Agronomic and ecological studies on the potato (*Solanum tuberosum* L.) in Southwest China. Seed and crop management

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Agronomic and ecological studies on the potato (*Solanum tuberosum* L.) in Southwest China. Seed and crop management

He Wei

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ter verkrijging van de graad van doctor
op gezag van de rector magnificus
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He Wei

Agronomic and ecological studies on the potato (*Solanum tuberosum* L.)
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Propositions

1. Designing more optimal seed potato flows in Southwest China can substantially contribute to yield improvement of potato.
   This thesis

2. The relatively weak competition in the current potato-maize intercropping system in Southwest China suggests that planting dates of the two species can be more closely synchronised and the density of both species can be increased, to achieve higher yields.
   This thesis

3. Any factor which leads to increased radiation interception by a potato crop is likely to increase its biological yield commensurately.
   Scott & Wilcockson, 1978. In: P.M. Harris (Ed.), The potato crop. The scientific basis for improvement. Chapman & Hall, London, pp. 678-704.

4. In China, sweet potato is a more versatile food source than Irish potato.

5. Technology should be more stimulated than science.

6. One of the most unfortunate things in human relations is misunderstanding. It is even worse when people are unaware of it.

7. A person from the East generally understands more the way of life in the West than a person from the West understands the way of life in the East.

8. Human intelligence is still poorly understood. This lack of understanding greatly impedes exploitation of human resources.

9. The more time spent in considering to do something, the more likely the one would become convinced to give it up.

Stellingen, horend bij het proefschrift van He Wei:
Agronomic and ecological studies on the potato (*Solanum tuberosum* L.)
in Southwest China. Seed and crop management

Wageningen, 9 december 1997

中国西南山区马铃薯
(*Solanum tuberosum* L.)
生态农学研究

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ABSTRACT

He Wei, 1997. Agronomic and ecological studies on the potato (*Solanum tuberosum* L.) in Southwest China. Seed and crop management. Doctoral thesis, Wageningen Agricultural University, Wageningen, The Netherlands, X+135 pp., English and Dutch summaries.

Potato is an important crop in sub-tropical Southwest China, where it is double-cropped in diverse ecological systems. Yields are higher at higher elevation. Spring crops show higher yields but lower light use efficiencies than autumn crops, especially at higher altitudes. The gaps between the actual and potential yields are mainly due to insufficient utilization of radiation and low light use efficiency of the actual crops.

Earlier planting in spring increased yield at 500 m asl. At 1200 m asl effects of planting time on yield were absent. In autumn, these effects were generally absent at all elevations, although plant stands were consistently and often severely reduced by early planting.

For spring crops, seed tubers should be older at lower altitude and younger at higher altitude than those commonly used. For autumn crops, seed tubers should be relatively old, both at low and high altitudes. Manipulation of seed sources can be done through selecting progenies of previous spring or autumn crops produced either at low or high altitudes, or from early harvest of the seed crop. The observed long-term after-effects of seed origins may have been associated with (unknown) effects on seed health.

Heavier seed tubers gave higher yields in all conditions in the range from 20 to 124 g. When numbers of sprouts were set equal per unit area, the effect of weight of seed tubers on final tuber yield per unit area was absent. Tuber numbers per stem increased as seed tuber weight decreased when the seed tubers used were young.

Cutting of seed tubers generally promoted plant emergence and increased stem numbers per plant in comparison with the whole seed tuber, per unit seed weight planted; cutting also spread a wilting disease probably mainly caused by *Pseudomonas solanacearum*, especially at lower altitude.

The results of seed or plant density in combination with the effects of planting time, seed tuber weight and intercropping showed that a denser spacing up to 10 seed tubers/m^2 consistently increased tuber yields. Plant stand was reduced by higher seed density in most experiments, but not at the expense of yield.

Higher total yield of combined potato and maize was obtained when one row of maize was alternated with two rows of potato than when two rows of maize were alternated with two rows of potato. Results suggest that planting dates of the two species can be more closely synchronized in the current intercropping system, to achieve a more efficient use of space and time.

Viruses, late blight and bacterial wilt caused varying degrees of yield loss in Sichuan, and they were closely associated with a number of biotic, abiotic and agronomic factors. Varietal resistances to the diseases, especially to late blight and bacterial wilt, were found. Parasitic nematodes were found in variable population densities. Defoliation by 28-spot beetle sometimes was severe.

This thesis provides some basic information on crop production and agronomic measures required for further crop improvement in this complex agro-ecological region.

Key words: *Solanum tuberosum* L., potential yield, light use efficiency, planting time, seed supply, seed age, seed weight, seed density, seed cutting, intercropping, disease, pest, Southwest China.

Preface

This thesis describes the main results from a PhD programme initiated in April 1993. Some earlier work is also included. The field work comprised an intensive period (1994-1995) of experiments in Sichuan. The experiments were based on my previous experience and surveys on the crop and on communications with researchers, agro-technicians and farmers. The thesis was written in Wageningen from March to December 1997. I enjoyed this "down-to-earth" work, although it was sometimes painstaking especially when I encountered unexpected difficulties during the implementation of the experiments. I would like to take this opportunity to express my sincere gratitude to the following persons and organizations that made my study possible and pleasant.

First of all, I am grateful to Mr. Ir. Jan C. Hesen for kindly introducing and recommending a study at the Wageningen Agricultural University. We had a pleasant interaction back in 1990 when Mr. Hesen (as senior consultant of FAO) visited Sichuan, China, with other scientists and economists from various international institutions, to advise on the project on potato and sweet potato processing. Mr. Hesen also helped me later to allocate the necessary financial support from the Calbee Foods Co. Ltd., to which I am also sincerely indebted. Dear Sir, thank you very much indeed for your continuous concern and support. I would like to thank your wife and your other family members and friends for their hospitality. Your cosmopolitanism is impressive. Your old-fashioned manner of gentleness and your sense of humour are also greatly appreciated.

My sincere gratitude goes to my *promotor* Prof. Dr. Paul C. Struik for his best academic advices, his continuous concern and interest, communication and visits during the field work in China, and especially during the writing-up of the thesis. The thesis could not be in the current shape without his invaluable knowledge, ideas, efficiency, responsibilities and efforts.

I also thank the Crops Institute and the Sichuan Academy of Agricultural Sciences (SAAS) for permitting me to study abroad and providing me with the research budget. Sincere gratitudes are due to the Wageningen Agricultural University for granting me a fellowship and its Department of Agronomy for providing facilities. Special thanks are due to Prof. Zhu Zhonglin and Li Yuejian, the President and Assistant-President of SAAS, respectively, and to Prof. Huang Gang, the Director of the Crops Institute of SAAS, for their concern and support throughout the long period of my research. I am particularly grateful to Prof. Tan Zhonghe for his continuous support and supervision of my thesis work in China. I am also

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Finally, I especially thank my wife You Misha and our son He Shimeng for their love, understanding, patience and support all the way throughout my study and stay in The Netherlands, and my parents, brothers and sisters (in-law alike), relatives and the other friends for their great deal of concern and help.

He Wei

Wageningen, November, 1997

Contents

Chapter 1

General introduction

The potato (*Solanum tuberosum* L.) has become a crop of worldwide importance, ranking fourth in production after wheat, rice and maize. Its distribution over the world started since it was introduced to Europe in the sixteenth century from its origin, the Andes in South America (FAO, 1991; Hawkes, 1992). Potato was introduced into China over 300 years ago (Hawkes, 1992) and was rapidly distributed to nearly every corner of this country (Ye, 1987) with a current annual hectarage of around 3 million ha (FAO, 1992) to 3.2 million ha (Anonymous, 1995). In sub-tropical Southwest China, potato is grown at different altitudes and in different seasons. This area covers about 40% of the total growing area in the country (Wang, 1994). In the Sichuan province alone, 517,400 ha of potato was planted in 1992, of which about 71% was planted in spring and 29% in autumn. Potato is mostly grown in mountainous areas ranging from 400 to 3,000 m above sea level but concentrating around 1,000 m asl in the eastern basin area of Sichuan. It is difficult to estimate the average yield per hectare due to the large variation, but generally it is much lower than yields in temperate regions. Yet, potato is an important crop because the other staple food crops will suffer even more from the different constraints encountered in some areas. Besides, the potential yields at higher altitudes in the tropics are close to those in the temperate regions (Beukema and Van der Zaag, 1990).

The Sichuan province can be roughly divided into the west and east parts. The west part consists of scarcely populated highlands whereas the east region is a hilly basin with a dense population. The potato is relatively suitable to be grown in the mountain area where yields of other important crops are low due to the relatively low temperature or lack of irrigation. The hectarage of arable land has been decreasing in recent years because of the fast urbanization. The multiple crop index (number of cropping seasons per unit land area per year) and overall technical input increased gradually.

The spring potato crop is planted between January and April and harvested between May and September depending on the altitude: the higher the altitude, the later the planting and harvesting dates. In the highland only one crop is grown per year. The autumn crop is planted between late August and mid-September and harvested between late November and early December at intermediate altitudes; a third (winter) crop is grown at lower altitudes during November-February to supply the urban market. Its tuber yield is low and it hardly contributes to the total annual potato production. Potato is intercropped with maize in about 70% of the total potato growing area in the spring (main) season. The tubers harvested are stored inside the farmer's house at room temperatures.

Formulation of the problem

Potato in China is a low input crop. It is traditionally grown by (small) farmers. The reasons why yields are low are partly unknown. The dominant yield limiting factors or their relative importance are not the same for the different locations, altitudes or seasons, but depend on the specific ecological conditions and cultural practices. R & D on the crop in the past has given priority to breeding varieties mainly for higher yield, better tuber shape and disease resistance. Little was done on crop physiology, production ecology and agronomy in the area compared with activities in the temperate regions (cf. Ewing and Struik, 1992) and in the tropics (cf. Midmore, 1992). The history of potato yield improvement over the last 40 years in The Netherlands and even in Europe indicates that this achievement can mainly be attributed to improved agronomic measures (e.g. high quality seed), and not to breeding (Vos, 1992; Struik et al., 1997). This may also be true for other parts of the world.

