of the duct system should be adjusted to the air velocity and the air distribution required. The ventilation rate depends on the availability and quality of cool air and the drying capacity needed (table 49). Cooling with a high air velocity (or high ventilation rate) is more effective than cooling with a low air velocity. As increasing the ventilation rate often does not increase evaporation (table 47), but reduces the number of ventilation hours required, it is usually advisable to equip stores with a ventilation capacity of no less than 50–80 m^3 air per 1000 kg per hour, however, 100–120 m^3 air per 1000 kg per hour is often preferred. The air velocity in the main ducts is often no more than 6 m per second when ducts are tapered and 3.5 m per second when the cross-section of the ducts is constant.

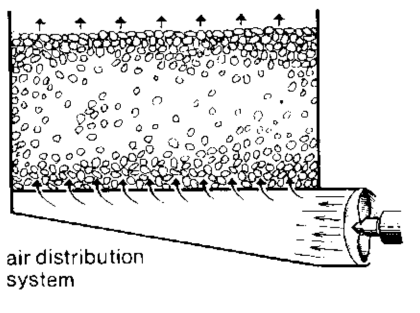

Fig. 73. Forced draught ventilation.

Table 49. Effect of ambient conditions on the requirements for air velocity.

Circumstances	Required air velocity
Cool air available during long periods	low
Cool air available during short periods	high
Available air is of low relative humidity	high
Potatoes are often wet when brought into storage	high
Potatoes are often dry when brought into storage	low

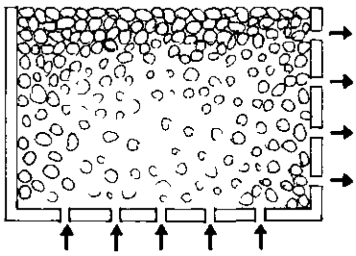

Fig. 74. Four examples with uneven airdistribution.

Fig. 74a. Most of the air disappears through perforations in the right-hand vertical wall. The potatoes on the left-handside of the bin particularly, are insufficiently ventilated.

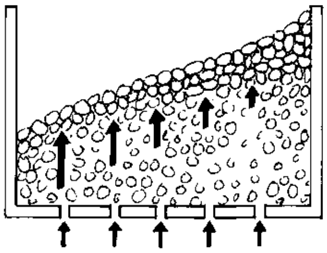

Fig. 74b. Resistance on the right-handside is higher than on the left. Potatoes on the right are insufficiently ventilated.

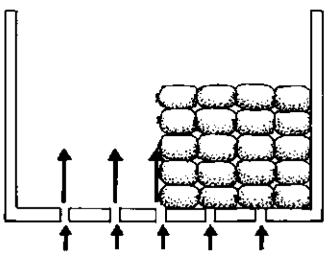

Fig. 74c. Storage area only partly filled with piled sacks. Most of the air will pass through storage area providing no ventilation inside the sacks.

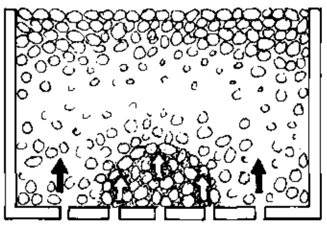

Fig. 74d. The potatoes in part of the bin are dirty (adhering soil and clods), increasing the air resistance there poor and consequently the ventilation in that part of the storage area is poor.

To ensure good air distribution the ratio of the distance between the lateral ducts (i.e. the air outlets) on the floor and the piling height of the potatoes should approximate 1 : 1.5 (distance = 0.70 piling height).

It is essential that the air velocity throughout the storage area should be uniform so that all the potatoes are cooled and/or dried at the same rate. This is only possible if the air resistance is also uniform. In figure 74 some examples are given to illustrate this point.

Bulked potatoes can be stored to a height of 4.00 m in a store equipped with a well-designed air distribution system and a fan of sufficient capacity, but bags of potatoes (their air resistance being higher) are often stacked to a lower height when the air used for cooling is close to the required storage temperature.

Forced draught ventilation systems are used in stores cooled with cold outside air and/or with refrigeration.

15.3.3 Temperature

Temperature largely determines how long potatoes can be stored (table 46). Temperature is determined by climatic conditions, method of storage and storage design.

15.3.3.1 Storage in the soil

The temperature of the potatoes will be the same as the soil temperature and a system of 'delayed harvest' may be applied up until the end of dormancy in regions with moderate temperatures and well drained soils.

Figure 75 shows that in mountain trials in the Philippines a 'delayed harvest' method of 2 months provides a good alternative for the farmer to store his potatoes.

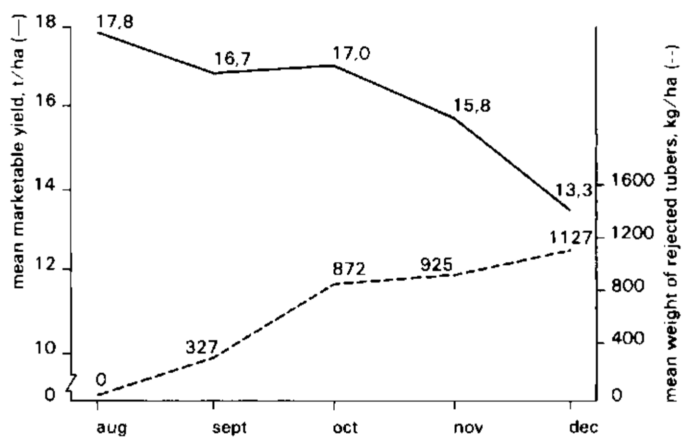

Fig. 75. Losses during delayed harvest of a potato crop (mature in August) in mountain trials (Philippines) (Potts et al., 1982).

15.3.3.2 Naturally ventilated stores

The temperature of potatoes bulked in a heap to a height of 1 m on a slatted false floor, is about the same as the outside average day-night temperature provided that the sun's irradiated heat on the roof of the construction is removed by ventilation (fig. 76).

J. Hunt (personal communication) demonstrated that storage losses were the same in a naturaly ventilated store with flap controlled ventilation during the cool night hours and in a similar store with continuous ventilation (average T_{min} 8–14 °C; average T_{max} 16–27 °C) for a storage period of 4–5 months. Since the actual ventilation of potatoes in a naturally ventilated store is caused by convective ventilation, a complicated airduct system and shutters which have to be open at night and closed during the day, will only have a limited effect.

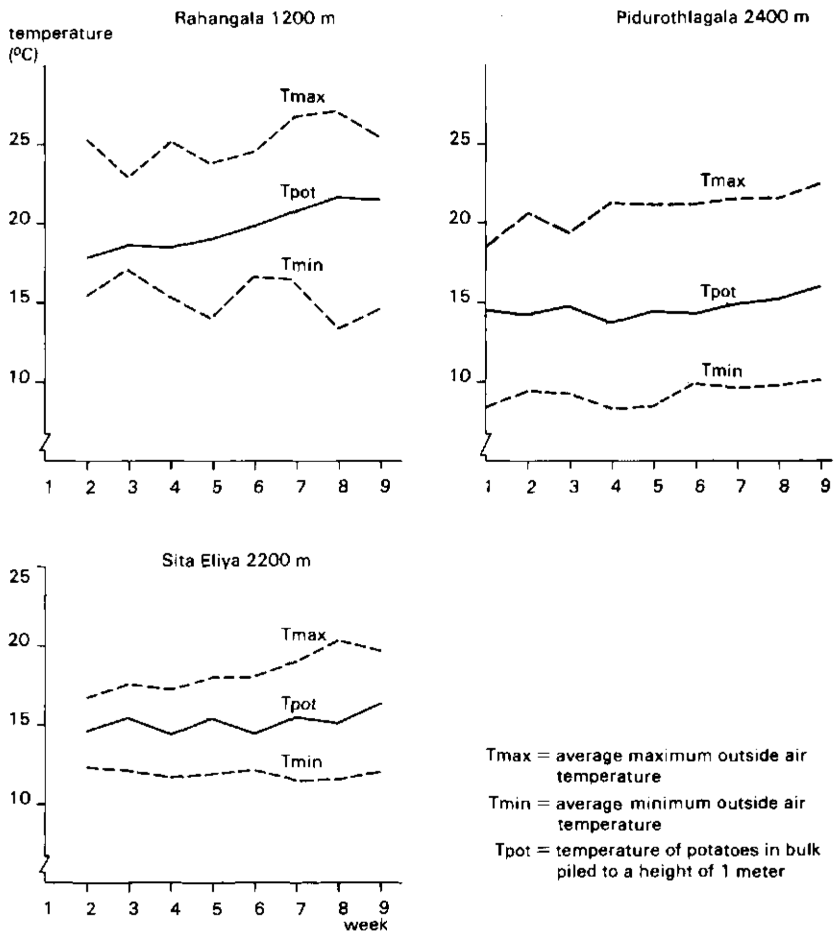

Fig. 76. Potato temperature (bulk storage) in naturally ventilated stores in Sri Lanka at three different altitudes.

In fact, the principle of a naturally ventilated store is a simple construction with a roof and walls with openings to provide sufficient ventilation. The roof and walls have to be adapted to environmental conditions. In such a store potatoes are either bulked (piling height dependent on temperature) or put in loosely woven bags or crates (no bigger than 1 m^3). If light can enter the store, the potatoes must be covered with straw to prevent greening of potatoes to be used for consumption.

15.3.3.3 Outside air cooling with forced ventilation

In well insulated buildings where the outside air is only blown into the building during cool spells ($T_{outside} < T_{potatoes}$) and is forced to blow through the potato piles, the temperature of the potatoes can be maintained at a level which is the same as the average minimum outside temperature ($T_{potatoes}$ is average T_{min}).

The ambient temperature characteristics of any given area enable us to decide whether outside air cooling can be used effectively. These temperature characteristics indicate whether outside air cooling is applicable or not. Apart from the average minimum temperature, it is necessary to know the lowest and the highest temperatures and how many hours per day outside air ventilation is possible. In figure 77 the temperature characteristics for the Netherlands are given.

In the Netherlands, where high ventilation rates are applied, it is necessary to ventilate 40–90 hours per month, 90 hours if the temperature has to be brought down (September–November) and 40 hours to keep the temperature low (December–February).

Figure 78 shows a vertical section through a storage bin with outside air cooling. During periods when the outside temperature is below 0 °C, the outside air is too cold for direct ventilation and cooling is done with a mixture of outside and inside air.

Outside air cooling with forced ventilation is applied when large quantities of potatoes have to be stored in one location and the average outside minimum temper-

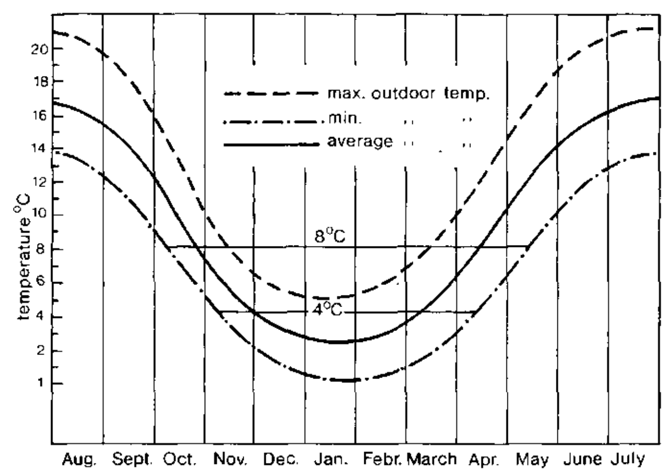

Fig. 77. Maximum, minimum and average temperature in the Netherlands (30 year average) (IBVL, Wageningen).

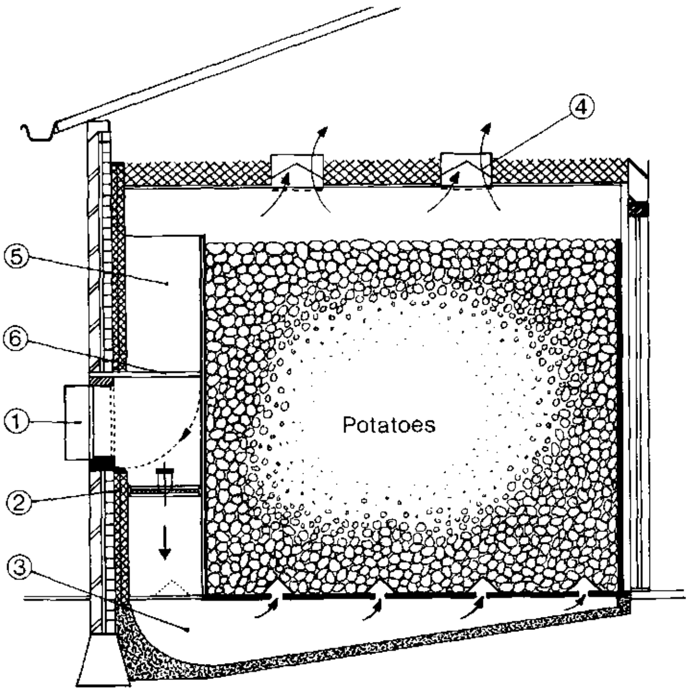

Fig. 78. Diagram of a potato store (IBVL, Wageningen). 1. Damper closing fresh air intake. 2. Ventilation. 3. Underground air duct. 4. Air outlet louvres in ceiling. 5. Trunk for internal air circulation when intake damper is closed. 6. Damper is in the horizontal position when ventilating with air from outside

ature is favourable. In forced ventilation stores of this kind, wall and roof insulation is required when:

- the minimum outside temperature during the storage season falls below freezing point
- the daily maximum temperatures are considerably higher than the minimum temperatures.

15.3.3.4 Refrigeration

If potatoes have to be stored for a long period and outside temperatures are such that in naturally ventilated stores or in forced ventilated stores with outside air cooling the low temperatures required cannot be achieved, refrigeration must be used. In refrigerated stores batches to be stored are sub-divided into smaller units or forced drought ventilation is applied. The type and system of air ducts needed is the same as that used with outside air cooling, but this is a closed system in which the air is re-circulated over cooling coils. Only from time to time is fresh outside air brought in to supply oxygen (5 m^3 fresh air per tonne per day). The cooling capacity needed is often calculated on the basis of the cooling required during the first few weeks of storage.

All the excess heat entering the building is removed by the refrigerated unit. These heat sources are:
- the heat content of the potatoes entering the store (field heat)
- respiration heat (heat produced by the potatoes in the respiration process)
- heat flow through walls, roof and floor
- heat production by fans
- heat supplied by air renewal
- heat supplied by leakage, machinery, people, etc.

Some data and formulas for estimating the cooling capacity and insulation required are:
- thermal conductivity: if tolerated heat flow through the storage structure is e.g. 10 W/m^2, the thermal conductivity or k-value (in W/m^2 per °C) of the walls is

$$\frac{10}{T_{outside} - T_{inside}}$$

- heat flow through walls, roof and floor (in Watt (W) or J/s): surface of roof, walls and floor (in m^2) $\times$ thermal conductivity (k-value) $\times$ $T_{outside} - T_{inside}$
- removal of field heat: to lower the temperature of 1000 kg of potatoes by 1 °C, 3600 kJ are needed. (Specific heat of potatoes is 3600 kJ/tonne per °C.)
- heat generation by potatoes: at various temperatures

2 °C	5 °C	10 °C	20 °C	25 °C	
11.5	7.8	18.1	33.8	38.0	W/tonne

- heat produced by fan: approx. 12 W for a fan with the capacity of 100 m^3 air per hour
- the heat supplied by leakage: machinery, people, etc. 5 % for a large store and 10 % for a small store is added to the total cooling capacity required.

These data and formulas are from Rastovski et al. (1987). (Further details can be found in this publication.)