The conditions in Sichuan are not favourable for growing potatoes due to low average solar radiation and high temperature at lower altitudes, high concentrated rainfall, disease and pest pressure, nutrient shortage, poor storage facilities, etc. A very important limiting factor is seed quality; especially the physiological status (either too young or too old) and health status (mainly virus infection) are suboptimal; seed quality may interact with nearly all cultural measures. Therefore, it is desirable to have a systematic study on potato growth and yield under the diverse ecological conditions in Sichuan. An analysis of the yield gap is useful to explicitly identify different stress factors in the different ecological situations; in addition an analysis of the seed quality situation and of effects of cropping practices related to seed management is relevant. Such analyses can help to evaluate cropping practices under the different conditions, and to gain better and more specific understanding of the production systems. Suggestions to narrow the current gap between the potential yield and the actual yield can then be made.

The objectives of the study

The objectives of this study were:

1) To analyze in detail and describe in a quantitative way the growth characteristics of potato

grown at different altitudes both for the spring and the autumn crops in Southwest China, mainly in Sichuan.

2) To investigate and evaluate quantitatively the effects of seed quality (age, weight, pre-sprouting treatment, and health), and the effects of cultural practices related to seed management (planting date, spacing, intercropping, cutting, seed flow) for different cultivars, under the different conditions in the double cropping area.

This study will contribute to a better understanding of the crop behaviour in the area and the results gained in the study can serve as a basis for further crop improvement both by developing better production systems and better breeding strategies.

Approach of the study

A large number of elevations is evaluated in field experiments for their potential yields of potato both in the spring and autumn seasons using local seed of suboptimal quality. Detailed studies are only carried out at three typical elevations and in the two main seasons.

A yield gap analysis is carried out based on a simple growth model, to differentiate and characterize the crop production under the different ecological conditions and the major yield limiting factors are identified in relation to canopy cover and light use efficiency, taking into account environment and physiological age of the seed used.

At three elevations and in the two different growing seasons (spring and autumn) a large number of small field experiments was carried out in several years. Dominant factors under investigation were various aspects of seed quality and seed manipulation.

Data recorded included weather data, and data on canopy development, dry matter accumulation and dry matter allocation, stem number, tuber number, and tuber dry matter content. This allowed a quantitative analysis of the abiotic and biotic causes of the relatively very low yields and poor quality. Furthermore, the effects of seed-related cultural practices were evaluated.

Outline of the thesis

The "potential" yields at different altitudes and in both spring and autumn seasons using local seeds are assessed using a simple plant growth model; these are compared with attainable and experimental (actual) yields, to identify and analyze the growth and yield limiting factors and to set a basis for rest of the studies (Chapter 2). The effects of planting times are studied, in combination with seed density and naturally confounded with effects of physiological age at three different altitudes and in both seasons, to identify the optimal planting time under the different cropping conditions (Chapter 3). The role of seed tuber origin, so typical for double cropping regions, is elaborately described and evaluated by selecting various seed flows differing in altitude, season and frequency of multiplication (Chapter 4). Then, more specific aspects of seed quality are evaluated; firstly, effects of seed tuber weight are evaluated in combination with other agronomic measures and with ecological conditions, to understand the specific effects on growth and yield at the same seed or sprout density (Chapter 5); secondly, cutting of seed tubers is tested as a tool to break dormancy or apical dominance and thus to produce more stems per unit weight of seed (Chapter 6). Since the dominant cropping system in the area is intercropping of maize and potato, effects of row-ratios and plant density in potato-maize intercropping systems are studied on yield and the competition, to achieve a more efficient use of space and time (Chapter 7). The most severe biological stresses on crop production, i.e. the main diseases and pests as affected by environment are preliminarily described, based on a series of field surveys, phytopathological tests and some experiments (Chapter 8). Finally, the general discussion integrates the previous chapters by highlighting the main results and implications of the project (Chapter 9).

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Chapter 2

Potential and actual yields of potato at different elevations and in different seasons in sub-tropical Southwest China

He Wei[1], Paul C. Struik[2], Wang Jun[3] and Zhang Xingduan[4]

Summary

Potential potato yields of 9 spring and 5 autumn seasons at elevations ranging from 150 to 2,650 m asl in sub-tropical China were assessed by a simple growth model and compared with attainable and experimental (actual) yields using local seeds. Generally, both potential and actual yields were higher at higher elevation because of cooler temperatures and longer growing periods. The spring crops showed higher potential and actual yields but had lower light use efficiencies than the autumn crops, especially at higher altitudes. Specific relationships were given for relevant potential and attainable yields over altitudes and seasons. Light use efficiency declined with ascending elevation during the autumn season. The ratio actual: potential yields (range 0.25-0.56) and the ratio actual: potential light use efficiency (range 0.34-0.70) were low because of drought stress, hot temperatures in the low elevations, presence of diseases and pests, low quality seed, and lack of adequate fertilization.

Key words: Yield potential, yield gap, growth model, light use efficiency, *Solanum tuberosum* L., potato.

Introduction

The potato (*Solanum tuberosum* L.) was introduced into China over 300 years ago and was rapidly distributed to nearly every corner of the country (Ye, 1987). The annual growing area is around 3 million ha (FAO yearbook, 1992) or 3.2 million ha (Anonymous, 1995). There are two main potato growing areas: one in the Southwest (40% of the total area) and another in the North. In the sub-tropical Southwest, the crop is grown in the mountains, where yields of other important crops can be low due to the relatively low temperatures or

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lack of irrigation. Potato can be grown in two seasons per year: the main (spring) season generally is from March to August, and the other (autumn) season is from September to December.

Actual and potential yields. The actual average tuber fresh yields at various elevations and in the two seasons in the area are generally low, ranging between 7 and 15 t/ha, mainly because of poor management of the crop; problems include lack of irrigation, lack of pest and disease control, and poor seed quality (both physiological and health status). However, potential yield is unknown although there are general reports on such aspects (Van der Zaag, 1984; Beukema and Van der Zaag, 1990). Knowledge on the potential yield would allow an assessment of the gaps between potential and attainable yields and between potential and actual yields. With this information, main constraints at different elevations and seasons can be identified and evaluated. Moreover, it is possible to use this information to optimize cultivation techniques and cultivar selection.

For the calculation of the potential yield a simple crop growth model can be used. A model is a simplified representation of a system studied (De Wit, 1993), based on system analysis (Leffelaar, 1993). The model by Van der Zaag (1984) has been proven to be reliable and easy to use (Van der Zaag, 1984; Demagante and Vander Zaag, 1988; Beukema and Van der Zaag, 1990; Hu, 1990; He and Vander Zaag, 1991).

Potato cropping systems in Southwest China. The seed flow from season to season and from elevation to elevation in the area is shown schematically in Fig. 1.

At and below around 500 m asl, the seed is not kept due to high temperature and has to be imported around November every year. The seed comes from the spring season's harvest at higher elevations. The seed is planted in December to January, and harvested in April to May before maize or rice is planted at the same field. An autumn crop of potato is rare at this elevation. A winter crop starting from December to March is sporadically grown at the elevations or at higher elevations beyond 500 m asl in the southern part of the sub-tropics (Wang, 1980).

At around 1000 m asl, the spring and autumn crops are widely planted and normally intercropped with maize, which is planted about 60 days later than potato. The major problem in this cropping system is that the growing season is too short for seed with a long dormancy, when seed from the same altitude is passed on from one season to the next (Malik

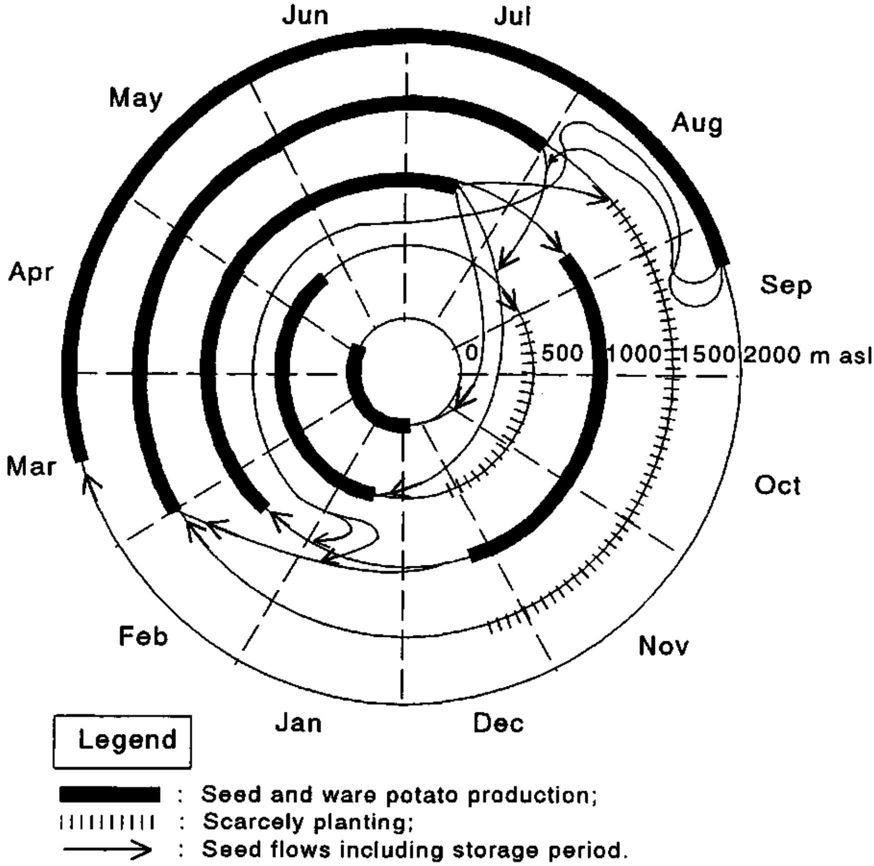

Figure 1. Cultivation of seed and ware potatoes and movement of seed potato from season to season and from elevation to elevation in sub-tropical Southwest China.

et al., 1991), or seed will be too old when it is stored for an entire growing season for local planting in the next growing season. Even the locally bred and relatively early variety CY56 has this problem. Moreover, farmers usually cut seeds into pieces prior to planting to break tuber dormancy and apical dominance, otherwise one seed tuber will produce only slightly more than one main stem on average irrespective of tuber size when stored for less than three months prior to planting.

Import of seed from abroad for direct mass production has never been practised and is even only seldom done from neighbouring areas due to the cost and difficulty of transport. In some cases, the autumn crop gives higher yields than the spring crop in the east of Sichuan, whereas in the West the trend is the opposite at similar elevation of 1000 m asl. This is probably because in the east the seed used for the autumn crop is derived from the preceding spring crop which in turn comes from the previous spring crop rather than the autumn crop, so that the growth vigour of such seed is higher than that derived from either one season after another or every other season. This situation is different from the one reported by Fahem and Haverkort (1988) for Tunisia, where seed for the spring is imported from the higher latitude and seed for autumn is derived from the locally multiplied previous spring crop. Sichuan farmers at 1000 m asl seldom import seed from higher elevations because the majority of the seed potato is produced at 1000 m asl and exported to other areas, especially at lower elevations.

At 1,500 m asl and above, in most cases only one potato crop is planted a year with about 70% of monocropping. At 1,500 m asl seed is kept for the next season or brought from lower elevations depending on dormancy and earliness of cultivars used. At elevations between 1,500 and 3,000 m asl, seed is simply kept for the next season or brought from higher elevations within the range. Over the past 10 to 20 years rapidly multiplicated cuttings and true potato seed (some of them introduced from the International Potato Center) have proved to be important alternative propagules in seed potato production systems.

The general trend of the potato cropping system in this subtropical area from lowland to highland described above is similar in a broad sense to that from equator to high latitude (50° N), which is described systematically by Haverkort (1990), although the pattern of cropping systems in terms of growing seasons in our study is more northward than in his description and in what et al. (1996) have modelled for different latitudes and altitudes, due to the cool and dull weather prevailing in Southwest China.

Materials and Methods

A series of experiments on potato germplasm evaluation was conducted at different elevations and in different seasons (Table 1). Data on canopy development (Burstall and Harris, 1983; Haverkort et al., 1991) were used to estimate the potential yields and to make comparisons with the actual yields. Calculated or attainable yields were based on the actual canopy development whereas canopy covers for potential crops were estimated to be 10% higher than the actual crops over most of the growing season following the procedure of Beukema and Van der Zaag (1990) and considering that a full canopy cover is hardly reached at altitudes below 1000 m asl due to hot weather, whereas above 1000 m asl it is reached for a short period of time only with current cultural practices. Actual (experimental) yields were the

Table 1. Potential and actual yields of different altitudes and seasons.

Site, Altitude (m asl), Latitude (°N)	Season	Potential yield (A) (t/ha)	Experimental yield (B) (t/ha)	Ratio of B/A
Canlubang, 150, 14	Spring, Dec-Mar	25	14	0.56
Chengdu, 500, 31	Spring, Jan-Jun	30	14	0.47
" " "	Autumn, Sep-Nov	23	12	0.52
Liangping, 750, 31	Spring, Feb-Jul	38	18	0.47
" " "	Autumn, Sep-Nov	25	14	0.56
Pengzhou, 1200, 31	Spring, Feb-Jul	49	19	0.39
" " "	Autumn, Sep-Nov	29	15	0.52
Chengqou, 1700, 31	Spring, Mar-Jul	67	17	0.25
Miangning, 2078, 28	Spring, Mar-Aug	86	32	0.37
Huizhe, 2110, 28	Spring, Mar-Aug	94	42	0.45
" " "	Autumn, Jul-Sep	52	24	0.46
Daqiao, 2580, 28	Spring, Apr-Sep	88	41	0.47
" " "	Autumn, Jul-Oct	54	19	0.35
Ninglang, 2650, 28	Spring, Apr-Sep	88	49	0.56
Range: 150-2650, 14-31	-	23-94	12-49	0.25-0.56

averages over several locally adapted clones and cultivars evaluated at the sites and the highest yield came from the best single variety after calculating the average of all replications.

Similar as in the models (Van der Zaag, 1984; Beukema and Van der Zaag, 1990), the potential growth rate was calculated as:

$$P = F \cdot P_o + (1-F) \cdot P_c \quad (1)$$

where P = daily gross dry matter production (kg CH_2O/ha/day) and F = fraction of the day the sky is overcast, as postulated by De Wit (1965) and revised by Goudriaan and Van Laar (1978) in estimating (interpolating) daily gross assimilation of P_c (clear day) and P_o (overcast) for different latitudes and months of the year. F can be calculated by:

$$F = (H_c - H_a)/(0.8 * H_c) \quad (2)$$

where H_c = the daily total incoming visible radiation (400-700 nm) on a standard clear day (in MJ/m^2), which is about half the global radiation (photosynthetically active radiation, i.e. PAR), and H_a = actual daily radiation (also in MJ/m^2).

The net P (P_{net}) is the product of P and a factor (ranging from 0.5 to 0.8) which reflects plant respiration (both maintenance and growth respiration) affected by temperature (Van der Zaag, 1984). The dry matter production (kg CH_2O/ha) per month is calculated by multiplying the average Pnet with the average percentage of light interception which is assumed to be equivalent to canopy cover (%) and by the number of days (Beukema and Van der Zaag, 1990; Haverkort et al., 1991). Estimation of calculated or attainable yield is identical to the above mentioned method but with actual canopy cover data.

Cumulative absorbed PAR can be determined by (Spitters, 1987):

$$\sum PAR_{abs} = \sum (1-\rho_c) \cdot PAR_{int} \quad (3)$$

where ρ_c = crop reflection coefficient for PAR set to 0.08; PAR_{int} = intercepted PAR/m^2. Use efficiency of absorbed light (LUE, in g/MJ) was therefore calculated by:

$$LUE = W / \sum (PAR_{abs}) \quad (4)$$

where W = plant dry weight (g/m^2).

Harvest index is estimated to be 0.75 for the hot area (< 1,000 m asl) and 0.80 for the sites above 1,000 m asl. The prevailing solar radiation intensity is high, which enables a large proportion of dry matter to be partitioned to the tubers despite the warm weather.

Results and Discussion

Agro-climatology of the zone. For potato production, the climate in the area has some negative characteristics: **a)**. unfavourably warm temperatures with a yearly average of 16-18°C in the lowlands, which is several degrees higher than that of other regions at the same latitude because of the presence of the well-known 'Qinling Mountains' in the north of the region, which protect the area against the penetration of cold northern winds; **b)**. shortage of sunshine (average 2.7 to 3.8 hours per day) and low annual solar radiation (average 9.2 to 10.8 MJ/m^2/day, global values), due to heavy cloud covers in the lowlands. The strong evapotranspiration and consequently accumulated cloudiness resulting from the convection of cold and warm airs along the margins of the basin are supposed to account for those low figures; and **c).** small day and night temperature difference. There are also positive characteristics: **a).** favourably cool temperatures in the highlands; **b).** a high average annual global solar radiation of 11 to 21 $MJ/m^2/day$ in the highlands. The annual rainfall in the area is 1,000-1,200 mm but most of it is concentrated in June, July and August; in the early stages of spring and later stages of autumn potato crops may suffer from drought.

Yield. Yields were generally higher for spring crops than for autumn crops. The potential and attainable tuber yields generally increased with higher altitudes in both seasons but particularly so in the main seasons until a certain altitude (around 2,000 m asl) beyond which yields tended to level off (Fig. 2A & 2B). This increase can probably be mainly attributed to the lower air temperature hence longer growing period and healthier seed tubers stored in the higher than in the lower elevations. The experimental yields were also increasing with altitudes. The "highest" tuber yields were relatively low, and the potential and attainable yields levelled off at elevations over 2,500 m asl. The findings were mainly caused by the lower total PAR absorbed at those elevations (Fig. 2C), which in turn can be accounted for by the suboptimal temperature that limited the growing period.

There was some scatter in the relation between experimental yield and altitude, e.g. a relatively low yield occurred in the site at 1700 m asl which may be due to the very heavy clay soil that hampered tuber bulking. Some of the scatter can also be due to the complex topography, which determines exposure to the sun, and thereby temperature and solar radiation. Despite this scatter, the general trend still showed how important an average lower temperature is for higher yield of potato. This temperature effect is further enhanced by the association between cooler conditions and more light.

In the mid elevations and above, actual tuber yield can come close to the potential yield. In one case it even surpassed its potential reaching a value of 98 t/ha (!) (Fig. 2A) at average plot basis which is comparable with the potential 100 t/ha in West Europe (Beukema and Van der Zaag, 1990). The tuber dry matter contents were measured to be generally from 18% to 21%. The results showed that there is much yield potential that remarkably exceeds current production in particular for the spring but also for the autumn crops. The gaps between potential and actual can partly be closed.

The ratios of experimental over potential yield were ranging from 0.25 to 0.56 (Table 1).