A refrigerated store in the Netherlands will need a cooling capacity of 330–500 kJ per hour or 90–140 W to store 1000 kg of potatoes.

15.3.4 Moisture and humidity

During storage potatoes should be kept dry, but excessive loss of water should be avoided. The following points should considered regarding the design and management of large stores:
- Stores with a forced draught ventilation system should have a sufficiently high ventilation capacity. When outside air is used for cooling, 70–120 m^3 per 1000 kg per hour of ventilation is usually applied depending on how long cold air is available. The fan capacity in a refrigerated store is determined by the refrigeration capacity installed in the plant. The fan capacity equals 0.26 m^3 per hour per kJ of the refrigeration capacity installed in the plant.
- Potatoes should be dried if brought in wet (many hours of ventilation lead to excessive water loss).

– Once the potatoes are dry, ventilation for cooling purposes should be kept to a minimum.
– The temperature of the air used for cooling should be considerably (2–4 °C) lower than the temperature of the potatoes.
– The insulation of a cold store should be sufficient.

15.3.5 Light

Light is a good alternative to low temperatures when storing seed potatoes. By storing seed potatoes in diffuse light the 'storage life' can be prolonged (table 46). Once the method had been introduced, farmers often adapt the system to their own situation (fig. 79d).

Seed potatoes stored in diffuse light often give a more vigorous crop than seed stored in the dark at higher temperatures. The diffuse light storage method is applied when there is a relatively long period (e.g. more than 4) months between harvesting the seed and the next planting period. If this period is short (e.g. 2–3 months) it is better to store the seed first in bulk until the end of dormancy followed by sprouting the tubers in diffuse light.

As the leading capacity of a diffuse light store is limited, the system is more suitable for storing small quantities of seed. Attack by insects is often a problem. Major problems are tubermoth and aphids. Aphids can transmit viruses via the sprouts.

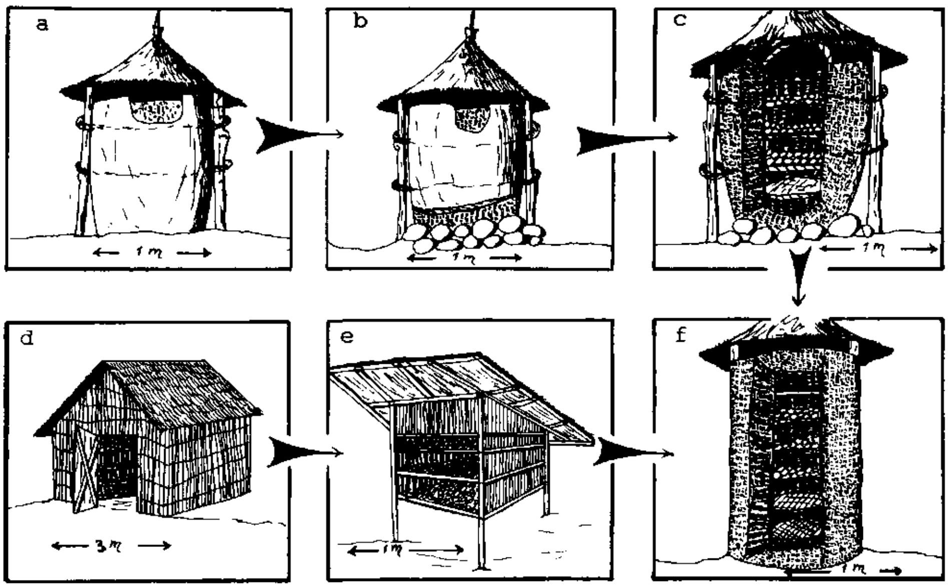

Fig. 79. Traditional and improved stores as tested in Rwanda (Haverkort & Rutayisir, 1984). a. Traditional without aeration. b. Improved with aeration for eating potatoes. d. Diffuse light store. c, e and f. Modifications for the farmers.

15.3.6 Chemicals

Chemicals can be used in potato storage to inhibit sprouting, to reduce attack by fungi and bacteria and to control insects.

Sprout inhibitors IPC-Cl IPC is widely used in the storage of potatoes for consumption. The chemical is either applied as a powder (tubers are dusted when loaded into the store) or as an aerosol (swing-fog). The aerosol application is provided through the 'fan-airduct' system. IPC-Cl IPC is not effective when storage temperatures exceed 15–18 °C. IPC-Cl IPC must not be applied to seed potatoes. Fusarex gives some sprout inhibition as well as some fungus control. It may be applied to seed potatoes but is not very effective.

Fungicides Various chemicals are used in seed production to reduce the spread of fungal diseases but only a few chemicals are known which reduce tuber rot losses in storage. Pre-storage treatment (spray application or dusting) with benzimidazoles or a combination of benzimidazoles with imazalil (e.g. thiabendazole 20–40 g a.i./tonne) reduces losses due to *Fusarium* and *Phoma*. 2-Amino-butane applied at a rate of 200 ppm (mg/l) reduces *Phoma* rot. There are no effective chemicals to control storage losses caused by bacteria.

Insecticides Several chemicals are able to control tubermoth in storage. Decis 0.2 %, Parathion, Sevin and Actylic. Aphids are controlled with Methamidophos, Demecron and others.

15.4 Storage methods and storage capacity

To store limited quantities of potatoes for a relatively short period of time, several low-cost storage methods are available. These simple methods can be used at farm level (fig. 79). If, however, larger quantities of potatoes have to be stored in one place and/or for a long period, high-investment stores are needed. These high-investment stores, depending on the local climatic conditions, may be either forced ventilation stores with outside air cooling or refrigerated stores. A storage operator has to decide how to pile or stack the potatoes. The vital questions are:
- How to load the store so that the maximum space is filled with potatoes and as little space as possible is not used for actual storage of potatoes?
- How to reduce the risk of losses to minimum?

If a store is equipped with a forced draught ventilation system, potatoes can stored in bulk or in densely stacked bags to a height of 3–4 m. 700 kg of bulked potatoes can be stored for each metre piling height per m^2 floor space. With densely packed bags this figure is 560 kg.

In stores with natural ventilation the potato stacking height is much lower, and larger quantities are sub-divided into smaller units. Bags are piled in rows two sacks wide and there is an open space of 30–40 cm between the rows. No more than 450 kg of potatoes can be stored this way per m^2 of floor space and per metre piling height. Seed potatoes to be stored in diffuse light are placed in chitting trays and no more than 250 kg of potatoes can be stored per m^2 of floor space and per metre piling height.

16 Seed potatoes: quality, use, supply and production

16.1 Quality

Tubers are generally used as seed for the production of potatoes (potato seed tuber), but under certain conditions botanical seed (true potato seed-TPS) may be used. Seed tuber quality (physiology, diseases) not only directly influences the crop grown from the seed, but also any diseases that are present on or in the seed may be transmitted to neighbouring crops or may be introduced into the soil. Some of these diseases (e.g. *Pseudomonas*, Wart disease, *Globodera*) once they have been introduced, may survive for a long time in the soil. The aim of a potato seed production programme is:

- to provide farmers with quality seed of the desired variety
- to avoid that harmful seed-borne or soil-borne diseases are spread and introduced into soils and areas that are 'clean'.

16.1.1 Multiplication rate and degeneration rate

The multiplication rate of potatoes is relatively low when the traditional multiplication methods are applied. In table 50 the seed rate and multiplication rate for various crops is given.

Compared with other crops the multiplication rate of potato tubers is relatively low (20–12). Taking into consideration that often only the smaller sized tubers are used as seed and that in many regions potato yields are still low, the multiplication rate (for seed) is often no more than 5-7 or even lower. The application of adequate growing technology such as proper soil tillage, use of organic manure and fertilizer, proper irrigation, sprouting seed (more sprouts), cutting seed, etc. will lead to a higher multiplication rate. Increasing the plant density will decrease the multiplication rate, but is often applied in seed production to stimulate the production of small tubers.

Table 50. Multiplication rate and seed rate per ha for various crops.

	Seed rate (kg)	Yield (kg)	Multiplication rate	Acreage ratio of seed crop to commercial crop
Wheat	120- 160	5000	40- 30	1: 30
Barley	80- 120	5000	60- 40	1: 40
Maize	25- 40	6000	240-150	1:100
Potato	1500-2500	30000	20- 12	1: 10

Table 51. Build-up of leaf roll in the progeny of seed imported in 1970 and first grown in spring 1970 and thereafter in the autumn cycle between 1970-1975 at Faisalabad (Saleem Mirza, 1978).

Variety	Percentage leaf roll in autumn crops					
	1970	1971	1972	1973	1974	1975
Désirée	0.1	0.2	8.3	18.7	21.0	57.5
Patrones	0.1	0.2	9.0	13.0	15.7	48.1
Multa	<0.1	<0.1	11.4	11.4	16.1	51.3
Wilja	<0.1	<0.1	8.3	9.3	13.3	54.4

Increasing the plant density to produce more 'seed size' tubers can only be applied when the price of the smaller tubers is sufficiently high in relation to the larger size tubers.

Because potatoes are multiplied by means of the tubers the seed stock gradually degenerates due to attack by viruses. During the growing season plants may be attacked by a virus and those plants generally produce virus infected tubers. When the virus infected plants (i.e. their tubers) are not removed from the fields an initially clean seed stock will be infected by viruses after a few generations (table 51).

The rate of degeneration varies from region to region and from cropping season to cropping season.

In figure 80 an example is given of a high and a low degeneration rate. In the high degeneration rate area a seed stock that was initially clean (0-1 % virus), after 1, 2 and 3 generations contains 10 %, 45 % and 100 % virus respectively. In the low degeneration rate area the percentage of virus after 1, 2, 3, 4, 5 and 6 generations is about 2 %, 7 %, 20 %, 55 %, 95 % and 100 % respectively.

Based on the multiplication rate and the degeneration rate, it can be calculated how much initially clean seed has to be introduced into a certain area to produce 1000 tonnes of seed for the production of eating potatoes.

Assuming that the multiplication rate is 7 and that the seed for ware growing should contain no more than about 15 % virus, in the high degeneration rate area the clean seed introduced can be multiplied once and in the low degeneration rate area can be

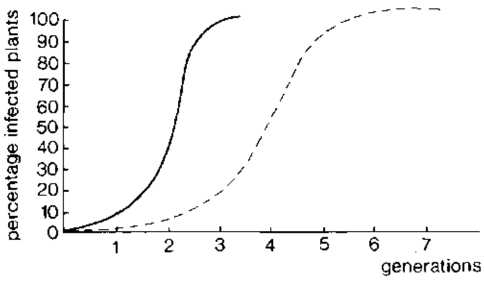

Fig. 80. Percentage of virus infected plants after multiplication under relatively high (—) and low (- - -) degeneration conditions.

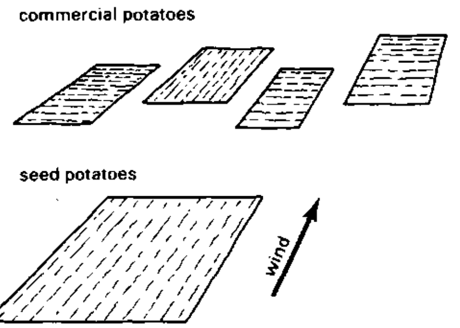

Fig. 81. Seed fields should be planted upwind from other fields or host crops to minimize aphid migration (Raman, 1980).

multiplied two or three times before the level of 15–20 % virus is reached. As a result, in the high degeneration rate area 1000/7 = 143 tonnes of clean seed has to be introduced annually when 1000 tonnes of seed is needed annually, while in the low degeneration rate area it will be necessary to introduce between 1000/7 × 7 = 20 tonnes and 1000/7 × 7 × 7 = 3 tonnes of good quality seed.

There are no simple measures for reducing the degeneration rate, when the aphid population is high and when there are plenty of infection sources (e.g. mixture of ware growing and seed multiplication) in the area. Possible ways of improving the degeneration rate are:
- separate fields for seed multiplication and ware production (fig. 81)
- spray seed multiplication fields to kill aphids (which is only effective when seed multiplication fields and ware production fields are separate)
- roguing virus diseased plants (effective when seed plots and ware plots are separate)
- destroying the haulm when the aphids appear in the latter part of the growing season.

Particularly in the low degeneration rate areas it is far more worthwhile to reduce the degeneration rate by applying these measures. Eventually these areas could develop into basic seed production areas.

16.1.2 Physiological age and storage of seed

The physiological stages of potato seed tubers influence sprout growth, germination and subsequent crop development (fig. 14 and section 3.4.1).

Potatoes are usually dormant immediately after harvest. During this dormant stage tubers do not sprout when placed in conditions that are favourable to sprout growth. When the dormant period is over, the tuber reaches it apical stage. Tubers in this apical stage produce only one sprout (or stem) but this apical sprout may branch if it is well developed. The next stage is the 'normal sprouting' followed by senility. When tubers start sprouting in the 'normal sprouting' stage, more than one sprout (or stem) will develop on the seed tuber. These sprouts may be branched when the seed becomes older. The seed then become too old, reach 'senility', and become too weak to produce a crop. The tuber is exhausted.

Table 52. Estimates of the duration of the 4 physiological stages of seed tubers stored at 4 °C en 12 °C in the dark.

Physiological phase	Duration of physiological phase (months after harvest)	
	storage temp. 4 °C	storage temp. 12 °C
I Dormant	2- 3	2-4
II Apical dominance	3- 6	3-4
III Normal sprouting	6-11	4-7
IV Senility	>11	>7

The duration of each of the phases (dormant period; apical dominance; 'normal sprouting'; and senility) depend on variety, growing conditions, stage of maturity at harvest and the storage conditions (table 52).

The higher the storage temperature the sooner the phase of senility is reached. When seed has to be stored for a relatively long period (e.g. where there is only one crop per year) the tubers (especially large quantities) are stored in cold stores at 2–4 °C. Where such cold stores are not available, storage in diffuse light stores is a good alternative.

Freshly harvested seed is usually dormant for a period of 2–3 months. During this dormant phase seed is not readily suitable for planting. Dormancy can be broken but this treatment is not easy when used on a large scale. Seed planted during the apical phase leads to a poor stem density crop. Higher stem densities can be achieved when the apical sprout is removed, allowing other sprouts on the tuber to develop.

The best stage for planting is phase III, the 'normal sprouting' phase (see also fig. 20). To ensure that the seed is at the required stage at planting it may be possible to adapt either the seed source and flow (i.e. the seed production season) or the storage method.

A diagram showing the planting and harvesting periods as well as the climatic data for the various regions in a country, is an important tool in determining possible seed sources, seed flows and storage methods (table 53).

In the example given, potatoes harvested at H_1 are still physiologically rather young when planted in the P_2 season, but at a good physiological stage when planted in P_3 and P_5. When seed harvested at H_1 has to be planted in P_1 again (next year, i.e. storage period 8 months) special storage facilities are required (cold stores or diffuse light stores). Seed harvested at H_4 is still at too young a physiological stage to be planted in P_3 (dormancy will have to be broken).

Storing seed for a relatively short period of time (e.g. 3–4 months) is fairly easy in the Nuwara Eliya district (in naturally ventilated stores), but difficult in the Jaffna district, where the outside temperatures are high. As the physiology of the seed is a major factor in seed quality, seed storage (duration and storage method) is an important aspect to be considered. In principle, seed should be at least 3 months old before it is planted again and no older than 5–11 months (depending on storage method and storage temperature).

Table 53. Potato production seasons and climatical data in Sri Lanka.