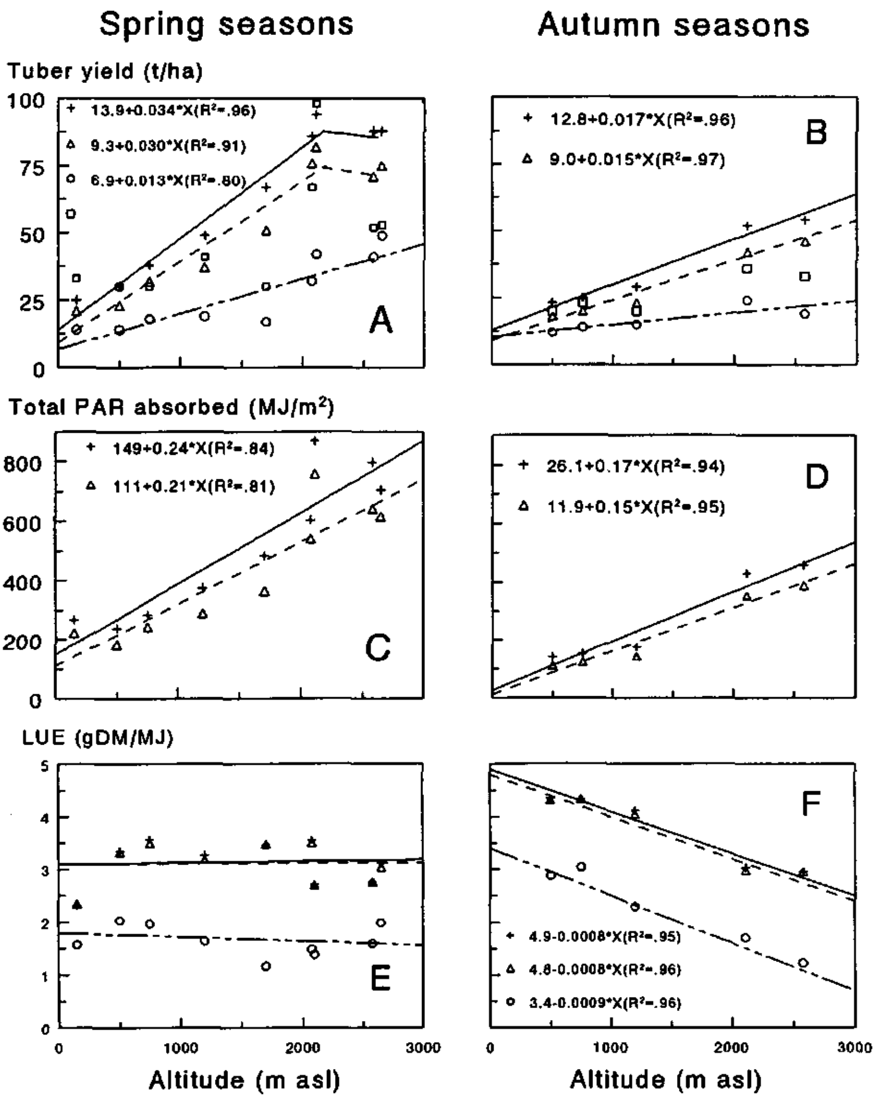

Figure 2. Assessment of potential and attainable tuber fresh yield (A & B), total absorbed photosynthetically active radiation (PAR) (C & D) and light use efficiency (LUE) (E & F) over altitudes and seasons, in comparison with those of the experimental ones. The correlations given are significant at $P<0.01$ or $P<0.001$ levels. + = potential; △ = attainable; ○ = experimental; and □ = the highest values.

They were generally lower for spring crops (average 0.44) than for the autumn crops (average 0.48, Table 1). These values are high, compared with the data (0.13 to 0.46) provided by Van der Zaag (1984) who probably used average yield at a larger area basis and from farmers' fields. The ratio can serve as an indicator of the quality of the cultural management of the crop.

PAR intercepted. Yields in the autumn seasons were lower than in the spring season. This can partly be attributed to the shorter growing period hence less total PAR absorbed by the plants than in the spring seasons (Fig. 2C & 2D). Another reason for the lower PAR intercepted is that seed tubers have not fully passed the seed dormancy in most cases (even with cut seed) when planted in autumn. Moreover, the heavy rain and heat at planting time (Aug-Sep) frequently delay the planting and may reduce plant survival by activating soil pathogens and pests. Therefore, the current autumn crop cannot intercept to the full extent the available solar radiation during the season.

Light use efficiency (LUE). LUEs in the autumn seasons were on average higher (potential from 2.95 to 4.35; experimental from 1.22 to 3.04 g DM/MJ PAR) than in the spring seasons (potential from 2.31 to 3.57; experimental from 1.16 to 2.03 g DM/MJ PAR) (Fig. 2E & 2F) because of the lower temperature and lower solar radiation levels in the autumn. The trend is opposite to the finding in Tunisia (Fahem and Haverkort, 1988) where temperature in autumn is higher than in spring. LUEs in the spring seasons were not affected by elevation. Absolute values for spring crops were comparable to the average LUEs of 2.30 to 2.57 under temperate conditions (Spitters, 1987), especially when we consider that Spitters (1987) stated that seasonal variation in LUE may exist because of variation in environmental conditions, and in morphology and physiology of the crop. In the autumn seasons, the LUEs decreased linearly with an increase in elevation (Fig. 2E), probably because of the lower average solar radiation in the lower elevations. Yet, the yields were higher in the higher elevations, stressing the importance of a long duration of canopy cover.

The variation in LUEs was in agreement with the results reported in the literature that the light use efficiency correlated negatively with light intensity (Kooman and Rabbinge, 1995) but not with latitude (Haverkort and Harris, 1987).

Production. The results stressed the importance of two parameters, i.e. the cumulative amount of light absorbed by the foliage and the light use efficiency. The yield of fresh harvestable product can be described by the equation for potato (as well as other crops') production:

$$FTW\ (g/m^2) = \sum PAR_{abs}(MJ/m^2)\cdot LUE(g/MJ)\cdot HI(g/g)\cdot 1/D(g/g) \qquad (5)$$

where FTW means fresh tuber weight (g/m^2); HI = harvest index (g/g); D = dry matter content of tuber or harvestable part (g dm/g fresh). Potential and attainable values (for yield, LUE and total PAR_{abs}) were closely correlated (Table 2). The experimental yields were relatively weakly correlated with potential and attainable yields (Table 2) which illustrates the potential for further increasing yield across the elevations. LUEs in the main season did not show significant correlations except for the relation between potential LUE and attainable LUE. In the autumn season (negative or positive) correlations were significant for the relations between each pair of altitude, potential, attainable, and experimental growth (Table 2 and Fig. 2F). The discrepancy between LUEs of the two seasons illustrates large differences among conditions and the variation in response of the crop to them.

Table 2. Correlation coefficients between altitude (al), potential (pt), attainable (at), and experimental (ex) yield, total PAR absorbed by plants, and LUE over seasons. *, **, *** indicate significant correlation at $P<0.05$, 0.01, and 0.001 levels, respectively (n=9, for spring; n=5, for autumn).

	Main (spring) season			Autumn season		
Fresh tuber yield (t/ha)						
	pt	at	ex	pt	at	ex
al	0.97***	0.94***	0.89**	0.98**	0.99**	0.84
pt		0.99***	0.89**		0.99***	0.90*
at			0.90***			0.88
Total PAR absorbed (MJ/m²)						
al	0.92***	0.90***	0.90***	0.97**	0.97**	0.97**
pt		0.99***	0.99***		0.99***	0.99***
LUE (g DM/MJ)						
al	0.05	0.03	-0.25	-0.97**	-0.97**	-0.98**
pt		0.99***	0.18		0.99***	0.95*
at			0.13			0.95*

Conclusions

1. Elevations strongly differ in actual and potential yields in both seasons studied.

2. The gaps between the actual and potential yield are mainly due to relatively long periods

of growth in which canopy cover is not sufficient, low light use efficiency (compared to its high potential) of the actual crops, which in turn can be caused by drought stress and hot temperatures in the low elevations, lack of fertilization, and presence of diseases and pests.

3. The low yields of the autumn crops can be attributed to the short growing periods resulting in lower accumulated light interception.

4. The effects of physiological age of the seed tubers on yield deserve attention as they may explain a considerable proportion of the variation in yield and in yield gap over seasons and elevations.

5. The differences in the ratios of actual (experimental) over potential yields between the main crops (average 0.44) and the autumn crops (average 0.48) can probably be attributed to the higher actual LUE of the autumn crop (average 2.23) compared to the one of the spring crop (average 1.65).

6. LUE responds differently to altitude in spring and autumn crops. In spring crops, it is more or less constant. In autumn crops, it decreases with increasing altitude, associated with increasing light intensities.

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Chapter 3

Planting time and seed density effects on potato in subtropical China

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Summary

Planting times of potato in subtropical China vary and are often not optimal; their effects were studied in association with those of plant density. The research programme included 10 trials at three elevations (500, 750, 1200 m asl) in the spring and autumn seasons of two years with several contrasting varieties and different seed origins. Earlier planting in spring increased yield at 500 m asl. This effect was associated with better light use efficiency, higher rates of photosynthesis, and more tubers per plant. At 750 m asl the effects of planting time in spring were opposite: later planting increased yield. At 1200 m asl effects on yield were absent. Effects of planting time in autumn on yield were generally absent at all elevations, although plant stands at early planting were consistently and often severely reduced. Denser planting yielded higher per unit area because of larger accumulated canopy cover but lower per plant. Higher density consistently reduced plant stand. Density did not interact with planting time, not even in those experiments in which planting time also affected plant stands.

Optimal planting time depended on the amount of rainfall prior to planting especially in the autumn season, but also on cultivar and dormancy of the seed tubers used. The earlier variety yielded higher than the later variety at low elevation, whereas the later variety yielded more at higher elevation. It is necessary to use cultivars that tuberize early to make better use of the limited growing period at lower elevation. The large variation of dormancy that affects plant growth and yield is caused primarily by differences in accumulated temperature sum (as affected by planting time, elevation of growth and storage, and season), genetics (variety), and their interaction with cultivation techniques.

Key words: Planting time, seed density, tuber yield, light use efficiency, *Solanum tuberosum* L.

Introduction

Potato (*Solanum tuberosum*) is an important crop in Southwest China. It is grown in the

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mountain area in various cropping systems depending on the elevation (He et al., 1997). Potato planting time in the area ranges from December to April for the spring crop and from mid-August to end of September for the autumn crop. Even at similar elevations and with the same cultivar the planting time may differ. Farmers have been recommended to plant their potato crop as early as possible. However, it has been observed that earlier planting will not necessarily result in earlier emergence or higher yield, when seed tubers of suboptimal quality are used. Effects of planting time on plant growth and tuber yield are associated with effects of soil moisture, sub-soil compaction (Allen and Wurr, 1992), and air or soil temperature.