	J	F	M	A	M	J	J	A	S	O	N	D
Nuwara Eliya (1900 m)												
T_{max}	15.9	21.8	21.7	21.9	21.1	18.7	18.6	18.9	19.4	19.8	19.9	1.9
T_{min}	8.4	7.4	8.8	10.0	13.0	13.3	12.7	12.5	11.9	11.3	10.7	9.6
rain	178	51	104	127	216	264	279	196	208	249	233	189
			P_1				H_1					
									P_2			
		H_2										
Badulla (1259 m)												
T_{max}	22.2	23.9	25.4	25.6	26.0	25.3	25.5	26.6	25.3	24.7	23.6	22.2
T_{min}	14.5	13.8	14.5	15.9	16.7	17.4	17.5	16.5	16.1	15.9	15.5	14.9
rain	167	61	124	165	156	51	51	79	112	234	264	205
											P_3	
			H_3									
						P_4				H_4		
Jaffna (3 m)												
T_{max}	28.4	29.8	31.6	32.1	31.2	30.4	30.1	30.0	30.1	29.8	28.9	28.4
T_{min}	22.3	22.4	24.3	26.8	27.6	27.2	26.6	26.3	26.3	23.2	23.8	22.9
rain	112	38	40	56	51	10	15	38	63	234	439	264
												P_5
			H_5									

P = planting, H = harverst.

16.1.3 Fungal and bacterial diseases, nematodes

Some fungal and bacterial diseases which have a considerable effect on potato crops as well as some nematodes, can survive in the soil for a long time (wart disease, bacterial wilt, *Globodera*). Once they have been introduced they are difficult to control.

The transportation of seed produced in areas where these serious diseases occur to other regions, may be the cause of 'clean' areas becoming infected. The introduction of these serious diseases must be avoided. Seed transport from 'infected' areas into regions where the disease is already present may be tolerated when the seed introduced is 'cleaner' than the seed found in that region.

With regard to the more common potato diseases, a certain level of contamination can be tolerated. This is especially the case with diseases that are already widely spread and do not cause serious damage to the crop (section 13.2.2).

16.2 Seed use and supply

Farmers can obtain their seed in various ways:

- continue to use their own seed stocks from previous crops
- buy good clean seed stock and use it for several generations
- buy good clean seed stock and use it for a limited number of generations
- buy seed for each potato crop.

Table 54 lists several factors which will affect the decision to use 'own seed' and/or seed from 'other sources'.

There are various methods that can be applied at the individual the farmer's level to improve farmer's 'existing seed stocks' and/or maintain 'newly introduced good seed stocks' at a good quality level for several generations. Farmers who do not use their own seed can obtain it from various sources (table 55).

16.2.1 Methods of improving and/or maintaining seed stocks at farm level

In areas with a low degeneration rate and fairly low temperatures improvements in seed quality can often be made by introducing better storage methods and introducing seed selection methods. The introduction of storage methods for seed encourages seed selection, since farmers who have invested in building better seed stores, will tend to use these stores to store good quality seed from selected plants and plots. In areas with a high degeneration rate and rather high temperatures solutions are less easy to find: selection is less effective, as new virus infections will occur during the growing season and improvements in storage methods are more difficult to implement (often cold stores are needed).

Table 54. Farm seed versus seed from other sources.

Farmers' own seed	Seed from other sources
Degeneration rate in the area is low	Degeneration rate in the area is high
Tubers harvested from previous crops to be used as seed are at the right physiological stage at the next required planting season	Tubers harvested from previous crops to be used as seed are not at the right physiological stage at the next required planting season
Storage methods and storage facilities for seed are available to the farmer	Storage methods and storage facilities for seed are not available to the farmer
Own seed quality is good	Own seed quality is poor
Reliable seed is not easily available on the market	Reliable seed is easily available on the market
The infrastucture (topography, farm size, plot size, road system, distance to the seed market) is poor	The infrastucture is good
The potato crop is a marginal crop: potato prices are low	The potato is a profitable cash crop
The prices of seed potatoes/prices of ware potatoes ratio is high	The prices of seed potatoes/prices of ware potatoes ratio is low
Funds for 'inputs' are not easily available	Funds for 'inputs' are readily available

Table 55. Seed sources.

The 'open' market
Regions and/or farmers known as good seed sources
Specialised seed growers
National or regional seed programme
Imports from seed producing countries

16.2.1.1 Adjustment of planting seasons

In areas where the time between harvest and the next planting season is too short (e.g. where seed produced during the spring crop has to be planted early in the autumn) it may be possible to plant the spring crop earlier to ensure that the seed for the autumn crop is at a better physiological stage. When there is only one crop a year in an area (e.g. because of the rainy season) and adequate facilities are lacking, it may be possible to produce seed potatoes in the dry season using irrigation so that the storage period of the seed can be kept to 3 or 4 months.

Another reason for considering adjusting the planting season is to avoid high aphid populations. Often after a period of high temperatures the aphid population is low and gradually increases as the temperature becomes lower (fig. 89). Examples are known where, with earlier planting (when temperatures were still rather high) virus infection was considerably reduced.

16.2.1.2 Selection

Selection is common practice for the maintenance or the improvement of seed stocks. Two methods of selection are used: negative selection and positive selection.

Negative selection Negative selection is where diseased plants are removed during the growing season by roguing (section 13.2.1.4). Diseased and deviant plants are removed by roguing to improve seed stock and to prevent the further spread of diseases. If roguing is applied properly, degeneration of the seed stock can be reduced and the stock can be kept at a reasonable level of quality for more generations. The effect of roguing is better in areas with a low degeneration rate than in high degeneration rate areas. If the percentages of diseased plants are high roguing is difficult to apply and its effect is limited.

Positive selection Positive selection is where plants that are true to type, vigorous and healthy looking are marked and kept as seed for further multiplication. There are various methods such as seed plot technique (figures 82 and 83) and clonal selection (fig. 84). In the seed plot technique the tubers of the marked plants are bulked and used for the next seasons seed production field.

In some areas it is necessary not only to mark the healthy looking plants, but also the plants infected with *Pseudomonas solanacearum*. This makes it possible to keep only tubers from the healthy looking plants which are not next to plants exhibiting symptoms caused by *Pseudomonas* which spreads easily in the field.

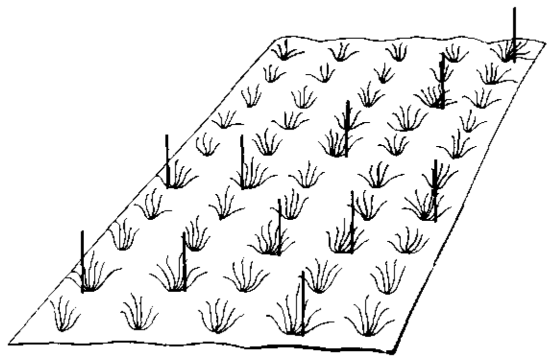

Fig. 82. Mark the best and most vigorous plants in the field with stakes (Bryan, 1981).

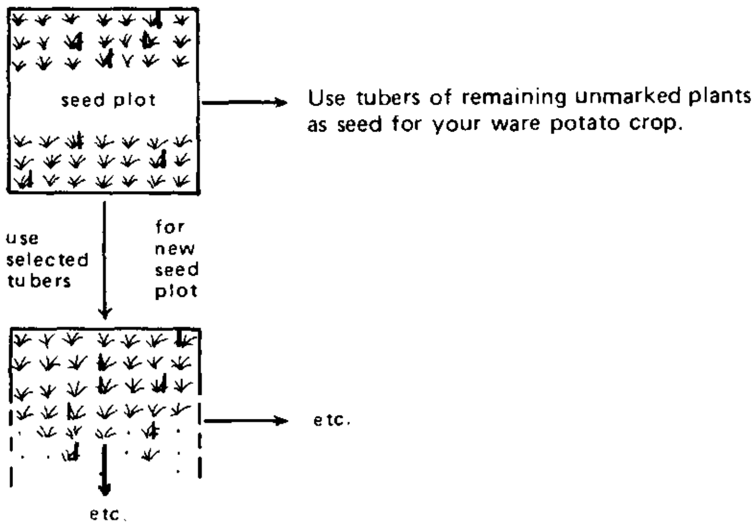

Fig. 83. Seed plot technique repeated each season (Bryan, 1981).

In a clonal selection programme the tubers of selected healthy looking plants are kept together and next season planted as progeny units. These progeny or clonal units are kept as separate units for 2 or more generations and then bulked (section 16.4.1).

16.2.1.3 Disinfection of seed

The most common chemicals used for tuber disinfection at farm level are benzimidazoles and carbamates. These chemicals are applied as dusts and reduce the spread of fungal diseases during storage. The use of chemicals, however, never can replace 'clean production methods' (section 13.2.3).

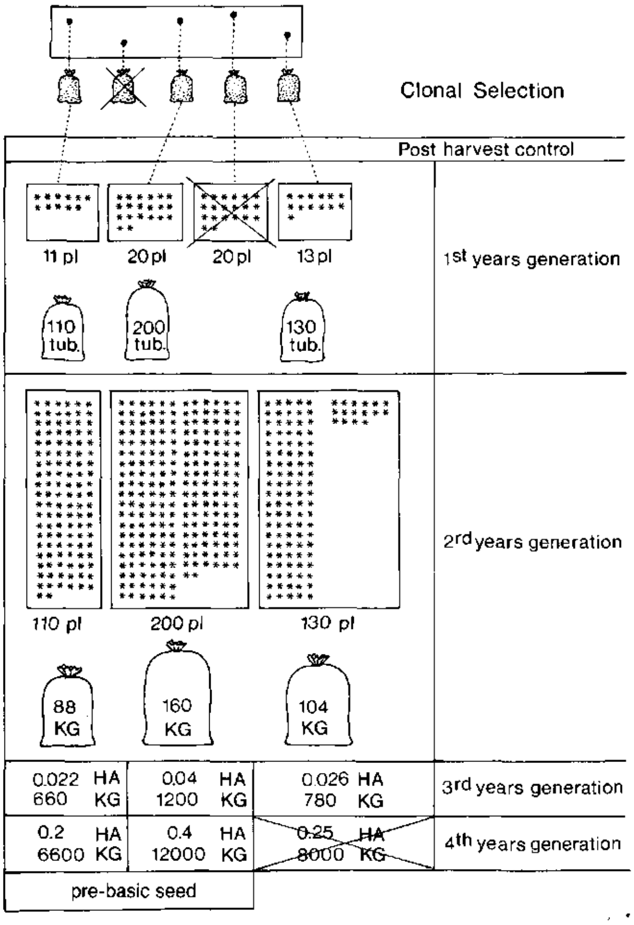

Fig. 84. An example of a clonal selection programme.

16.2.2 Seed sources

The reasons why farmers do not use their 'own seed' are summarized in table 54 and possible sources of seed are given in table 55.

The quality of seed purchased on the 'open' market is often unknown. The buyer can only judge its external quality (size, *Rhizoctonia, Fusarium*, common scab, etc.). In some countries there are 'traditional' seed producing areas. It is known that 'better' seed is available from these areas than from other areas. Often these 'traditional' seed areas are situated in low degeneration areas and the seed is grown at a given time of the year so that by the time of delivery the seed has reached the right physiological stage to be planted in the region where it is in demand. The buyer knows that the seed is from a region where 'better' quality seed is produced, he can judge the external quality, but has no guarantee of the internal qualities. If the buyer knows the producer and has visited the crop during the growing season, there are more guarantees.

It may be that in some regions farmers specialise in seed production and that there is direct contact between the producer and the buyer of the seed. In which case the seed producer wants to consolidate the relationship with his clients and consequently there will be more guarantee of the quality.

Seed programmes have been developed or are developing in several countries. These seed programmes are either complete seed programmes (including the production of basic seed) or are based on the multiplication of imported high quality seed stocks. For economic and technical reasons potato production in many countries is based on imported seed. In some cases imported seed is used immediately to produce table stocks, but in many cases it is multiplied one or more times.

16.3 Seed programmes

After healthy potato plants have been obtained by selection, meristem culture or heat treatment, the seed tubers must be multiplied without acquiring substantial levels of virus infection. This is achieved through seed programmes and potato seed certification schemes, which also will ensure cultivar purity, trueness to type and control of bacterial and fungal diseases which are spread on or in tubers.

A region where the population of *Myzus percicae* is relatively small during the potato growing seasons and where sources of infection are few, is desirable for the production of seed potatoes.

Effective schemes operate a 'flush through' system starting each year anew with fresh, carefully chosen, healthy plants. Progenies of these are multiplied separately as individual clones for 2–4 years before combining all the clones of the same cultivar. During this period the clones are rigorously checked for virus infection by visual inspection and by serology, indicator plants and post control tests (e.g. post control plots, 'Florida' test, etc.). In several basic seed programmes stem cutting techniques and other rapid multiplication techniques (e.g. vegetative multiplication in test tubes, etc.) have been included to help to eliminate bacterial, fungal and nematode infections associated with tubers.

Seed stocks that come through the clonal selection procedure without any detectable virus infection next pass into a series of seed classifications or grades for which strict tolerances are set. A stock remains within a particular grade only if the levels of infection stay within these tolerances; after a certain number of multiplications down grading is compulsory in most schemes to ensure 'flush through'.

16.3.1 'Complete' seed programmes versus 'incomplete' programmes

As the multiplication rate of potatoes is rather low (table 50) several multiplications are needed, whereby a certain amount of basic or pre-basic quality seed is multiplied into large quantities of seed (certified seed) which will be used for the production of ware potatoes. In the process of these multiplications clean seed stocks may become re-infected with viruses. This often happens in areas of high degeneration (table 51, fig. 80). Table 56 shows the amount of seed that can be obtained from an initially clean seed stock.

Depending on the multiplication rate, 2–3 generations are needed to produce

Table 56. Seed production in kg at different multiplication rates.

Generation	Multiplication rate		
	5	8	12
0-initial clean stock	150	150	150
1	750	1 200	1 800
2	3 750	9 600	21 600
3	18 750	76 800	259 200
4	93 750	614 400	3 110 400
n	150×5^n	150×8^n	150×12^n

3000–4000 tonnes of potatoes from 150 kg of clean seed pre-basic or basic. In areas where the degeneration rate is low, it is possible to multiply clean seed for 2 to 3 generations, maintaining the quality at an acceptable level, but in areas with a high degeneration rate this will be rather difficult. Here the quality will be lost after just a few generations, hence the amount of basic seed required to produce the same quantity of seed for ware potato production will be much larger than for low degeneration rate areas (section 16.1.1). Countries that have low degeneration rate areas can have their own complete seed programme, including the production of pre-basic seed. The pre-basic and basic seed is then produced in the area where the degeneration rate is lowest. Countries with higher degeneration rates often have an 'incomplete' seed programme and import good quality seed for further multiplication.

In this situation the production of a limited amount of pre-basic seed will have little impact since this seed can only be kept to be multiplied for a few generations. A high degeneration rate is not the only limiting factor to a complete, independent seed programme, there is also the fact that part of the seed programme 'disappears' during the multiplication programme to other destinations (e.g. to the consumption market). A complete seed programme requires manageable resources. The most difficult part of a seed programme to organize is the last stages of multiplication in which quantities of seed have to be multiplied. If this part of the programme is not organized first, the production of relatively small amounts of pre-basic seed has little impact.

16.3.2 Organization of a seed programme and its objectives

The production of high quality pre-basic seed requires a high level of technical expertise and is usually done by government bodies (e.g. Ministry of Agriculture) at specialised seed farms, by universities, research institutes or by selected growers. Propagation after the pre-basic or basic stage is done by individual private growers or growers organizations (e.g. cooperatives) in most countries (fig. 85a). Roguing, spraying, etc. is done by the farmers, but, to protect against fraud, inspection and certification are often the responsibility of a governmental or another impartial agency. The inspectors of such inspection agencies examine the growing crop, take samples to test and give guidance to seed growers.