Planting density interacts with planting time and also needs to be evaluated for its effect on growth and yield. In practice, plant density varies, although 45,000 to 52,500 plants/ha is suggested to be the optimum in Northern China (Liu and Men, 1983) and 60,000 plants/ha in the Southern highlands of Sichuan for the sole crop (Ai, 1982), values in the upper range of common densities in temperate regions (Allen and Scott, 1980). However, the recommendation of plant densities should depend on cultivar, seed tuber age, seed tuber size and other factors because they affect the number of main stems per seed tuber. A lot is known on effects of plant or stem density in relation to other factors, especially seed tuber status and size, under temperate conditions (Allen and Scott, 1980; Allen and Wurr, 1992). Vander Zaag et al. (1990) made a comparison of spacing of potato between two contrasting environments (temperate and tropics) and suggested that further experiments need to be done with a range of cultivars at intermediate environments.

So, more knowledge is required on the effects of planting time in interaction with plant density, cultivar and seed origin for the different seasons and elevations, and to identify optimal combinations in Southwest China. To provide a scientific basis for this, ten experiments were carried out under different conditions.

Materials and Methods

The 10 factorial trials included two to three planting dates, several varieties, and three plant densities arranged in a split-plot design, simulating a two-factor experiment with main-plot factor as a combination of two original factors planting date and variety, and the subplot factor density, in three replications. Experiments were carried out at three different elevations, in two seasons and two years (Table 1). In Chengdu autumn 1995 and Pengxian, split-split plot designed experiments were conducted with main factor variety, subplot factor

Table 1. Experimental details and treatments of the Trials 1 to 10.

Location	Chengdu (104.2° E, 30.6° N, 500 m asl)			
Trial	Trial 1	Trial 2	Trial 3	Trial 4
Season/Year	Spring '94	Autumn '94	Spring '95	Autumn '95
Planting dates (day/month)	21/1, 4/2, 18/2	23/8, 7/9, 16/9	20/1, 3/2, 17/2	1/9, 16/9
Seed size (g)				
cv. 813-17 (V_1)	Approx. 40	Approx. 35	29	Approx. 30
cv. CY56 (V_2)	Approx. 45	Approx. 40	32	Approx. 35
Seed origin/source*	Autumn '93 (LP/PX)	Spring '94 (CD)	Autumn '94 (CD/PX)	Spring '95 (CD)
Plant spacing (cm)	20x60, 30x60, 40x60	20x60, 25x60, 35x60	20x60, 30x60, 40x60	20x57, 25x57, 35x57
Gross plot dimension (m)	3.0x3.5	2.4x3.5	2.4x3.0	1.7x3.0
N-application (kg/ha)	70	70	70	70
P_2O_5-application (kg/ha)	50	50	50	50
K_2O-application (kg/ha)	50	50	-	-
Harvest (day/month)	8/6	5/12	9/6	6/12
Location	**Liangping (107.8° E, 30.6° N, 750 m asl)**			
Trial	**Trial 5**	**Trial 6**	**Trial 7**	**Trial 8**
Season/Year	Spring '94	Autumn '94	Spring '95	Autumn '95
Planting dates (day/month)	24/1, 4/2, 19/2	1/9, 10/9	21/1, 12/2, 1/3	25/8, 21/9
Seed size (g)				
cv. 813-17 (V_1)	49	40	48	47
cv. CY56 (V_2)	40	40	48	47
Seed origin/source*	Autumn '93 (LP/PX)	Spring '94 (LP)	Autumn '94 (LP)	Spring '95 (LP)
Plant spacing (cm)	20x60, 30x60, 40x60	20x50, 25x50, 35x50	20x60, 30x60, 40x60	20x50, 25x50, 35x50
Gross plot dimension (m)	3.0x3.3	1.0x3.3	2.4x3.3	1.0x3.3
N-application (kg/ha)	Approx. 40	Approx. 40	Approx. 100	Approx. 100
P_2O_5-application (kg/ha)	Approx. 50	Approx. 50	-	-
K_2O-application (kg/ha)	-	-	-	-
Harvest (day/month)	17/6	24/11	27/6	9/12

To be continued.

Table 1 (continued).

Location	Pengxian (103.7° E, 31.3° N, 1200 m asl)	
Trial	Trial 9	Trial 10
Season/Year	Spring '95	Autumn '95
Planting dates (day/month)	29/1, 26/2	15/8, 23/8, 3/9
Seed size (g)		
cv. CY56s (V_{2s})	47.5	-
cv. CY56a (V_{2a})	41.7	Approx. 22 (cut pieces)
cv. CY56p (V_{2p})	24.5	Approx. 22 (cut pieces)
cv. No.22-2s (V_{3s})	-	Approx. 22 (cut pieces)
Seed origin/source *		
V_{2s}	Spring '94 (PX)	-
V_{2a}	Autumn '94 (PX)	Spring '95 (PX)
V_{2p}	Spring '94 (PX)	Spring '95 (PX)
V_{3s}	-	Spring '95 (PX)
Plant spacing (cm)	27x57	27x57
Gross plot dimension (m)	1.71x3.0	1.71x3.0
N-application (kg/ha)	50	50
P_2O_5-application (kg/ha)	50	50
K_2O-application (kg/ha)	-	-
Harvest (day/month)	19/7	12/12

* The seed came from CD=Chengdu, or LP=Liangping, or PX=Pengxian; V_{2s}, V_{2p}, and V_{3s} followed the seed flow spring '94 - spring '95 - autumn '95; V_{2a} followed the seed flow spring '94 - autumn '94 - spring '95 - autumn '95.

planting date and with (sub-sub plot) or without density treatments. *P1* stands for earliest planting time; *P2* was about 15 and *P3* about 30 days later. Density treatments within spring or autumn seasons were similar, and varied a little across the seasons. *D1* stands for the densest planting (20 cm within-row distance), *D2* for the intermediate spacing (25-30 cm), and *D3* for the widest spacing (35-40 cm). Three cultivars (CY56, 813-17 and No.22-2 in the order of increasing duration of seed dormancy) were used for the experiments. Different seed sources (seed from spring or autumn) and a purple flower mutant CY56p were added in trials 9 and 10. Seed tubers were planted whole except in trial 10 where they were cut before planting (Table 1). The planting dates were chosen in such a way that the extremes enclosed the period normal in practice. In analyzing the results, the data of No.22-2 were discarded because emergence of the plants was very low in autumn 1995 due to poor physiological quality (partly still dormant) of the seed tubers of this variety.

Basic soil characteristics of the experimental sites are shown in Table 2. The soil fertility was intermediate and fertilizers of N and P were applied as commonly recommended. There were two to five periodic destructive harvests followed by the final harvest for most experiments.

Table 2. Basic soil characteristics at the different experimental sites.

Parameter	Chengdu (500 m asl)		Liangping (750 m asl) yellow clay	Pengxian (1200m asl) sandy loam
	Site A purple clay	Site B purple clay		
Total N (%)	0.123	0.129	0.109	0.451
Available N (mg/100 g)	7.16	8.77	7.72	32.5
Total P_2O_5 (%)	0.224	0.282	0.142	0.559
Available P_2O_5 (mg/kg)	190	198	102	101
Total K_2O (%)	1.66	1.83	2.00	2.66
Available K_2O (mg/kg)	301	83	63	242
Total Ca (%)	0.96	0.38	0.11	0.97
Exchangeable Ca (mg/100 g)	345	202	76	280
Total Mg (%)	0.68	0.63	0.42	1.00
Exchangeable Mg (mg/100 g)	22.2	17.9	4.9	20.7
Organic matter (%)	2.59	2.28	1.66	7.09
pH	7.68	5.47	4.22	6.50

Leaf area index (LAI) was assessed by directly measuring the leaf area using a portable area meter (LI-3000, USA). Assessment of the intercepted photosynthetically active radiation (PAR) was done using a Tube Solarimeter & Microvolt Integrator (Delta-T Devices Ltd., UK) placed above and below the canopy (Szeicz et al., 1964). The difference of the measured values (global radiation) times 0.5 (Spitters, 1987) will be the intercepted PAR (PAR_{int}), which after being divided by PAR above the canopy ($I_0(PAR)$), gives the following equation for the fraction of intercepted PAR: $PAR_{int}/I_0(PAR) = 1\text{-}\exp(-k \cdot LAI)$, where k=light extinction coefficient and LAI=leaf area index. K-values were determined by fitting the data with the equation according to Beer's law (Monsi and Saeki, 1953 as cited by Haverkort et al., 1991; see Table 6). Absorbed PAR was determined by: $PAR_{abs} = (1-\rho_c) \cdot PAR_{int}$ (Spitters, 1987), where ρ_c=crop reflection coefficient for PAR often set to 0.08, using global solar radiation data of local meteorological stations. Finally, light use efficiency (LUE) was determined by dividing actual total plant dry matter (including roots) by cumulative PAR_{abs}.

In both autumn seasons in Chengdu 1994 and 1995, plant emergence was incomplete due to some flooding prior to earlier planting in particular. Plots in that part of the experiment were discarded; an alternative CRD statistical procedure was then used and interactions were not analyzed.

Major data collection. Data collected included plant emergence, canopy development measured by a grid (Burstall and Harris, 1983), radiation (and other climatic data) taken from the meteorological stations and measured both in Chengdu and Wanxian, destructive harvest data and periodic LAI, number of (above ground) main stems and branches, photosynthesis rate of whole plants measured by ^{14}C according to the method described by Chen (1983), fresh and dry yield data (drying initially at 105° for 10 minutes followed by drying at 90° C for 15 hours). Field data were recorded at a smallest plot basis.

Computation. Data of the results were analyzed statistically by performing programmes MSTAT-C and COSTAT. The arc sine transformation of percentages was used before analysis, unless the percentage data lay in the ranges of 0% to 30% or 30% to 70% or 70% to 100% (Snedecor and Cochran, 1980).

Results

Characteristics of weather. In Chengdu (500 m asl), air temperature during the spring growing season's main phase April and May was higher in 1994 than in 1995. Rainfall was scarce in both years and irrigation was therefore continued especially in the 1994 spring season. Rainfall generally concentrates during mid June to late August (Fig. 1). Solar radiation was relatively constant during the spring growing season (Fig. 1). In autumn, temperature, radiation and rainfall declined with time, most dramatically in Chengdu. In Liangping (750 m asl), air temperatures were slightly lower than in Chengdu, due to its higher elevation, while rainfall was relatively more scattered over the seasons (Fig. 1). At Dabao Pengxian (1,200 m asl), normally, the annual average air temperature lies between 11.5 and 12°C, with annual average precipitation of 1,200 mm, most of which is concentrated in June, July and August. In winter, air temperature falls to -5 to 0°C, while in summer it increases to over 30°C. Total solar radiation over the seasons was similar (no data recorded) to that of Chengdu and Liangping in the way that hours of sunshine were fewer but instant radiation levels were apparently higher than at the other two locations. However, the favourable lower temperatures ensure a longer growing period and therefore will better suit potato growth and yield.

Growth. In Chengdu spring 1994, seed tubers of cvs. 813-17 and CY56 were not sprouted at planting for the first two planting dates. Emergence was still very low in late March 1994, both in Chengdu and Liangping, due to low growth vigour of the seed (which was not cut and of autumn origin), the low air temperature and the dry conditions. In 1994 the emergence in the experiments in Liangping was about 15 days later than usual.

In Chengdu, field emergence was intensively recorded. Field emergence in Chengdu on April

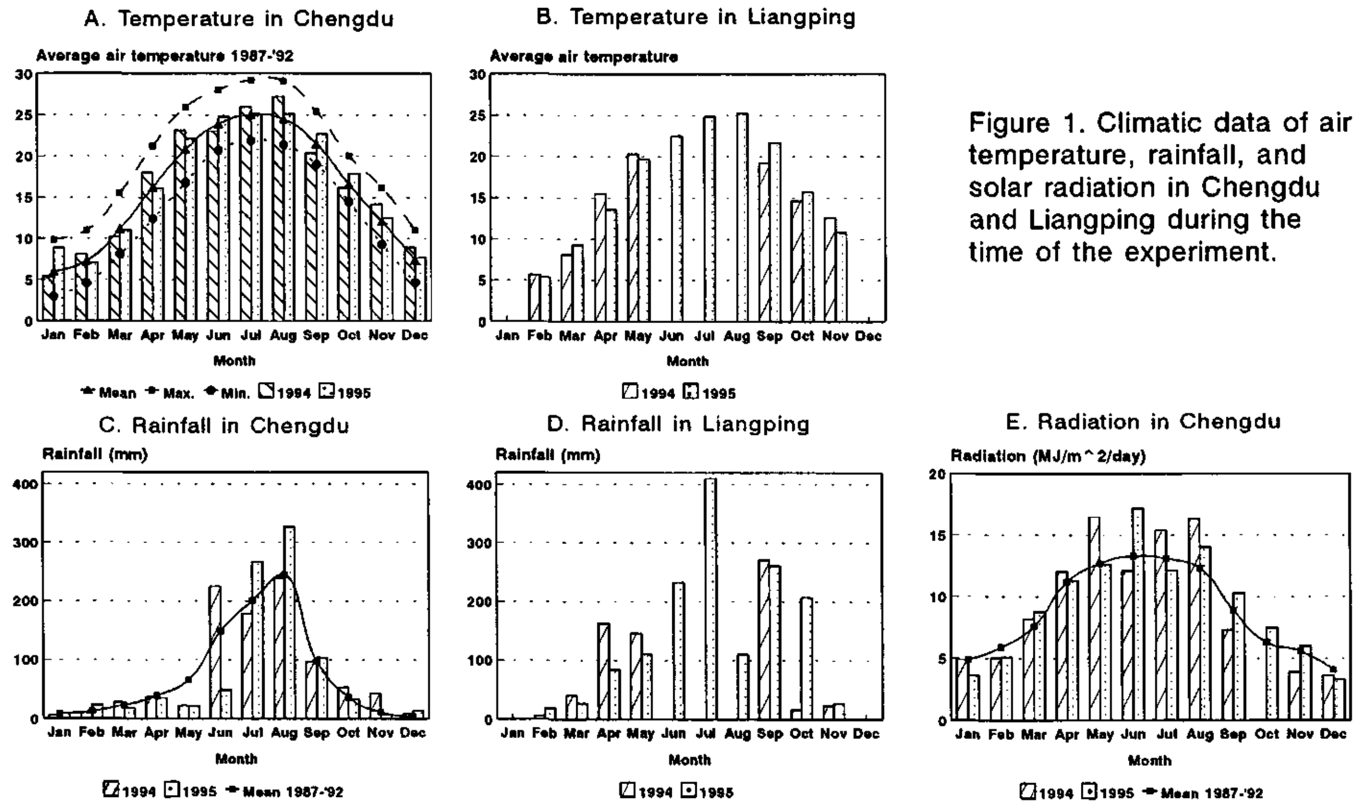

Figure 1. Climatic data of air temperature, rainfall, and solar radiation in Chengdu and Liangping during the time of the experiment.

1 (56 DAP) for cv. 813-17 was highest for P2, followed by P1 and P3, while for CY56, P1 had the highest emergence followed by P2 and P3. On April 12 (67 DAP) these trends still existed for both years (data not shown). Cv. 813-17 generally emerged earlier, and this is consistent with the observation that when P3 was planted the seed tubers of 813-17 had longer sprouts than those of CY56. In Chengdu, CY56 tuberized earliest in the first planting (P1), while for cv. 813-17 tuberization was at the same time for the first two planting times (P1 and P2) but severely delayed by P3. At higher altitude (in Liangping), the effects of planting time were smaller for both varieties. In Chengdu, tuber bulking started later for cv. 813-17 than for CY56 (Fig. 2), while in Liangping cv. 813-17 showed earlier tuber bulking than CY56 (Fig. 3). In Chengdu, the earlier the planting the larger the proportion of tuber dry matter at final harvest; a larger proportion of dry matter was allocated to tubers at final harvest for CY56 than for cv. 813-17; in Liangping, dry matter partitioning was similar for planting times and cultivars (Fig. 3). The dry matter proportion of stems and petioles gradually declined over time in the two locations and varieties. Canopy cover was highest for P2 throughout the season followed by P1 and P3; it did not differ much for the two varieties (data not shown).
Samplings were not frequent enough for the experiments in Pengxian to allow statements on growth of the crops.

Yield. In Tables 3 to 5, it is shown that final tuber yield parameters were affected by planting time, density, cultivar, season, and elevation. There were a few statistically significant interactions but the trends remained consistent. Therefore only the effects of the main factors are presented.

The final plant stands of earlier planting in autumn were reduced and may have reduced final tuber yield both in 1994 and 1995, especially in Chengdu (Table 3). In spring crops, plant stands hardly differed for different planting times. In general, earlier or intermediate planting (within the season) gave higher tuber yields per unit area than later planting in Chengdu (500 m asl) for both seasons but particularly for the spring crop. The trend for tuber yield at the intermediate elevation seems to be opposite: later planting resulted in higher or similar yields compared with earlier planting for both seasons (particularly for spring). For the highest elevations effects of planting time within a season were small. Tuber dry matter content ranged from 17% to 20% (data not shown). Increased tuber yields per plant partly compensated for the lower final plant stands when caused by early planting.

Differences in tuber yield were associated with large differences in tuber number and/or

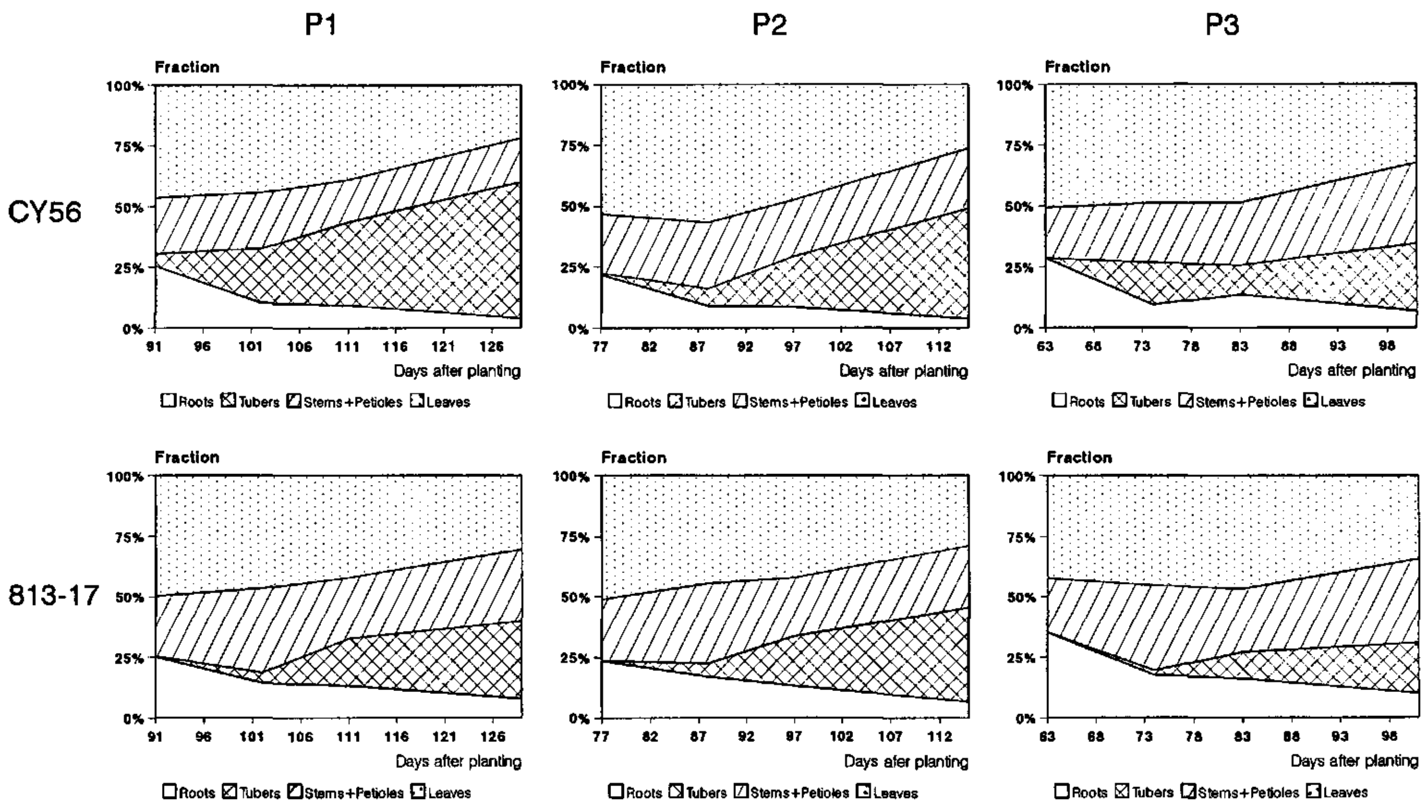

Figure 2. Dry matter partitioning over time for the three planting times (P1, P2, and P3) and the two varieties (CY56 and 813-17), grown in Chengdu, spring, 1994.