In countries where seed plots are small, scattered and not easily accessible it is

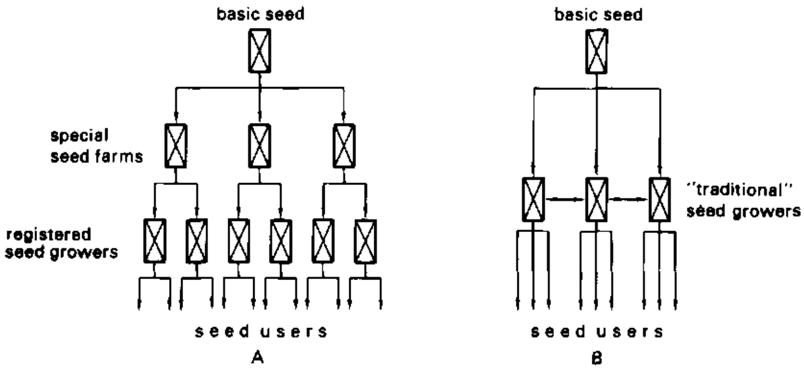

Fig. 85. Organization of seed programmes.

difficult to organize the farmers and to supervise seed production in all its phases. In this situation, it may be a good idea to make use of the 'traditional seed growers' in the country. When these 'traditional seed growers' in low degeneration rate areas are supplied with relatively small quantities of good quality seed, this seed will be multiplied and distributed through the existing channels (fig. 85b).

Often in high degeneration rate areas relatively large quantities of good quality seed or locally produced good quality seed are introduced each year. Individual farmers then buy a small amount of good quality seed each year to be multiplied for 1-2 generations. When this multiplication takes places on fields scattered amongst ware crops (with a fairly high level of virus infection) the quality of the seed stocks introduced will degenerate quickly. When this good quality seed is first multiplied in isolated areas (areas where there are no infection sources) the degeneration rate is lower and better use is made of the available stocks of good quality seed. In certain high degeneration rate regions, seed programmes for multiplying good quality seed in isolated areas have been successful (table 57).

Table 57. Percentages of samples with 0-2%, 2-5%, 5-10% and > 10% PLRV infection of all varieties of the lots accepted in all zones in Bangladesh.

Seed sources	Percentage of PLRV				Number of samples
	0-2%	2-5%	5-10%	> 10%	
First generation 1981-1982	54	30	11	5	166
First generation 1982-1983	72	24	4	0	219
First generation 1983-1984	76	17	6	1	254
Second generation 1982-1983	55	29	14	2	56
Second generation 1983-1984	81	12	6	1	73

The data in table 57 refer to the situation in Bangladesh, where after one multiplication under uncontrolled conditions, clean seed has an average of 8–12 % virus (compare with fig. 80). Table 57 shows that with the BADC multiplication programme (i.e. isolated plots, roguing, control of aphids, early planting) the spread of virus can be restricted to a large extent. In this programme which ran from the 1983–1984 season (total production 4000 tonnes), 76 % and 81 % of the seed stocks multiplied once and twice respectively, had less than 2 % virus.

In countries which have two crops a year – a spring crop and an autumn crop – imported seed is normally used for the spring crop, while tubers harvested from the spring crop are used as seed for the autumn crop (fig. 86).

The seed harvested during H_1 is often physiologically too young to be planted early in the P_2 season. Seed harvested at H_2 will not be at a proper physiological stage to be planted in P_1. A seed programme with the aim of producing better seed for the P_2 season should give high priority to the following aspects:

– Seed in better physiological condition can be achieved by planting earlier during the spring (P_1–H_1) and by better storage of the seed.

– Virus infection can be reduced by planting the seed in isolated areas, roguing and applying aphid control.

Figure 87 shows a different situation.

Provided the infrastructure at the high elevation is adequate, seed to be planted at the low elevation during the P_1–H_1 season could be produced at the high elevation during the P_3–H_3 summer season. Seed for the P_2–H_2 season could be taken from the H_1 harvest.

Seed programmes may be either centralized or de-centralized. The objectives of

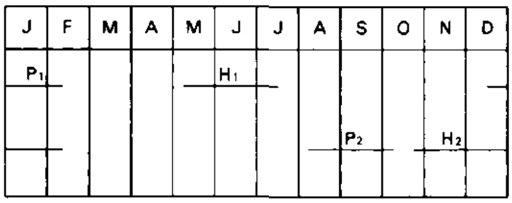

Fig. 86. Spring season (P_1–H_1) and autumn season (P_2–H_2).

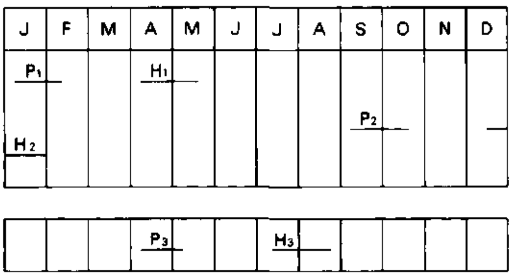

Fig. 87. Spring season (P_1–H_1), autumn season (P_2–H_2) and summer crop (P_3–H_3) at high elevation.

seed programmes differ from country to country and from region to region. The objectives and priorities of a seed programme have to be clearly defined. In doing this it should be borne in mind that the producer plays an important role in any such programme, and that in the end, it is the potential user of the seed who will determine the success or failure of the seed programme.

16.3.3 The seed market and seed quantity and quality

The quantity and quality of seed to be produced by a seed programme will depend on the seed market. Seed markets can only be developed if the seed produced and offered is:
- from the variety that is in demand
- of the desired quality (e.g. health standard, physiological stage, tuber size, etc.)
- regularly available at the required planting periods in sufficient quantities
- competitive in price.

Farmers' preferences for 'own seed' as compared with 'seed from other sources' are summarized in table 54.

Seed for supply to the seed market should have only a low percentage (e.g. 0–2 %) of virus infected tubers, if the seed is to be used for further multiplication. When it is to be used for the immediate production of ware potatoes, a higher percentage of virus infection may be tolerated (e.g. 10 %).

In high degeneration rate areas the demand may well be constant, while in low degeneration rate areas the market is likely to fluctuate. In these low degeneration rate areas farmers can maintain seed stocks and at the same time there will be a lateral spread of the seed that has been introduced into the area.

16.3.4 Management, production and storage

Serious management problems are often encountered in large scale seed programmes.

The final stage of complicated and sophisticated seed programmes, including the production of basic seed, is similar to a simpler multiplication scheme. In both cases relatively large quantities of seed have to be produced by multiplying locally or imported seed under strict control to produce certified seed, to be able to make optimum use of expensive seed stocks and to guarantee quality.

A seed programme has to be economically viable and therefore the organization of production, handling, storage and marketing are all vitally important, requiring the following to be taken into consideration:
- skill and experience of the farmer
- size and distribution of farms and fields
- growing conditions
- organization of the seed growers
- storage facilities
- transport facilities and distances
- marketing aspects.

Seed is considered to be high value produce. Many losses can be avoided by proper management and storage and suitable facilities are essential to a successful seed programme. Storing large quantities is much more difficult than storing smaller amounts of seed. In a well designed store, potatoes can be kept at or brought to the required physiological stage.

16.3.5 Seed quality and rational use

Official centralized seed programmes that are initially successful may grow to large dimensions as the demand increases and ever higher targets are set. This may involve the following risks:
- Increasing production has a negative effect on quality.
- Production on too large a scale causes management problems with the result that yields decrease and seed plots are lost.
- An excess of seed, which cannot be sold for the purpose for which it was intended.
- A negative effect on the development of the farmer's own seed production and traditional seed systems.

A better alternative is when a programme restricts itself to the production of a limited quantity of high good quality seed which is then distributed to farmers who use the seed stocks for more than one generation ware patato production, and to farmers who further multiply the high quality project seed. This way the limited seed stocks available are used in a more rational way.

In seed programmes, not only the quality and quantity of the seed should be considered, but also its rational use. It is essential to the development of a seed programme that it supplies its seed to the most strategic places in the country, where it can be used for further multiplication and further distribution. Suitable pricing of the seed may also be an important aspect in rational seed use.

An official seed programme will, in most cases, not be able to produce the total seed requirements of the country and therefore it will have to provide existing seed systems with good quality seed for renewal of the existing systems and with extension services for maintenance of seed stocks.

16.4 Basic seed production

There are various methods for pre-basic and basic seed production: clonal selection rapid multiplication of pathogen tested plant material, in-vitro (i.e. test tube) multiplication of pathogen tested plant material and from botanical seed (true potato seed: TPS).

16.4.1 Clonal selection

The principles of a clonal selection programme are described in section 16.2.1.2 (fig. 84). The procedure followed in a more sophisticated clonal selection programme are:
- Healthy looking, high yielding and true to type plants are selected from fields with a good standard of health. The tubers of each plant selected are harvested and kept apart from the rest to be planted in the next growing season as plant units.
- In a post-harvest control one or two tubers of each plant progeny are checked for the presence of any virus (by breaking dormancy, raising plants from them and judging these by symptoms, serology and indicator plants). If a virus is found in one

of the tubers all the tubers belonging to the plant progeny in which the infected tuber was found are rejected.

- The tubers from the selected plants are planted in the field for multiplication in such a way that plant progenies (clones) are kept apart (fig. 84). During the growing season, the plants are inspected for diseases (symptoms, serology, test plants). If one diseased plant is found in a plant progeny (clone), all the plants of that clone are rejected and removed from the field. At harvest the tubers of each healthy clone are kept separate from the rest.
- Clones are multiplied separately for 2–4 generations.

In the more sophisticated clonal selection methods, both visual inspections and laboratory tests are used. This is mainly done to determine those diseases which show weak symptoms, such as PVX and PVS. These two viruses are contact transmitted and clones that are found to be free of PVX and PVS cannot be contaminated by means of aphid transmission (PVS in very special cases); hence the clones can be kept free from these diseases for some generations. The disease tolerance levels, especially in the early stages are zero. Clonal selection programmes should preferably be carried out in areas where aphid populations are low and conditions for production are good. In areas with high aphid populations, clonal selection programmes often give disappointing results as re-infection occurs too quickly.

16.4.2 Rapid multiplication

Rapid multiplication by means of sprout cuttings, single-node cuttings, stem cuttings, leaf-bud cuttings is used to multiply clean plant material of a certain variety of which a limited amount of clean material is available. Another reason for using

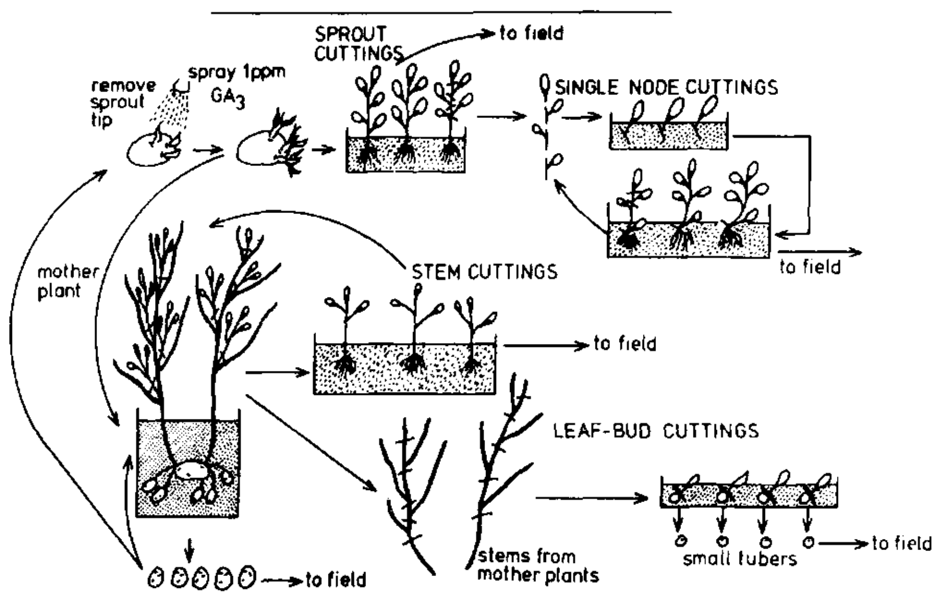

Fig. 88. Rapid multiplication methods (Bryan et al., 1981).

rapid multiplication methods is that the stems further multiplied, are separated from the tubers which may carry latent bacterial and fungal infections (e.g. black leg, *Phoma*). With rapid multiplication fewer plants have to be tested for viruses and the number of multiplications in the field can be reduced compared with a clonal selection programme.

The first steps in any rapid multiplication method are carried out in aphid-proof screen or glass houses. The mother plants are also kept in these screen houses. The programme requires thorough testing and strict sanitation to ensure that the plant material used for multiplication is, and remains, pathogen free. The rooted stem cuttings, single-node cuttings or sprout cuttings are either grown in the open or in screen houses. When grown in screen houses, there is less risk of re-infection, but the number of cuttings that can be grown is restricted by the size of the screen house.

Being labour intensive and expensive this method has its impact when the material produced can be multiplied and be kept free from diseases for some generations.

16.4.3 Multiplication in test tubes (in-vitro multiplication)

With this method sterilized buds from healthy plants are put into test tubes on a solid medium of Murashinge and Skoog and placed at 20 °C in light. After one month the plantlets that have developed are cut into separate pieces each with a single bud (3–10 buds): each bud is transplanted into a test tube with fresh medium. This procedure is repeated successively. It is a laboratory method and can be used when outside conditions are unfavourable for potatoes. As the outside conditions become more favourable, the plantlets are transplanted to soil (in pots) and later placed in the open air or in screen houses. Screen houses are used to prevent re-infections occurring.

The multiplication rate is high with this method. One bud can, in theory, produce 3^6 (= 729) to 10^6 (= 1 000 000) plantlets within 6 months. Each plantlet could produce 2–5 tubers.

In-vitro multiplication for the production of basic seed has replaced the early steps of clonal selection where there are major problems with bacterial and fungal diseases and/or where it is essential to produce sufficient basic seed stocks within a short period of time.

Recently, much attention has been paid to the use of in-vitro plantlets for the production of micro-tubers (in-vitro tubers) or mini-tubers, which are produced by in-vitro plantlets in soil in a greenhouse or a screen house. These tubers (micro-tubers are usually between 2–10 mm and mini-tubers are between 10–20 mm) are then planted in the open field to produce pre-basic seed. Crops from very small seed tubers reach plant maturity resistance to viruses later than 'normal' seed tubers, which increases the risk of infection.

16.4.4 True potato seed (TPS)

In some countries TPS is used as a seed source while in other countries it is being used on a experimental scale. This seed is almost entirely disease free (most viruses are not transmitted by botanical seed). There are various approaches:

- direct seeding

- seedlings raised in seedbeds and then transplanted
- seedlings grown in nurseries at high densities to produce seed tubers (seedling tubers).

The last two methods appear to have the best prospects. Plantlets grown from TPS in a nursery can be transplanted 25–40 days after sowing, when the plantlets have 4–5 leaves and are 8–12 cm high. The planting distance of the plantlets is 25–30 cm between hills and 2–3 plantlets per hill (10–15 plants per m^2). High yields have been obtained, but crops from botanical seed require a longer growing period. Comparing a crop planted as transplants from TPS with one planted as tubers on the same date, after the same amount of time the crop from the development of the transplanted TPS will be 2–3 weeks later than the crop grown from tubers. When damaged by adverse weather conditions during the early stages of growth, a crop grown from tubers will recover better than a crop grown from TPS.

The method whereby seedlings are grown in nurseries at high densities (e.g. 100 seedlings per m^2) to produce seed tubers for crop production potentially offers prospects. On 1 m^2 4–5 kg of relatively small tubers (500–600) can be produced. As TPS can easily be distributed, a combination method of TPS and seedling tubers may be suitable for the development of decentralized seed tuber production.

TPS can either be from 'open pollinated' flowers of established varieties or be hybrids from parents selected for this purpose. Since in TPS production sexual reproduction takes place, all the plants grown from TPS are of different genotypes (e.g. early or late maturing). Under short day conditions the difference between these types will be less apparent than under long day conditions.

Making use of TPS to produce seedling tubers, followed by a selection of the superior types offers a good opportunity to introduce new genotypes into remote areas where the degeneration rate is low and tuber seed storage is feasible. The use of hybrid seed (local varieties × introduced germplasma) may be preferable in this situation (see also Umaerus, 1987).

16.5 Seed potato production and virus diseases

In many countries virus diseases and degeneration due to viruses is a major problem. Potatoes can be infected with virus mechanically (due to contact, tools, etc.) by insects (mainly aphids), nematodes and fungi. When the foliage is infected the virus can be transported to the tubers. Once the tubers are infected and used as seed they give rise to virus infected plants which usually produce virus infected tubers. The main methods used to control virus diseases are basically those intended to prevent infection and may be summarized as follows:

- reducing the number of infection sources
- growing potatoes in areas where the vector population is low or growing them during periods when the vector population is low
- controlling the vector
- promoting plant maturity resistance
- using virus resistant varieties
- using mineral oils.

16.5.1 Infection sources and isolated areas

Two different sources of infection should be considered: those within the field and those from outside the field.

The infected plants in a potato field are the main sources of mechanically transmitted viruses, however, it is also known that some viruses remain active on implements or animals for a long time and this may bring infection into potato fields from infected plants outside. Non-persistently transmitted viruses can be spread from sources outside as well as from inside the field. Persistently transmitted viruses can be transmitted over much longer distances than non-persistent ones (section 13.3).

To restrict the spread of viruses, the number of infected plants should be kept low and if found, they should be removed from the field as soon as possible (roguing). Neighbouring fields should also be cleaned of virus infected plants and if possible, high quality seed should be used throughout the whole area.

Especially when seed potatoes are produced in areas where the aphid population is rather high, improvements can be made by growing potatoes in isolated blocks (fig. 81). It should only be allowed to grow seed potatoes in these blocks, while the production of potatoes from low quality seed with a high percentage of virus should be prohibited. As a consequence of establishing such blocks, farmers who want to grow potatoes either have to participate in the seed programme or have to use high quality seed for the production of ware potatoes. In areas where the aphid population is low there is less need for isolation.

16.5.2 Low vector population

As aphids are the main vectors of viruses which affect the growth of seed potatoes, production areas should be selected where the aphid population is low or where it will not reach a hazardous level by the time the crops produce an acceptable yield.

The population of *Myzus persicae* in the Netherlands often stays low until about the middle of July when the population builds up.

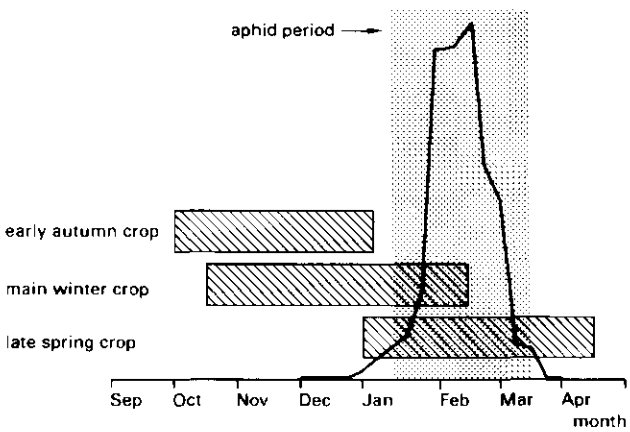

Fig. 89. Crop season in relation to aphid incidence (Pushkarnath, 1976).

By the time the aphid population has grown too high and at the time the aphids start to move (winged aphids) the haulm of the potato has been destroyed to restrict infection and prevent the transport of any virus to the tuber. Areas with low vector populations generally have cold winters, cool springs and cool, windy and rainy weather in the growing season.

Mountainous areas with high elevations are also known as areas with low aphid populations. Often such areas are traditional seed producing regions. Low aphid populations may also be expected during and after periods of high temperature (fig. 89).

This is the case on the plains in India for example, where seed production became successful when it was shifted from January–February to October–December. At the beginning of the latter the temperatures are still rather high for potato production, but the aphid population is still low and clean seed can be produced.

16.5.2.1 Aphid population

For the planning as well as the execution of a seed programme it is important to know the areas and periods of the year when the aphid population is low. This makes it possible to select areas suitable for seed production, to adjust planting periods and to determine harvesting time (i.e. haulm destruction dates). Suitable methods are trapping, plant counts and leaf counts.

- Yellow traps: trays painted yellow inside and filled with water and a detergent are placed near or inside a potato field. The traps are raised to a height above the crops. The trays are examined at regular intervals (e.g. twice a week). The data obtained not only gives an indication of the number of aphids present, but also their level of activity.
- Plant counts and leaf counts do not give a reliable indication of the number of winged aphids present. Plant count is done with randomly selected plants which are beaten over a board and the number of aphids from the plant are counted or estimated. With leaf counts, four fully expanded leaves (two from the lower half and two from the upper half of a plant) from 25 randomly selected plants are cut off and the number of aphids on the under surface of each leaf are counted. The counts give an indication of the start of the build-up of the aphid population. It appears to be difficult to find any correlation between aphid incidence and possible virus infections.

Important data which should be considered are:

(1) number of aphids and efficiency of the aphids in transmitting viruses
(2) number of infection sources
(3) stage in crop development (plant maturity resistance)
(4) when the aphids are present
(5) level of resistance of the cultivars grown.

It is generally assumed that critical levels of aphids are reached when more than 5 winged aphids that can transmit virus easily, are caught per trap within a week (or 2 aphids per day on two successive days) or when more than 20 aphids are counted per 100 leaves. These assumptions may be used as a guideline but cannot be taken as a rule.

16.5.2.2 Degeneration tests

Degeneration tests give a more direct indication of virus infections which can occur in different locations and at different planting periods. Although these tests measure virus infection under the given conditions directly, the results need to be interpreted with care and the level of infection in the surrounding fields has to be taken into consideration. Possible experiments for determining virus infection pressure are:
- (A) relating various planting and harvesting dates to virus infection
- (B) planting 100–200 tubers from a batch of seed of a known health standard in various potential seed growing areas to determine degeneration rate
- (C) planting clean seed in a plot with a central row of virus infected plants (infection source).

To evaluate the level of virus infection in these trials a tuber is taken from each plant at harvest time to determine whether the plant is infected or not. This is usually done by replanting this tuber in the next planting season. For experiment B two tubers from each plant may be harvested: one for virus evaluation with the ELISA and one to be replanted in the same area to examine the rate of degeneration. For experiment C it is important that tubers for virus evaluation from each row are kept separate from each other to be able to determine how the virus spreads in the plot (infection from outside or from inside the plot).

These types of experiments are labour intensive and reliable results are only available after several years. Potential seed areas are usually already known and seed programmes developed in those areas. A system in which samples are taken from seed plots at harvest to be planted in a central field (check-plots or verification plots) to determine quality, is a procedure which provides good insight into the standard of health of the seed produced. When proper records are made of the fields from which the samples are taken (e.g. location, isolation, seed source and quality of the seed planted) the results obtained can give valuable data for making improvements in the seed production procedure and accurately identifying suitable seed areas.

16.5.3 Vector control

Aphid control reduces the spread of viruses, especially persistently transmitted viruses within the field. However, infection from sources outside the field is only slightly controlled. The effect it has reducing the spread of non-persistently transmitted viruses from infection sources both inside and outside the field is limited. Better results will be obtained when all potato fields grown in isolated areas are treated with insecticides. The treatments are:
- granulates applied at planting (e.g. Temik or Disyston) which control the aphids for 8–10 weeks
- spraying with systemic insecticides (e.g. Metasystox) at 50 % emergence and twice subsequently at intervals of 2 weeks.

Before starting roguing it is always advisable to kill any aphids present on the plants (e.g. with parathion) to avoid the spread of virus.

16.5.4 Mineral oils

Mineral oils sprayed (15 l/ha) at weekly intervals have resulted in a decrease in the spread of non-persistently transmitted viruses (e.g. PVY). Examples are known where treatment has reduced virus spread by 2/3 (e.g. 3 % of PVY instead of 10 %). Treatments with mineral oils may reduce yield by 5–15 %. Mineral oils cannot be combined with compounds containing tin used in late blight control. Combination with other chemicals to control late blight is possible, however.

16.5.5 Maturity resistance

Potatoes are most susceptible to viruses when they are young. Susceptibility decreases later. Cultural practices should be such that maturity resistance is reached when the vector (i.e. aphid) population reaches a detrimental level. Possible methods of achieving early maturity resistance are:
- pre-sprouting
- early planting
- moderate nitrogen application.

16.5.6 Resistant varieties

There are various forms of resistance:
- Immunity resistance to PVX, PVY and PVA based on dominant genes has been found and introduced into commercial varieties. This immunity resistance gives complete protection against most of the strains of each group of viruses.
- Hypersensitive resistance is often based on dominant genes which are extremely sensitive to a certain strain of virus (e.g. certain strains of PVX) and result in necrosis after artificial inoculation. Under field conditions the cultivar is protected.
- Field or partial resistance gives a certain level of protection. Cultivars with a high level of field resistance are under field conditions are less easily infected than those with a low level of field resistance. Field resistance (e.g. to PLRV) is based on a polygenic system.
- Tolerance is the capacity of a plant to sustain a disease. Cultivars with a high level of tolerance are less sensitive to a virus infection than varieties with a low tolerance level and consequently, the yield reduction caused by the virus is limited. Cultivars with a high tolerance level may become symptomless carriers of a virus.

16.6 Seed quality and inspection

Disease aspects of seed quality are influenced by the incidence of soil-borne diseases in the field, the quality of the seed planted, diseases present in the neighbouring fields (isolation), the prevailing weather conditions which influence the spread of diseases (e.g. aphid populations), diseases present in the seed plot and measures taken to prevent their spread (i.e. planting time, harvest date, roguing, application of chemicals), harvesting procedures, storage methods and sorting and grading procedures. Inspections are carried out at several stages (table 58).

Where more than one organization (cooperatives, private firms, research organi-

Table 58. Inspection procedures

Before planting
Inspection of the fields where seed is to be planted
- size of the field, location accessibility
- agronomical value: e.g. irrigation facilities

Laboratory tests of soil samples
Inspection of the quality of the seed to be planted
- origin and source
- class and grade
- certificates and labels
- incidence of tuber diseases

Field period
Inspection on planting date and harvesting (haulm destruction) date
- aphid population
- number of infection sources

Visual inspection of the crop
- growing conditions of the crop
- agronomical practices applied
- occurrence of diseased plants, off-types: numbers and percentage
- roguing procedures applied
- chemical control measures applied
- occurrence of infection sources in neighbouring fields (distance)

Laboratory tests
- leaf samples taken from the field for virus identification

Post harvest
Screening of tuber samples taken from the harvested seed lot
- tests on plants grown from the tuber: greenhouse-'open-air'
- direct tests on tubers and sprouts

Storage
Inspection of storage methods
- storage methods
- mixing lots
- occurrence of aphids

Sorting and packing
Lot inspection
- sizes
- occurrence of diseases
- packing material and weight of packed units

zations) and the farmers (or seed producers) linked to these organization are involved in seed production, an independent inspection agency is needed. This agency will be responsible for the development of standards and regulations as well as inspection to ensure that the regulations are implemented and that certified seed meets the requirements of the standards. Inspection services undertake visual inspections and usually the laboratory tests required as well (laboratory facilities other than those used for testing may be needed). Independent inspection services contribute to the production of a more uniform standard of seed quality by the various seed production organizations and individual farmers. An independent inspection service also gives contract seed growers for organizations (cooperatives, private firms, etc.) a certain guarantee of whether or not the seed produced is acceptable on the basis of its quality and not on the basis of the market situation.

A seed inspection service can only have an impact on seed quality if the seed producers and seed producing agencies support the service.

The primary responsibility for quality will always lie with the producers and their own agencies. An internal quality control system within seed producing agencies is vitally important. These agencies are usully in closer contact with the farmers producing the seed and are therefore, in a better position to be able to judge quality and select batches for further multiplication than inspection services. Establishing an independent Inspection Service will not be a high priority in all circumstances. It is not essential, for example, if:

- A research institute is producing the pre-basic seed (and is the only source) to be distributed to the traditional seed growers from where lateral spread takes place.
- Government farms are producing seed for distribution.
- When infrastructure (i.e. plot size, scattering of plots, topography, accessibility, etc.) is such that decentralized seed production is a better approach to seed supply.

Internal quality control systems are always required.

16.6.1 Field inspection

Supervision by producers and field inspection by internal quality inspection teams or independent seed inspection services are usually necessary. Laboratory tests can never replace field inspection as only relatively small samples can be tested in the laboratory while an experienced field inspector will be able to evaluate a large proportion of the plants in a seed plot. Field inspectors need to be in close contact with the farmers. Their relationship with the producer should be more that of an advisor than a policeman.

A field inspector must be interested in diseases as well as in production aspects. It should be appreciated that inspectors can only evaluate fields where growing conditions are optimum.

16.6.2 Laboratory tests

The laboratory methods available for the detection of viruses in potato plants are:

- serology
- indicator plants
- callose test
- electron microscopy.

Although all these methods have their value, only those that can be applied on a large scale and give quick response are widely used:

- serology (including ELISA test): PVY, PLRV, PVX, PVS, PVA
- A-6 test: PVY, PVA, PVX
- callose test: PLRV.

As laboratory facilities are often limited, only relatively small samples can be examined. The sample size is often more of a limiting factor in obtaining reliable data than the testing methods themselves. The sample size required to obtain sufficient, reliable results depends on the percentage of infected plants in the field. It can be calculated that, theoretically, the minimum sample size should be 400, 300 or 200 plants or tubers if the tolerances are 1 %, 2 % and 3 % respectively. In the first generations of a clonal selection programme, where the tolerances are zero or extremely low, most of the plants would have to be examined.

It should be understood that a seed programme should never be based on laboratory tests only. When selecting and inspecting, the main work is done in the field (i.e. looking for symptoms).

16.6.3 Post-harvest control

Seed inspection often includes post-harvest control to detect virus infection which can occur during the latter part of the growing season. This procedure can also detect virus infection which earlier showed only indistinct symptoms that can easily be missed.

The results of post-harvest control tests should be made available as soon as possible after the harvest. Some fungal, bacterial and virus diseases can be detected in the tuber immediately when the correct analyses are used. Some viruses can only be detected on plants grown from the tubers.

At harvest a number of tubers are collected at random, dormancy is broken (10 minutes 1 mg GA per litre) and they are planted in greenhouses or out in the open at a place where there is little virus infection. The plants are visually assessed and if necessary, laboratory tests are carried out.

It is also possible to detect viruses in the sprouts of the tuber with the ELISA test. For high class seed with a low tolerance level, the sample size should be at least 400 tubers per hectare. This type of post-harvest control is not usually applied to crops intended for the production of seed of a lower class.

16.6.4 Bulk inspection

During a field inspection, only those diseases which affect the foliage are addressed. But, to determine tuber characteristics (e.g. presence of diseases, defects, size, sprouting, etc.) a bulk inspection is required shortly before delivery.

16.6.5 Verification plots, check plots or control plots

Control plots (also called verification or checkplots) are particularly valuable in the development of seed programmes. Samples (e.g. 100–200 tubers) of all the seed crops inspected (or if there are too many, field samples from seed crops selected at random) are planted in one field for observation throughout the growing season.