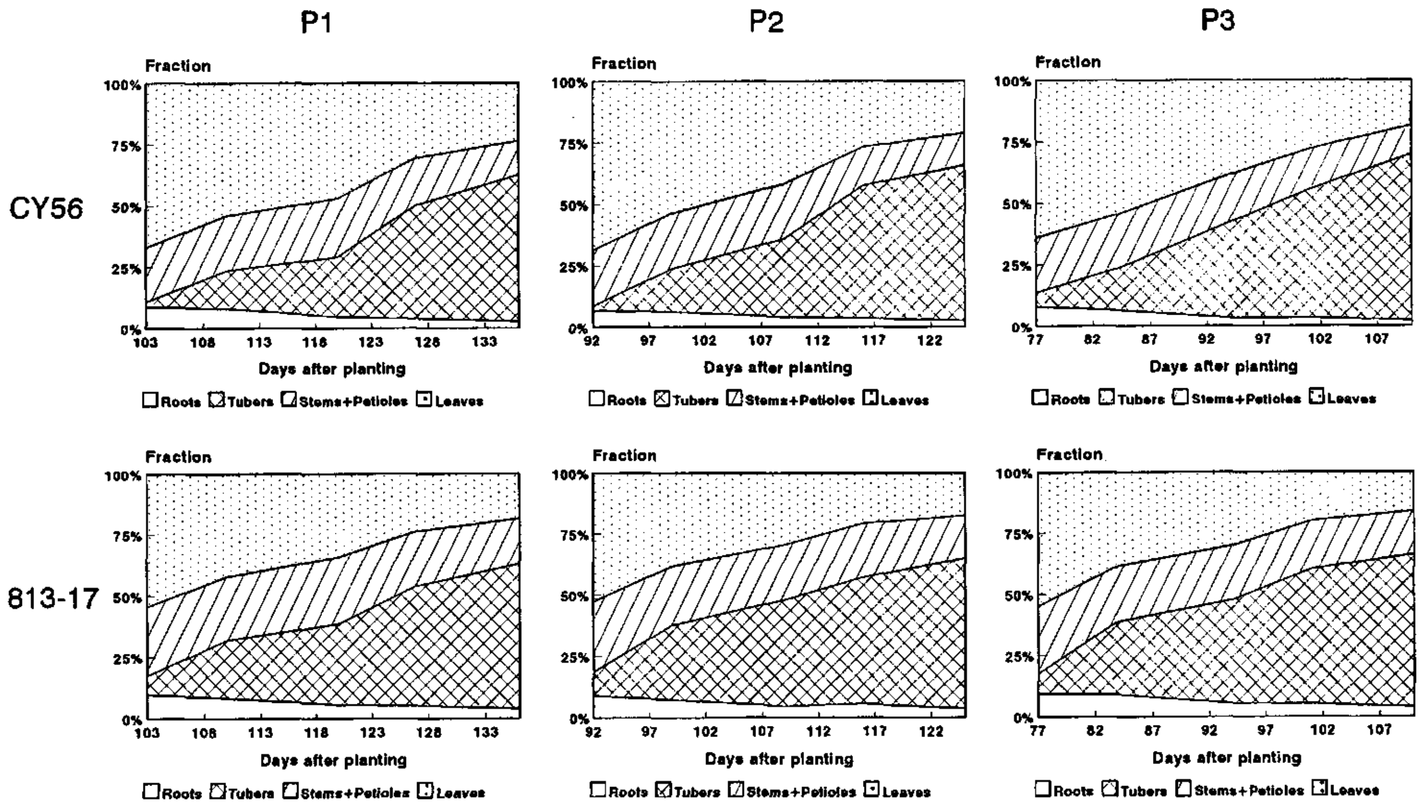

Figure 3. Dry matter partitioning over time for the three planting times (P1, P2, and P3) and the two varieties (CY56 and 813-17), grown in Liangping, spring, 1994.

Table 3. Effects of planting time on final plant stands and tuber yield characteristics at Chengdu (500 m asl), Liangping (750 m asl) and Pengxian (1200 m asl), spring and autumn seasons, 1994-95 (Trials 1-10).

Season/Year	Planting time	Final plant stands (%)	Tuber (TB) yield t/ha	Tuber (TB) yield g/plant	TB No. #/plant	TB Weight (g)
Chengdu						
Spring 1994	P1	90	6.4 ab	119	4.1 ab	29
	P2	92	6.9 a	124	4.5 a	28
	P3	89	5.0 b	94	3.7 b	25
	STAT	ns	(*)	ns	*	ns
Autumn 1994	P1	40 b	6.1	213 a	3.8	54 a
	P2	71 a	6.2	133 b	3.8	35 b
	P3	65 a	5.1	120 b	3.6	33 b
	STAT	*	ns	**	ns	***
Spring 1995	P1	84 ab	6.6 a	135 a	4.0 a	33 a
	P2	88 a	5.3 b	106 b	4.0 a	25 b
	P3	78 b	2.9 c	66 c	3.1 b	20 c
	STAT	(*)	***	***	***	***
Autumn 1995	P1	57 b	7.2 a	178 a	5.8 a	31 a
	P2	79 a	6.8 b	124 b	5.0 b	25 b
	STAT	***	(*)	***	(*)	(*)
Liangping						
Spring 1994	P1	93 b	8.5 b	163 b	3.9 b	51 b
	P2	95 a	10.0 ab	190 a	3.8 b	61 a
	P3	95 ab	10.9 a	206 a	4.8 a	54 b
	STAT	(*)	*	*	(*)	**
Autumn 1994	P1	82	11.5	187	5.7	34
	P2	87	11.3	177	6.3	29
	STAT	ns	ns	ns	ns	ns
Spring 1995	P1	92 a	7.1 ab	107 ab	3.5	50 a
	P2	90 b	5.6 b	88 b	3.6	37 b
	P3	92 a	7.5 a	116 a	3.9	43 ab
	STAT	*	(*)	(*)	ns	**
Autumn 1995	P1	71 b	8.7	165 a	4.5 b	38 a
	P2	87 a	8.9	139 b	6.4 a	22 b
	STAT	***	ns	*	**	***
Pengxian						
Spring 1995	P1	79	10.6	215 a	6.6 b	37 a
	P2	84	10.1	189 b	7.7 a	26 b
	STAT	ns	ns	*	*	***
Autumn 1995	P1	70	5.7	120	3.3	37
	P2	78	5.8	118	3.9	30
	STAT	ns	ns	ns	ns	ns

Note: (*), *, ** and *** indicate significant levels at *Probability* < 0.10, 0.05, 0.01 and 0.001 (F test), respectively; ns = not significant. Different letters in a column indicate significant differences at *Probability* < 0.05, according to Duncan's Multiple Range Test.

Table 4. Effects of plant densities on final plant stands and tuber yield characteristics at Chengdu (500 m asl) and Liangping (750 m asl), spring and autumn seasons, 1994-95 (Trials 1-8).

Season/Year	Plant density	Final plant stands (%)	Tuber (TB) yield t/ha	Tuber (TB) yield g/plant	TB No. #/plant	TB Weight (g)
Chengdu						
Spring 1994	D1	81 b	7.4 a	102 b	4.1	26 b
	D2	92 a	5.7 b	109 ab	4.0	27 b
	D3	97 a	5.2 b	125 a	4.2	29 a
	STAT	***	***	*	ns	*
Autumn 1994	D1	60	7.5 a	162 a	4.2 a	38
	D2	63	5.1 b	122 ab	3.6 b	33
	D3	74	4.2 b	118 b	3.2 b	38
	STAT	ns	**	(*)	**	ns
Spring 1995	D1	80 b	6.4 a	97	3.6	26
	D2	83 ab	4.8 b	104	3.8	26
	D3	87 a	3.6 c	105	3.8	26
	STAT	(*)	***	ns	ns	ns
Autumn 1995	D1	66	7.8 a	139	5.0	29
	D2	72	6.8 ab	142	5.2	27
	D3	78	6.0 b	151	5.9	25
	STAT	ns	(*)	ns	ns	ns
Liangping						
Spring 1994	D1	90 b	10.9 a	153 b	4.1	53
	D2	96 a	10.0 ab	187 a	4.1	54
	D3	97 a	8.5 b	218 a	4.3	60
	STAT	***	*	**	ns	ns
Autumn 1994	D1	80 b	13.3 a	174	6.1	30
	D2	83 b	11.5 b	179	6.0	30
	D3	91 a	9.4 c	193	6.0	34
	STAT	**	***	ns	ns	ns
Spring 1995	D1	81 c	7.6 a	93 b	3.5	40
	D2	93 b	6.9 a	107 ab	3.7	44
	D3	100 a	5.7 b	112 a	3.8	46
	STAT	***	**	*	ns	ns
Autumn 1995	D1	77	10.0 a	140	5.1	30
	D2	77	9.1 a	153	5.5	30
	D3	83	7.4 b	162	5.7	31
	STAT	ns	**	ns	ns	ns

Note: (*), *, ** and *** indicate significant levels at *Probability*<0.10, 0.05, 0.01 and 0.001 (F test), respectively; ns=not significant. Different letters in a column indicate significant differences at *Probability*<0.05, according to Duncan's Multiple Range Test. D1, D2 and D3 means highest, intermediate and lowest density, respectively.