A control plot can be used for many purposes:

- to demonstrate the value of the seed produced (e.g. presence of diseases and physiological aspects)
- to provide an overall picture of the total seed programme (e.g. seed growing areas,

seed growers, inspectors)
- to pinpoint problems in the seed programme
- to make data available which is needed to improve and adjust regulations and quality requirements
- to train personnel working on the seed programme.

16.6.6 Seed inspection regulations

Regulations should be adapted to local conditions and to the quality of seed to be produced. For basic seed (or foundation seed) the tolerances are very low, while for certified seed, higher percentages of diseased plants may be allowed (tables 59, 60 and 61).

The tolerances in post-harvest control are usually 6 to 10 times higher than those applied to field inspection. Observations made during field inspection can only give an indication of the quality of the seed produced. A post-harvest control programme in combination with field inspection gives more exact data on the real quality of the seed, if:
- the sample of tubers is sufficiently large (e.g. 300–500 tubers)
- the sample is taken correctly
- the post-harvest test is reliable.

The tolerances judged acceptable according to European Common Market regulations (basic seed crops should have no more than 4 % of visibly virus-diseased plants and certified seed crops no more than 10 % leaf roll, severe mosaic and crinkle plants) are generally higher than the tolerances mentioned in the national legislation of the EEC member countries.

Table 59. Field tolerances (number of affected plants in %) for basic and certified seed, as applied in four countries (Oosterveld, 1987).

		Canada[1]	France[1,3]	The Netherlands[1,3]	United Kingdom[2]
Severe mosaic, including leaf roll, stipple streak and crinkle	basic seed	0.25	0.33	0.09	0.1
	certified seed	1.0	1.0	0.25	2.0
Mild mosaic	basic seed	0.25	0.33	0.09	0.5
	certified seed	1.0	1.0	2.0	5.0
Erwinia spp.	basic seed	0.1	0.5	nil	0.5
	certified seed	2.0	1.0	5 plants/ha	2.0
Varietal impurity	basic seed	0	0.1	0	0.05
	certified seed	0.1	0.2	0	0.5

1. Three official inspections for basic seed and two for certified seed.
2. Two official inspections for basic seed and one for certified seed.
3. The data presented for basic and certified seed concern those for grades E and A, respectively. From the categories basic and certified seed, the grades E and A are generally marketed.

Table 60. Tolerances during field inspection in the Netherlands.

Class	Disease index[1]	Number of black leg plants per ha
S	2	0
SE	2	0
E	3	0
A	4	5
B	8	10
C	12	15

1. Disease index = multiplication factor × % diseased plants.

Table 61. Multiplication factors applied by inspectors in assessing the disease index at initial and later inspections in the Netherlands.

	S and SE		E		A and B		C
	1st	later	1st	later	1st	later	final
Potato stipple streak, crinckle, severe mosaic	32	64	16	32	16	32	6
Mosaic	32	64	16	32	4	8	2
Mild mosaic	32	64	16	32	2	2	1
Latent disease	32	32	3	3	1/4	1/4	1/4
Leaf roll	8	32	8	32	8	32	6
Aucuba mosaic (F), stem mottle	4	8	4	8	2	6	6
Verticillium	1	1	1	1	1	1	–
Suspects	1	2	1	2	1	2	–
Gaps, open places	0.5	–	0.5	–	0.5	–	–

16.6.7 Seed certification in the Netherlands

Certification agent:
The General Netherlands Inspection Service for Field Seeds and Seed Potatoes (NAK) is a non-governmental, non-profit organization. The seed potato committee consists of:
Seed grower, Seed user, Breeder, Seed merchant, Representative of the Ministry of Agriculture, Representative of the Regional Inspection Services and some Experts as Consultants.
Supervisor: Ministry of Agriculture
Classifications

S, SE } pre-basic seed
SE, E } basic seed

A, B, C } certified seed

Classification is based on:
- plant quarantine regulations
- quality of seed planted (class)
- field inspection and additional laboratory tests
- lifting dates (haulm destruction dates)
- post-harvest control
- bulk inspection.

16.6.7.1 Plant quarantine regulations

Sites where seed is to be grown are inspected for the presence of *Globodera* by soil sampling. The crop rotation on each farm is recorded in order to ensure that the existing potato cropping regulation is not violated.

16.6.7.2 Quality of the seed planted

In general, a seed crop can only be certified to a standard which is at least one class lower than that of the seed used for its production. This automatic downgrading

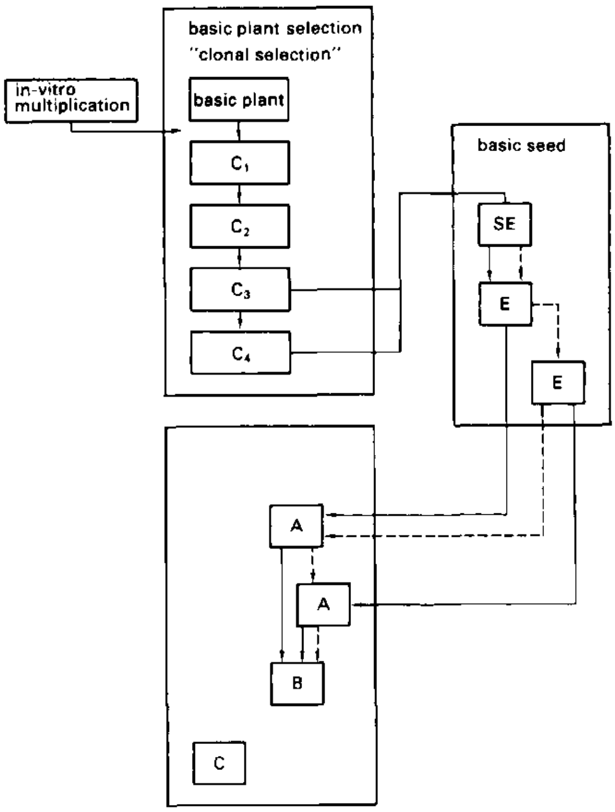

Fig. 90. Classification of seed potatoes in the Netherlands.

ensures that seed stocks are constantly renewed by being built up from clonal selection programmes. The clonal selection system and the system of classification (with automatic downgrading) is given in figure 90.

16.6.7.3 Field inspection and additional laboratory tests

Clonal selection material

- Clonal selection material should be true to type. Samples of all clones (approved C_2 or C_3) are compared with other clones of the same variety at the Central Control Field of the NAK.
- No visible disease symptoms may be observed in the 1st year clone.
- One leaflet of all the 1st year clones must be examined in the laboratory (ELISA: Y, A, X, S).
- A minimum of 50 2nd year clone plants are examined in the laboratory.
- In principle, clones are kept separate but under certain conditions they may be bulked.
- The tolerances for C_1 are: 0 = no diseases (virus- bacterial) are allowed. C_1 is destroyed if any diseases are found. C_2 to C_4 may be placed in any class whose standards can be met.
- At least 100 plants of the 3rd and 4th year (C_3 to C_4) have to be tested in the laboratory.

Tolerances during field inspection

- To determine the percentage of disease, at least 4 × 100 plants have to be examined from each field.
- The maximum disease index for the various classes is given in table 60. Disease index = percentage of diseased plants × multiplication factor. The multiplication factors are given in table 61.

Additional laboratory tests during field inspection

- For certain varieties and classes, additional laboratory tests can be carried out (e.g. high classes, susceptible varieties, varieties in which virus symptoms are hardly discernable).
- At least 200 plants per hectare of classes SE and E, and 100 plants of classes A.
- The results of the laboratory tests are reported to the inspector and he has to confirm these in the field. If the laboratory results are not confirmed, fresh samples are taken. For classes SE and E: 400 plants (leaves) and for classes A, B and C: 200 plants (leaves).

Isolation In most seed production areas the number of infection sources is kept down by the fact that the ware grower is not allowed to use seed from a lower class than B. The distance between seed fields and other potato fields must be at least 2 m if there is any risk of these becoming sources of virus infection transmitted by contact. This distance must be at least 25 m if there could be any infection sources for viruses transmitted by aphids.

16.6.7.4 Lifting dates – haulm destruction dates

To avoid virus infection when aphid populations increase late in the growing season, haulm destruction dates are fixed each year for each variety, class and region. These dates are based on:
- presence and activity of aphids
- susceptibility of the variety
- stage in crop growth
- infection sources present.

The NAK issues a recommended haulm destruction date and the regional inspection services provide the final haulm destruction date, but the final date for basic seed should generally be no later than the recommended date for the next class. Crops which are not harvested (or where the haulms are not destroyed) by the final haulm destruction date are placed in a lower class.

16.6.7.5 Post-harvest control

Samples for post-harvest control are taken during harvest. The apical eyes together with part of the flesh are scooped from the tubers collected. Dormancy is broken by immersing them for 10 minutes in a 1 ppm (mg/l) Gibberellic Acid solution. Next the scoops are planted 10 cm × 10 cm apart under aphid-free conditions (e.g. in a greenhouse). After 4–5 weeks single stem potato plants will have grown. The symptoms of any major viruses will become visible within a few weeks, when visual observations can be made, but additional serological tests may be required.

The sample size and virus tolerances differ for the various classes:

S and SE	300–400 tubers	1 : 300
E	200–300 tubers	3 : 200
A	100–200 tubers	5 : 100
B	100–200 tubers	8 : 100
C	100–200 tubers	10 : 100

Post-harvest control is compulsory for classes S and SE; class E is the principle subject to post-harvest control, but in most cases not executed if haulms are destroyed at the recommended date and the envolved varieties have a good level of virus resistance. Very susceptible varieties in class E have to undergo post-harvest control even if the haulms are destroyed before the recommended date. Classes A and B are often not submitted to post-harvest control, provided that haulm destruction was done in time.

16.6.7.6 Bulk inspection – certification

Approved crops are lifted, transported and stored under NAK supervision. After grading and sorting, but before certification, the inspector examines the tubers for diseases and misshapen and damaged tubers.

Each bag or crate is certified and sealed. The certificate indicates:
- variety

- class
- the number of the grower.

This number makes it possible to trace not only the grower but also the inspector and his findings during inspections.

16.6.7.7 Verification plots

The NAK has at its disposal the Central Control Field and the Regional Inspection Services of the NAK have their Regional Verification Plots which are used for:
- comparison of clones selected on clonal selection farms (section 16.6.7.3)
- planting samples from inspected seed batches of various classes produced during the previous year's seed programme: (1) to evaluate the results of the seed programme in the various regions (2) to collect data for the benefit of seed certification regulations and methods (3) to serve in training programmes.

16.6.8 Development of seed tolerances

Certification standards have to be adapted to the practical situation in the region or the country where the regulations have to be introduced and applied. Existing regulations and standards can be used as guidelines for developing standards and tolerances but cannot be copied.

In developing seed regulations it is essential to consider for what purpose the seed is being used and what standards can be maintained. It is evident that the tolerances for pre-basic and basic seed should be very low. Such seed forms the basis for the production of certified seed. Especially when the certified seed is to be produced in rather high degeneration rate areas the tolerances of basic seed to virus diseases should be low to ensure the lower grade seeds are produced with as acceptable a quality as possible.

The standards set in the regulations should be such that they can be met. Often it is better to start a programme with rather high tolerances and to adjust these later as the programme develops and the need for higher standards has been demonstrated.

Most standards in regulations refer to field inspection. Field inspection standards do not give the actual quality of the seed that is being produced. Results of field inspection can only give an indication of the expected seed quality because infections which occur later in the growing season do not always exhibit symptoms. Therefore, the tolerances for field inspection are about 5 times lower in many certification regulations than the tolerances for a post-harvest control sample.

17 Varieties and breeding

17.1 Developments in potato breeding

The development of the potato in its place of origin took place at the diploid level (2n - 2x - 24 chromosomes). Further differentiation at the same ploidy level may have occurred by inter and intra specific hybridization, mutation etc. Polyploidization probably took place by natural chromosome doubling, production of unreduced gametes and hybridization between different ploidy levels. Most commercial potato cultivars are tetraploids (2n - 4x - 48 chromosomes) and are derived from *Solanum tuberosum* var. *andigenum*, but diploids are also cultivated (e.g. *Solanum phureja*).

Selection for higher yields must have already taken place in South America in prehistoric times. It is most likely that the improvements made resulted from seedling selections of uncontrolled pollinations. Probably some of these seedlings possessed certain characteristics (e.g. skin colour, shape, yield, resistance) which caught the attention of the farmers and were kept for further multiplication. The survival of odd-numbered polyploids and favoured cultivars was facilitated by the vegetative propagation of tubers.

In the 16th century the tetraploid cultivated potatoes of the *Andigena* group was introduced into Europe and breeding for adaptation started. The potato was taken to many parts of the world by European settlers during the 18th century: North America, South Africa and Australia. Colonial influences also contributed to the introduction of the potato into Asia and Africa. Breeding programmes developed in the countries where potatoes were introduced. Although there has always been some exchange of genetic material between breeding programmes in Europe and America, the genetic basis of most breeding programmes was relatively small at first, due to the limited initial introductions from South America. From the original *Andigenum* introductions into Europe, the *Solanum tuberosum* var. *tuberosum* was developed.

This *S. tuberosum* var. *tuberosum* has less vegetative growth, earlier tuberization and a shorter growing cycle and is more tolerant to heat than *S. tuberosum* var. *andigenum* of South America. The outbreak of diseases such as *Phytophthora infestans*, *Synchrytium endobioticum*, virus diseases and *Globodera* sp. have not only stimulated breeding activities, but also the collection of new germ plasm from the place of origin. This has led to the breeding of new varieties from crosses, involving either wild and primitive species or new introductions of the *Andigena*. Many of the newer varieties now have genes or chromosome segments not found in the *tuberosum* potatoes.

17.2 Vegetative reproduction

Potatoes are normally propagated by vegetative reproduction and any selection will stay true to type (except for rare mutations). New varieties can be selected as plants from crosses in the F1 generation. Therefore, it is relatively easy to use wild crosses, induced mutations and artificially produced polyploids in the production of new varieties, as there is no need to become true to type after sexual reproduction. As is the case with most vegetative propagated crops, potato cultivars are heterozygous.

The advantages of vegetative replication by means of the tuber are:

- It is possible to select cultivars in the F1 generation.
- Plants grown from tuber seed develop quickly, making it possible to produce a potato crop in a short period of time.

The disadvantages of vegetative reproduction are:

- Care must be taken to keep selected plants free from viruses during their multiplication.
- Many established varieties and other parental material used in breeding programmes are extremely heterozygous and in crosses they transmit their good qualities only to a very small proportion to their progeny.
- Genotypes may not flower or be pollen sterile.
- Selection during the seedling stage and the first clonal year is very inefficient because methods of propagation and plant growth conditions differ from the normal crop situation.
- Tubers intended for vegetative replication cannot be stored easily and must be grown at least once every year.
- Multiplication rate of potatoes grown from tubers is low.

17.3 Phenotype variation

The phenotypic variance (Vp) of a cultivar is determined by its genetic composition (Vg) and by the non-genetic environmental conditions (Ve) with the formula $Vp = Vg + Ve$. The fact that the potato is a tetraploid and that the environment has a strong effect on the phenotype, make it difficult to study the inheritance of its characteristics.

17.3.1 Tetraploids

As most potato cultivars are tetraploids and potatoes at the tetraploid level seem to have the highest yield potential, most potato breeding programmes are implemented at the tetraploid level. In this system there are four homologous chromosomes and five genotypes possible at each locus: AAAA (quadriplex), AAAa (triplex), AAaa (duplex), Aaaa (simplex) and aaaa (nulliplex).

Three types of gametes are possible: AA, Aa and aa, The progeny of a crossing involving a resistance controlled by a dominant gene, may be expected to exhibit a ratio between resistant and non-resistant genotypes of at least 1 : 1. This is the case when a nulliplex is combined with a simplex. However, when a duplex is used as a source of resistance, the ratio between resistant and non-resistant genotypes is 5 : 1, while a ratio of 35 : 1 is achieved by selfing the duplex. From the examples given it

Table 62. Frequency of occurrence of race non-specific resistance to *Phytophthora infestans* (Black, 1960).

Reaction group of parents	Percentage of seedlings in reaction groups				
	1	2	3	4	5
2 × 2	0	29	56	15	0
2 × 3	0	8	70	19	3
2 × 4	0	8	26	53	13
3 × 3	0	8	18	70	4
3 × 4	0	0	13	75	12
4 × 4	0	0	2	79	19

1 = highly resistant; 2 = fairly resistant; 3 = slightly resistant; 4 = normally susceptible; 5 = very susceptible

is clear that with tetrasomic inheritance a relatively large proportion of the phenotype with a major gene can be expected in a progeny, while there will only be a small proportion of the genotype aaaa.

Several important characteristics in potato breeding are inherited in a single dominant gene fashion (*Synchitrium endobioticum*, race-specific resistance to *Phytophthora infestans*, hypersensitivity to PVX, PVA, PVY and immunity resistance to PVX and PVY, resistance to *Globodera* sp.). Although it is relatively easy to incorporate these genes in a breeding programme, the problem is that in some cases the single dominant gene only gives protection for one race of the pathogene (gene for gene resistance). This has caused serious problems in breeding for *Phytophthora* resistances where soon after the introduction of a cultivar with vertical (or major gene) resistance, new races of the pathogene developed for which the new cultivar had no protection.

In many cases it is difficult to breed for recessive traits in auto tetraploid populations:

- The frequency of appearance in progenies is low.
- There are a multitude of possible genotypes.
- The environmental factors greatly affect the phenotype variation.

An example of the low frequency of desired genotypes is given in table 62.

17.3.2 Diploids

Diploids are frequently used in breeding programmes. These diploids are useful wild and cultivated species, as are diploids (2n - 2x - 24) extracted from tetraploids. Haploids can be extracted from tetraploids by using certain lines of *S. phureja* as a pollinator for the induction parthenogenesis on tetraploids and thus the production of haploid seed. Haploids from tetraploids are used for several reasons:

- It is often difficult to establish crossings between the many useful wild and cultivated diploid species and tetraploids. When haploids are extracted from the tetraploids, such combinations can be made at the diploid level.

– In theory inheritance studies, development of more homozygous material, combination of specific genes and population improvement are easier at a diploid level than at a tetraploid level.

Breeding work can be done more efficiently at 2x level than at 4x level but higher yields and greater adaptability can be expected at the tetraploid level. It is assumed that a pre-breeding programme for the development of parental material can be done at diploid level but that development of cultivars has to be done at the tetraploid level.

Diploids can be doubled by colchicine to produce tetraploid parental lines.

Using First Division Restitution (FDR), 2n gametes with an unreduced chromosome number, to resynthesize tetraploids also offers opportunities. FDR 2n gametes transmit a large proportion of the parental diploids to the tetraploid progeny. The genetic diversity obtained at diploid level by crossing useful diploids (from tetraploids) is then raised to the 4x level by 4x–2x or 2x–2x crosses. Also the number of chromosomes can be raised through somatic hybridization (section 17.7.1)

Although the production of haploids from tetraploids is relatively easy, it is still difficult to select genotypes with required characteristics. This is especially true for characteristics controlled by polygenic systems and characteristics that are strongly influenced by environmental conditions. Haploids are often not very well adapted and thus it is difficult to select for yielding capacity, yield stability, tuber size, tuber shape, quality, earliness, etc.

17.3.3 Wild and primitive potato species

Genes important for resistance have been reported in many potato species. Some examples are given in table 63. Such species may differ in their chromosome numbers, appearance, adaptation, yielding capacity, resistance, quality and earliness from the

Table 63. Some sources of resistance.

Late blight	**Verticillium wilt**
S. demissus	*S. tuberosum*
S. bulbocastanum	
S. stoloniferum	**Bacterial wilt**
S. andigenum	*S. bulbocastanum*
	S. chacoence
Common scab	*S. phureja*
S. commersonii	
S. chacoense	**Virus A, Y**
S. jamesii	*S. stoloniferum*
Wart disease	**Leaf roll virus**
S. demissum	*S. andigenum*
S. acaule	*S. etuberosum*
S. tuberosum	
	Cyst nematode
Aphids	*S. andigenum*
S. berthaultii	*S. vernei*

cultivated *Solanum tuberosum* cultivars. It is the task of the breeder to incorporate the desired characteristics of such species into cultivars and to remove those that are undesirable.

After a characteristic has been identified in a species, there is often a long way to go before the material can be used by commercial breeders.

In their efforts to incorporate wild and primitive species, scientists face problems with sterility, incompatibility and odd chromosome numbers etc. Breeders use special breeding techniques such as: bridge crosses, haploidization, chromosome doubling, etc. During this process important characteristics may be diluted or even lost and after each step the material has to be screened to check whether the desired characteristic is still present. This appears to be especially difficult for characteristics controlled by polygenic systems. Most success in making genes available from wild and primitive material for practical breeding purposes has been obtained with characteristics controlled by single dominant genes. Many successful breeders use commercial varieties and advanced breeding material that have been developed from wild and primitive species by institutions and scientists that specialize in handling this material.

17.3.4 Environmental variation

Environmental conditions not only affect the growth and production of a certain cultivar, but also greatly influence the effect of the resistance genes present in a particular cultivar. The effects of day length and temperature on the partitioning of dry matter to haulm and tuber, the 'sink' effect on the increase of net assimilation as well as the effects of environmental factors on earliness of cultivars are described in chapter 4.

There are differences with regard to disease resistance. Certain resistances (e.g. major gene resistance to *Phytophthora*, immunity resistance to PVX and PVY) are quite stable and not influenced by environmental conditions, whereas the levels of others (e.g. race, non-specific resistance to *Phytophthora*) are. Cultivars with high levels of field resistance to *Phytophthora* under long day conditions show a lower level under short day conditions.

The strong environmental effects on the phenotype makes selection difficult. This is particularly the case where characteristics are inherited quantitatively by polygenic systems. The reaction of the plants to the presence of polygenic systems is indeterminate and can only be determined under special conditions with a large number of plants (e.g. yield, quality, resistance to common scab, tolerance to *Pseudomonas*, etc.). When conditions are not favourable to demonstrating differences between genotypes, no selection can be made.

17.3.5 Expected progress in breeding

Progress in breeding depends on genetic systems and the selection methods available (table 64). When characteristics are inherited in a single dominant gene fashion and when the presence of such genes results in complete protection from a disease or in a clearly defined reaction (+) or while this protection or clear plant reaction does not exist (–) in the of absence the gene, progress in breeding can be made quickly. Breeding progress is much slower when the genetic system is polygenic and the

Table 64. Reaction of plants and genetic systems.

	Genetic system	Plant reaction
Phytophthora infestans		
race specific resistance	single dominant	+ or −
race non-specific resistance	polygenic	interm. (±)
Virus Y		
immunity resistance	single dominant	+ or −
field resistance	polygenic	interm. (±)
PLRV resistance	polygenic	interm. (±)
Globodera rostochiensis	single dominant	+ or −
Yield	polygenic	interm. (±)
Quality	polygenic	interm. (±)

reaction of the plants is indeterminate (±).

When a single dominant gene is involved, a repeated back-crossing programme is often used. As long as the gene involved is present, the level of resistance remains unchanged. When polygenic systems are involved, breeding progress is much slower because:

- A low proportion of the crossing progeny has the desired characteristics.
- It is time-consuming to find optimum crossing combinations (specific and general ability to combine).
- Screening of genotypes is difficult because plant reaction to genes is intermediate and the difference between Ve and Vg is often large.

17.4 Breeding objectives and choice of parents

Depending on the situation (e.g. existence of an independent seed programme), a breeding programme would be:

- a programme for testing varieties developed elsewhere
- a traditional breeding programme using existing varieties and advanced breeding material developed in centres of excellence
- selecting varieties from segregating populations produced elsewhere
- development of parental material.

In many scientific breeding programmes much emphasis is placed on disease resistance using wild species, whereas the experience of many breeders of commercial varieties is that a breeding programme which concentrates too strongly on disease resistant genes from wild and primitive species is only likely to have long-term benefits. They realise that a perfect potato does not exist and that a potato variety is always a compromise. High yield, stable yield and storability remain the most important characteristics. In most parts of the world it is now generally accepted that the choice of parents should be based on the following:

- A *Tuberosum* variety (*S. tuberosum* ssp. *tuberosum*), producing high yields under long-day conditions and adapted as much as possible to the area for which varieties

are to be bred, should always be one parent in a cross.
- When the desired characteristics cannot be found in a *Tuberosum* the next best choice is the *Andigenum* cultivars.
- If these are also not available, cultivated diploids are used.
- Wild species are only used if there are no other alternatives.

17.5 Flowering, pollen and seed

To be able to make the desired crosses it is essential that the parental material flowers over a sufficient length of time and that the flower buds or flowers do not drop. There are several very successful methods of preventing bud abscissions and for obtaining flowers.
- grafting potato cuttings onto tomato root stocks
- growing on a brick. Sprouted tubers are planted on a brick or tile above the soil level and covered with sand. When the roots have grown through the sand into the soil, the sand is washed away; this allows the new tubers to be removed when very small.
- Providing long-day conditions, by giving additional light (300 W/m^2).

Pollen sterility often occurs. In breeding programmes involving several crosses or back-crosses it is often possible to retain pollen fertility in the offspring until the final generation. Storage of pollen can be useful in breeding programmes. Pollen deteriorates more slowly at lower temperatures (+2.5 °C for 1 month, dried anthers at -20 °C for two years).

Most freshly harvested seed is dormant but this disappears after several weeks of storage. Seed often retains a certain degree of dormancy after 9 months of storage and seed stored for 20 months tends to germinate better. Seed and tuber dormancy seems to correlate. Dormancy of seed can be broken immediately after harvest by immersion in a solution of 1500 ppm (mg/l) Gibberellic acid for 24 hours. After treatment the seed is washed, air-dried and sown. Seed can be stored dry under normal laboratory conditions for at least 20 years at -20 °C.

17.6 Selection procedures

Botanical seeds are sown in pans or in nurseries and transplanted in pots (diameter 10 cm) or sometimes in the open field. When plants are close to maturity, one tuber of each selected plant is usually kept for planting in the following clonal year.

There are only a few characteristics that can be selected for at the seedling stage: growth too wild or weak, skin colour, immunity to PVX and PVY (if inoculation techniques have been applied), etc. Selecting the best clones (genotypes) may not be very efficient as there will be only one plant per genotype and there is a wide variation in seed (size and physiological age). Moreover early and late maturing genotypes are often grown mixed, with the result that earlier genotypes are suppressed by late types. At harvest time 6–8 tubers from the selected plants are kept for the next clonal generation. The number of selections (genotypes) retained in the later clonal generations decreases, while the number of plants per selection increases (table 65).

During the first clonal years, selection is based on performance, maturity yield estimates, etc. In the later stages of selection when more plants and tubers are

Table 65. A method commonly used for selecting and multiplying potato clones.

Season	Genotypes (e.g.)	
1	40 000 seedlings and kept for futher selection	
2	30 000 clones at one tuber per clone;	4 000 selected
3	4 000 clones at 6 tubers per clone;	400 selected
4	400 clones at 24 tubers per clone;	100 selected
5	100 clones at 48 tubers per clone;	25 selected
6	25 clones at 96 tubers per clone;	6 selected
7	5 clones at 300 tubers per clone;	3 selected
8	3 clones at 1200 tubers per clone;	2 selected

available, special tests, proper yield analysis and adaptability trials as well as storage trials can be carried out.

As the chance of breeding a successful variety is fairly small a breeder has to start with a large number of seedlings each year and has to set clear priorities for selection criteria.

17.7 Breeding methods

In practice a breeder will rarely follow only one specific breeding system but generally uses a synthesis of various systems.

Pedigree method This is a method which aims to incorporate a large number of desired genes in a single clone by the process of a succession of crosses between parents, each of which could contribute a different set of desired genes. At each step recombinations are selected with the greatest accumulation of all genes. This method is appropriate for those characteristics that are easily inherited.

Back-crosses This method is used when a certain characteristic of an unadapted donor variety has to be incorporated into adapted varieties. Back-crossing is repeated until the characteristics of the adapted variety have been recovered with the addition of the specific genes from the donor. The variety is not usually the same as the back-crossing parents.

A back-crossing programme is most effective when the characteristics to be incorporated are controlled by dominant genes and suitable and easy selection methods are available.

Progeny testing In this method the selection of parents is based on the performance of the progenies from various crosses. Groups of potential parents are intercrossed and their progenies evaluated. The mean performance of the progenies of a certain parent in relation to the mean performance of all progenies under examination gives an indication of the general combining ability of that parent. The deviation of the performance of a specific progeny from what would be expected on the basis of the general combining ability of the two parents is called the specific combining ability.

Parents to be used for further breeding are selected on the basis of their specific and general combining ability.

Recurrent selection This method is used to increase the intensity of characteristics inherited quantitatively by polygenic systems. A variable population is created and selections are made for the desired character. Selected clones are then intercrossed to generate a basis for the next cycle of selection. This procedure is repeated for several cycles. Genetic diversity is preserved with this method. It can be used, for example, to create populations with high levels of dry matter content.

17.7.1 New methods and techniques

Classical potato breeding methods have some fundamental limitations. New methods such as: (1) induction of somaclonal variation with selection in vivo or in vitro, (2) somatic hybridization where intact parental genotypes and cytoplasms are combined and (3) gene transfer by genetic engineering (transformation of existing varieties) have been discussed and their potential for potato breeding has been evaluated Hermsen et al. (1987). At this stage of research it is too early to predict results, but it is evident that initial successes obtained so far refer to single dominant genes for quantitative characteristics and not polygenic traits.

Table 66 Properties of potato cultivars.

a. **Yield**	d. **Resistance to disease**
a.a. emergence	d.a late blight foliage
a.b. haulm development	d.b. late blight tuber
a.c. number of stems	d.c. *Alternaria*
a.d. tuber initiation	d.d. wart disease
a.e. maturity	d.e. scab
a.g. tuber yield	d.f. *Globodera*
	d.g. spraing
b. **Tuber quality**	d.h. leaf roll
b.a. colour of skin	d.i. virus A
b.b. shape of tubers	d.j. virus Y
b.c. size of tubers	d.k. virus X
b.d. shallowness of eyes	
b.e. dry matter content	e. **Tolerance to weather and physiological disorders**
b.f. cooking quality	e.a. second growth
b.g. frying quality	e.b. little potato
b.h. chip quality	e.c. drought
b.i. internal bruising	e.d. high temperature
c. **Keeping quality**	e.e. wind
c.a. length of dormant period	
c.b. sprout development	
c.c. susceptibility to tuber rot	
c.d. susceptibility to *Fusarium*	
c.e. susceptibility to decay after cutting	

17.8 Varieties and their properties

Throughout the world many potato varieties (cultivars) have been developed and are grown on a commercial scale. Their names and characteristics are published in handbooks, leaflets and descriptive lists of varieties. The characteristics mentioned in these publications often refer to the environmental conditions in which these properties have been recorded.

As only a few characteristics are the same under the different agro-climatic conditions and many of them react strongly to environmental conditions, it is essential to screen and evaluate varieties with this in mind before introducing them in places other than the country of origin. In a country with different climatic zones and growing seasons, varietal characteristics and behaviour must be determined in relation to such zones and growing seasons.

A number of important varietal characteristics are listed in table 66. In a variety testing programme special attention is paid to those characteristics that are strongly affected by environmental conditions while the more stable characteristics (properties not strongly affected by environmental conditions) can be found in varietal descriptions already published.

The properties as indicated, are frequently important, but they do not have the same significance under all circumstances, and the importance of each has to be evaluated carefully for each country. In some cases it will also be necessary to include other characteristics that are very important for specific areas.

Apart from compiling a list, summarising various major characteristics, it has proven to be of great value to give a short description of the cultivar. This description should include:

- The significant major properties of the cultivar indicating its value.
- For what purpose it can be used.
- What risks are taken when it is used.

17.9 Determination of characteristics

Many properties have to be evaluated indirectly while there are more exact methods of determination for others.

17.9.1 Indirect evaluation

Careful observation and measurements of the growing plants and the harvested product enable the researcher to determine the major important characteristics. It should be understood, however, that each observation and measurement made in any particular place and season is certainly valuable but many such observations and measurements are required to establish the various properties with any degree of accuracy. Not only is the reaction of a variety to 'normal' conditions important but also its behaviour under more abnormal circumstances.

It is essential to prepare a report of each trial, including the observations made, the final results and a description of any factor which might have influenced the results (e.g. condition of the seed, seed bed, weather conditions, fertilization, outbreak of disease, etc.).

Each trial, even when not very successful, will provide information about the varieties being tested but it should be realised that the information obtained from one trial will be limited. Each trial should be analyzed statistically, and it is also essential to determine why the existing conditions and the treatments administered gave the results obtained. When making final selections, observations and judgments made are often more important than yield data.

17.9.1.1 Yield characteristics

Yield depends on many factors: available growing period, growing cycle of the crop (variety), moisture supply, etc. To determine and to be able to explain yield, all relevant factors have to be considered. These factors are:

- condition of the seed at planting time
- time between planting and emergence
- percentage emergence
- number of stems per plant
- foliage development
- foliage ground cover
- length of tuber growth and maturity
- reaction of the crop to extreme weather conditions
- water supply
- disease and pest attack, etc.

Planting time, field conditions, etc., should also be recorded. As planting time greatly affects the crop cycle, the potential growing period and the available growing period, it is essential that variety trials are planted at the right time. At least 20 plants should be harvested from each plot to determine yield (see also section 5.4).

17.9.1.2 Tolerance of weather conditions and physiological disorders

These characteristics can only be observed when certain weather conditions occur and when circumstances are favourable to the development of physiological disorders. It is necessary to make observations whenever an opportunity presents itself.

17.9.2 Direct tests

Where direct evaluation does not provide sufficient information on varietal characteristics or existing data obtained elsewhere cannot be used, because they are highly influenced by environmental conditions, special tests will be required.

17.9.2.1 Potato leaf roll virus

Two tubers of each variety (or clones) to be tested are planted in 3 to 10 positions at random between rows of leaf roll infected tubers (fig. 91). Some varieties whose level of resistance is known are included as a reference. An exposure field of this kind is laid out in an area where it may be expected that aphids, responsible for the transmission of potato leaf roll virus, will be present during the growing season.

About 5 tubers per plant are harvested from each of the growing varieties at the

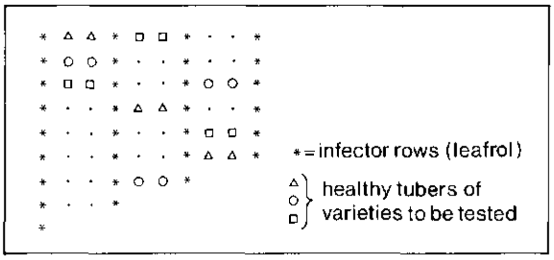

Fig. 91. Exposure field for testing varieties for PLRV resistance.

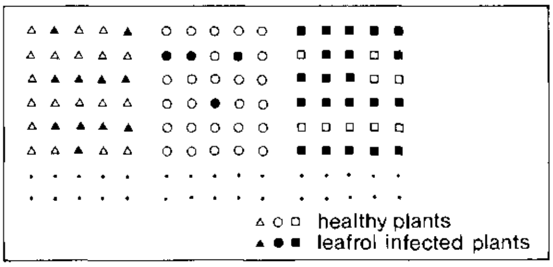

Fig. 92. Evaluation field for testing PLRV.

end of the growing season, to be planted in an evaluation field the next season (fig. 92). The percentage of plants of each variety in the evaluation field with leaf roll virus due to the infection pressure on the exposure field, can be determined. This gives an indication of the relative resistance of each of the varieties to leaf roll virus.

17.9.2.2 Field resistance to viruses X, S, M, Y

Field resistance to these viruses can be determined in a similar way to the method used for leaf roll. Other methods used are tuber or stem grafting. When grafted with virus infected tuber or stem grafts, varieties with a high degree of field resistance often produce a severe necrotic reaction.

17.9.2.3 Immunity to viruses A, X and Y

A reliable method of testing immunity is again a grafting technique. Shoots of the variety to be tested are grafted onto rootstock of a tomato plant inoculated with the virus. If the shoot of the grafted potato remains healthy it may be concluded that the variety is immune to the virus involved.

17.9.2.4 Virus tolerance

Varieties react differently to different viruses. Varieties with a high tolerance do not, generally, show clear symptoms when infected with the particular virus and the reduction in yield will be minimal. Tolerances can be measured by comparing the yield of healthy plants with that of virus infected plants.

17.9.2.5 Resistance to common scab

Common scab only attacks potato tubers when they are at a young stage and surrounded by dry soil. Such conditions have to be reproduced when testing varieties for scab resistance.

Reliable results are obtained by planting tubers in pots filled with infected soils. These are then placed in the open field on ridges. The roots grow through the holes in the bottom of the pot and the plant can take up water from the ridges and subsoil. Inside the pot the soil remains more or less dry (or becomes dry soon after it is wetted by rain), thus creating conditions favourable for attack by *Streptomyces*.

The percentage of the tuber surface attacked by common scab is an indication of the susceptibility of the variety. A number of known varieties should be included in the test as a reference.

17.9.2.6 Late blight resistance

Assessing late blight resistance under field conditions is rather complex.

- Two different types of resistance may occur: R-gene, major gene, vertical or race specific resistance and field, horizontal or race non-specific resistance.
- The level of field resistance varies at different stages of plant development or maturity.
- Blight attack only takes place when environmental conditions are favourable and inoculum is present.

Some of the difficulties met are illustrated in figure 93 which shows the results of testing genetic material in the Toluca Valley of Mexico.

Owing to the relatively late appearance of races to which plants carrying the less common R-genes, R_5, R_8 and R_{10} are not resistant, the degree of field resistance of clones containing one or more of these genes cannot be determined accurately. The degree of field resistance in varieties carrying R-genes cannot be measured if the strains which attack these varieties either do not occur often or only appear late in the season.

As field resistance is linked to late maturation, it is essential not only to record blight attack but also the stage of maturity of the varieties involved. Moreover the effect of day length on maturity also affects the susceptibility of this variety to late blight (i.e. short day conditions increase the susceptibility).

Frequent observations must be made to determine differences in resistance. When late blight is assessed in field trials in areas where it is not certain that conditions are favourable to the development of the disease or when it is expected that there will be an insufficient number of strains, appropriate measures must be taken (e.g. sprinkler irrigation, provision of sources of infection, inoculation of the field with the strains required).

To determine other special varietal characteristics, the material is often planted in fields where it may be expected that differences will become visible: e.g. a field contaminated with *Pseudomonas, Verticillium* wilt, common scab, etc. Other loca-

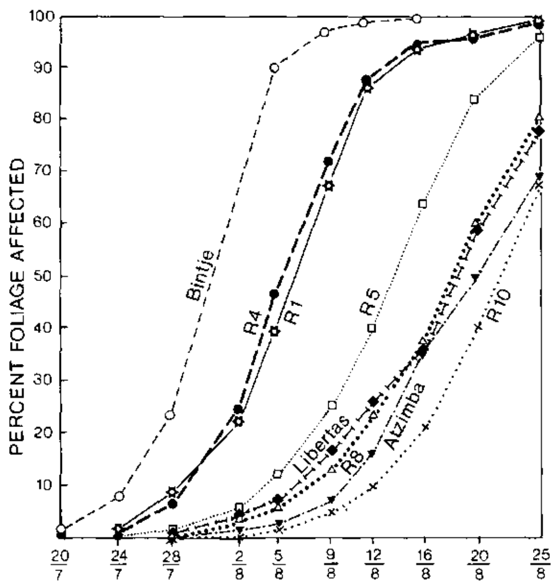

Fig. 93. Percentage foliage attack caused by *Phytophthora infestans* on some R-gene differential hosts and on susceptible and moderately field resistant varieties (CIP Annual Report, 1976).

tions can be used to study varietal reactions to drought, late planting and frost resistance.

17.10 Variety testing programme

A variety testing programme is intended to select new varieties to be grown in a given area. The aim is usually to replace varieties grown currently and/or to find varieties that can be grown in addition to those already available.

In a variety testing programme attention has to be paid to all major characteristics of the varieties under consideration but it should be remembered that the 'ideal' variety has yet to be found and that all varieties have certain weaknesses which often just have to be accepted. It is more realistic to take 'Good adaptation, stable yields, good storability, acceptable quality and acceptable levels of disease resistance' as the major criteria for selection.

If a country has its own independent seed programme a variety testing programme could include any available variety, but where such a programme has not yet been established (or cannot be established) tests should be restricted to those varieties for which seed can be obtained from other sources.

Depending on the number of varieties to be tested, a variety testing programme might include two or three phases. After each phase it is decided whether the variety is to be rejected or kept for further testing. The programme may consist of the following phases:
- preliminary trials

- regional trials
- introductory trials.

As in many variety testing programmes only a limited number of varieties can be tested, especially in the final phase, it is desirable to eliminate varieties which give poor performance as soon as possible. It is a often good policy only to include varieties that have proved their value in testing programmes as commercial varieties elsewhere.

17.10.1 Preliminary trials

When a large number of varieties are to be tested, the varieties are subjected to preliminary trials. These preliminary tests should preferably be undertaken at research stations, provided that conditions and methods of cultivation are such that these stations represent the conditions found in the main potato growing areas. As it is too optimistic to expect that new varieties will be resistant to all pests and diseases, pests and diseases are controlled in these trial fields as in normal practice.

The aim of preliminary trials is to make a first evaluation and to determine whether further testing of a certain variety is justified. These trials can also give an indication of purposes for which the variety should be further tested.

In preliminary tests a variety is often planted in small plots, without replications (approx. 30–45 plants per plot). If the amount of seed available permits, it may be useful to carry out preliminary tests in two or more locations.

It is vitally important that the variety trials are planted during the same period as the farmers plant their crops, while the same production technology (i.e. seed storage, cultivation methods, etc.) is applied as is used in local farmers' fields.

The observations are often restricted to the number that can be made directly during the period of growth and at harvest. Often this can only be used as a comparative figure.

17.10.2 Regional trials

Varieties which appear to be promising in the preliminary tests of varieties that have proved their worth in other areas under similar ecological conditions, should be included in the regional testing programmes in major potato growing areas representing the various agro-climatic districts.

In selecting the varieties to be tested in each of the regional trials the purpose of the crop must be considered. Each trial includes 10–15 varieties and usually has 3–4 replications in a plot of approx. 80–100 plants in 4–6 rows. Regional tests may continue for 2–3 seasons.

17.10.3 Introductory trials

Varieties successful in regional trials are distributed to farmers to be grown more or less on a commercial scale. These introductory trials are not only essential for farmers to become familiar with new varieties but also to assess how the varieties will react under farm conditions and with existing storage facilities.

Some properties of a variety often do not show up in small-scale trials but only during large-scale introductory trials.

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Annex 1.
Calculated daily gross assimilation (kg CH_2O per hectare per day) of a closed canopy with a spherical leaf angle distribution (derived from Goudriaan & van Laar, 1978).
Rate of leaf photosynthesis at light saturation = 30 kg CO_2 (20.45 kg CH_2O) per hectare per hour.

North Lat.[1]		15 Jan.	15 Feb.	15 Mar.	15 Apr.	15 May	15 June	15 July	15 Aug.	15 Sept.	15 Oct.	15 Nov.	15 Dec.
0°	Pc	425	438	446	442	430	420	424	437	446	442	429	420
	Po	200	208	213	211	203	197	199	207	213	211	203	197
10°	Pc	382	409	435	453	457	456	457	456	445	420	390	374
	Po	177	192	207	217	218	217	218	218	212	198	181	172
20°	Pc	331	372	416	455	477	485	482	466	434	389	343	320
	Po	148	170	195	217	228	232	230	223	205	180	155	142
30°	Pc	270	324	386	448	488	506	499	468	414	348	286	256
	Po	115	144	177	211	233	241	238	222	192	157	123	108
40°	Pc	200	265	346	432	492	520	509	461	383	295	219	184
	Po	80	112	153	199	231	245	240	215	173	128	89	72
50°	Pc	125	196	293	404	488	529	513	445	340	231	144	108
	Po	43	76	123	181	224	245	237	202	148	93	52	35
60°	Pc	45	119	227	365	480	539	515	419	284	157	67	35
	Po	10	39	89	156	213	241	230	183	116	55	17	5
70°	Pc	0	31	150	318	477	577	535	390	217	74	0	0
	Po	0	7	49	125	200	243	226	160	79	18	0	0

Pc = daily totals of photosynthesis on a clear day; Po = daily totals of photosynthesis on an overcast day.

1. For South Lat. see Annex 2.

N.B. Gross assimilation at places between latitudes given should be interpolated e.g. gross assimilation on a clear day at 14° N. Lat. on 15 January is $381 - 4/10 \times (381 - 331) = 361$ kg CH_2O per hectare per day.

Annex 2.

Daily total incoming visible (400-700 nm) radiation in 10^6 J/m^2 for a standard clear day. The month when used for Sout Lat. is given between brackets, e.g. 20° South Lat. in August the radiation is: 11.73×10^6 J/m^2. (Goudriaan & van Laar, 1978).

North Lat.	15 Jan. (July)	15 Feb. (Aug.)	15 Mar. (Sept.)	15 Apr. (Oct.)	15 May (Nov.)	15 June (Dec.)	15 July (Jan.)	15 Aug. (Feb.)	15 Sept. (Mar.)	15 Oct. (Apr.)	15 Nov. (May)	15 Dec. (June)
0°	14.00	14.72	15.16	14.95	14.26	13.77	13.97	14.68	15.17	14.94	14.23	13.77
10°	12.17	13.44	14.67	15.43	15.48	15.34	15.41	15.51	15.09	13.95	12.55	11.80
20°	10.00	11.73	13.68	15.38	16.22	16.47	16.38	15.84	14.48	12.49	10.50	9.53
30°	7.59	9.65	12.21	14.81	16.45	17.12	16.87	15.64	13.37	10.62	8.17	7.05
40°	5.06	7.30	10.32	13.74	16.18	17.29	16.86	14.93	11.80	8.40	5.67	4.50
50°	2.61	4.80	8.07	12.20	15.44	17.01	16.41	13.75	9.80	5.96	3.19	2.11
60°	0.61	2.34	5.58	10.25	14.31	16.43	15.60	12.15	7.47	3.42	1.00	0.32
70°	0.00	0.38	2.98	7.99	13.06	16.09	14.85	10.28	4.89	1.10	0.00	0.00
80°	0.00	0.00	0.63	5.66	12.87	16.72	15.24	8.81	2.22	0.00	0.00	0.00
90°	0.00	0.00	0.00	4.86	13.02	16.99	15.47	8.73	0.19	0.00	0.00	0.00

N.B. Radiation at places between latitudes given should be interpolated e.g. radiation at 52° N.Lat. on 15 Juni is $17.01 - 2/10 \times (17.01 - 16.43) = 16.89 \times 10^6$ J m^{-2}.

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