Table 5. Effects of varieties and seed origin on final plant stands and tuber yield characteristics at Chengdu (500 m asl), Liangping (750 m asl) and Pengxian (1200 m asl), spring and autumn seasons, 1994-95 (Trials 1-10).

Season/Year	Variety	Final plant stands(%)	Tuber (TB) yield t/ha	Tuber (TB) yield g/plant	TB No. #/plant	TB Weight (g)
Chengdu						
Spring 1994	813-17	93 a	4.9 b	83 b	4.0	21 b
	CY56	87 b	7.3 a	141 a	4.2	33 a
	STAT	**	**	**	ns	***
Autumn 1994	813-17	65	4.7 b	110 b	3.6	31 b
	CY56	65	6.8 a	161 a	3.8	41 a
	STAT	ns	*	**	ns	**
Spring 1995	813-17	84	3.1 b	63 b	3.0 b	21 b
	CY56	82	6.8 a	141 a	4.5 a	32 a
	STAT	ns	***	***	***	***
Autumn 1995	813-17	75	6.4 b	123 b	5.4	23 b
	CY56	68	7.6 a	161 a	5.2	31 a
	STAT	ns	(*)	**	ns	*
Liangping						
Spring 1994	813-17	94	10.7 a	206 a	4.7 a	51
	CY56	95	9.0 b	167 b	3.7 b	57
	STAT	ns	*	**	*	ns
Autumn 1994	813-17	86	11.9 a	186	5.5 b	35 a
	CY56	83	10.9 b	177	6.5 a	28 b
	STAT	ns	(*)	ns	*	*
Spring 1995	813-17	92 a	7.4 a	113 a	4.4 a	41
	CY56	91 b	6.1 b	95 b	2.9 b	46
	STAT	*	*	(*)	**	ns
Autumn 1995	813-17	73 b	7.9 b	146	4.7 b	33 a
	CY56	85 a	9.7 a	157	6.2 a	27 b
	STAT	***	**	ns	**	*
Pengxian[1]						
Spring 1995	CY56s	58 b	7.7 b	209	8.6 a	25 b
	CY56a	95 a	11.9 a	203	4.7 b	45 a
	CY56p	92 a	11.5 a	195	8.2 a	25 b
	STAT	*	*	ns	*	**
Autumn 1995	CY56a	60 b	4.8 b	119	3.1 b	38
	CY56p	88 a	6.6 a	118	4.1 a	29
	STAT	*	(*)	ns	*	ns

Note: (*), *, ** and *** indicate significant levels at *Probability*<0.10, 0.05, 0.01 and 0.001 (F test), respectively; ns=not significant. Different letters in a column indicate significant differences at *Probability*<0.05, according to Duncan's Multiple Range Test.

[1] CY56s, CY56a, and CY56p stand for the variety CY56 with previous spring and autumn origin, and purple flower mutant (spring origin), respectively.

mean tuber weight in a non-consistent way. The effects of plant density were generally consistent over all trials (Table 4). The denser spacing (D1) always resulted in lower relative plant stands at both locations and in both seasons and years. This could be due to more air moisture and easier spread of diseases between the adjacent plants for the denser treatment. The denser spacing (D1) had a higher yield per unit area (due to its larger canopy duration, data not shown) but lower yield per plant than the density treatments D2 and D3, except in Trial 2 (Chengdu, autumn 1994) because in that trial it produced more tubers per plant (Table 4). Tuber number per plant and average tuber weight were not affected by the density treatments in most trials, indicating that inter-plant competition hardly affected these parameters at these relatively low leaf area indices.

The two varieties responded differently to treatments in different locations and seasons (Table 5). Cv. CY56 yielded higher than cv. 813-17 in Chengdu mainly due to the larger tubers of CY56 in both seasons and years; cv. 813-17 yielded higher than CY56 at the intermediate elevation in most cases (except for autumn 1995), mainly due to more tubers per plant in spring and larger tubers in autumn. At Pengxian in spring, cv. CY56 spring source (CY56s) had the lowest yield per unit of area due to its poor plant survival; CY56 autumn source (CY56a) had the highest yield due to its high plant survival; CY56 spring source with the purple flower mutant trait (CY56p) yielded similarly to CY56a and showed similarly high plant survival. Apparently the storability of the seed of the mutant CY56p is improved compared to the normal type.

Higher elevations generally produced higher tuber yields at least in spring, partly associated with higher plant survival. There was no apparent yield difference between spring and autumn crops with the exception of Pengxian where yield in spring was higher than in autumn (usually the difference is much smaller), but the physiological status of the seed tubers may have been a crucial factor here. A third planting on September 3 resulted in extremely low yields (usually well below 3 t/ha; data not shown) whereas for the spring crop a third planting could still produce substantial yields. This is because the spring season usually is longer than the autumn season, especially at higher altitude.

Light extinction (k) and use efficiency (LUE). Light extinction coefficients (k) varied a little for varieties and planting times and ranged from 0.47-0.57 (Table 6). LUE (g DM of total plant biomass/MJ of absorbed PAR) was significantly influenced by planting time and variety (Table 7). LUEs were higher in autumn (about 3.0 g DM/MJ PAR) than in spring (about 1.9 g DM/MJ PAR) seasons mainly due to lower values for solar radiation in the

Table 6. The light extinction coefficients (k) which fit the relationship between intercepted fraction of solar radiation ($f_{int} = 1 - e^{-k \cdot LAI}$, in percentage) and leaf area index (LAI, m^2/m^2) with the 2 varieties and 3 planting times in Chengdu, spring 1994. Four times of measurement plus 2 interpolations on LAI from April 20 to May 27 were taken. **, *** indicate statistically significant at $P<0.01$, 0.001 levels, respectively (n=6).

Variety/Planting time	k value	R^2 value
813-17 (V_1)	0.47	0.75**
CY56 (V_2)	0.55	0.70**
1st planting	0.49	0.61**
2nd planting	0.47	0.79***
3rd planting	0.57	0.84***

Table 7. Relationships between total plant dry matter (TPDM, g DM/m^2) and PAR absorbed by plants (PAR_{abs}, MJ/m^2) with fitted LUEs (g DM/MJ) of the 2 varieties and 3 planting times (averaged over all other treatments) in Chengdu, spring 1994. *** indicates statistically significant at $P<0.001$ (n=6).

Variety/Planting time	Relationship	R^2 value
813-17 (V_1)	$TPDM = -12.6 + 1.97 \cdot PAR_{abs}$	0.96***
CY56 (V_2)	$TPDM = -7.3 + 1.86 \cdot PAR_{abs}$	0.98***
1st planting	$TPDM = -16.9 + 2.09 \cdot PAR_{abs}$	0.96***
2nd planting	$TPDM = -12.7 + 2.24 \cdot PAR_{abs}$	0.98***
3rd planting	$TPDM = -1.2 + 1.43 \cdot PAR_{abs}$	0.98***

Table 8. Photosynthesis rate measured in Chengdu, on May 19, 1994 using labelled ^{14}C, when light intensity was 292 W/m^2, in CO_2 mg/h/plant.

Variety	Planting time	Leaf	Stem	Total plant
813-17	P1	13.3	1.7	15.0
	P2	18.7	1.5	20.2
	P3	12.1	2.6	14.7
Average		*14.7*	*1.9*	*16.6*
CY56	P1	11.9	0.8	12.7
	P2	11.2	1.3	12.5
	P3	8.3	0.7	9.0
Average		*10.5*	*0.9*	*11.4*
Average over cvs	P1	12.6	1.3	13.9
	P2	15.0	1.4	16.4
	P3	10.2	1.7	11.9

Note: Differences between means of treatments of variety and planting time are all statistically non-significant at $P<0.05$.

autumn (He et al., 1997a), confirming previous results from literature (Vander Zaag et al., 1990; Kooman et al., 1996). LUEs of varieties differed and varied according to planting date in a way that was consistent with differences in yield (Table 3) and photosynthesis rate measured in the field (Table 8).

Discussion

At lower elevations in spring, the growing period was more limited than at the higher elevations and the temperature was suitable for the 1st and 2nd planting, so the earlier planting from late December to mid-January should be encouraged. Planting even earlier than that probably makes no sense and planting after mid-February will significantly reduce tuber yield because the heat in May will impede or even stop tuber growth. At higher elevations in spring, planting could be delayed by about 1 month until some time in February. Planting before February reduces emergence and final yield. Some farmers in the Hubei mountains plant seed tubers deep and as early as November and results are similar to the proper later planting (Xie Chonghua, personal communication). Planting after March at the intermediate elevation would delay emergence. Moreover, early autumn (from early to mid-November) night frost would damage the leaves not yet senesced, resulting in low tuber yield. In sub-tropical areas, risk of early spring frost is absent in contrast to other regions with otherwise similar conditions (Haverkort, 1990). The average temperature is the dominant factor that shapes the growth pattern of the crop in dependence of planting times. Similar results have been found by Cho and Iritani (1983).

The differences in performance of varieties illustrate that varieties which tuberize later are better adapted to higher than to lower elevations, whereas an early tuberizing variety is better adapted to lower elevations. Temperature is again the crucial factor governing this difference in performance.

In the autumn, the most important constraint to high yield for both lower and higher elevations may be the low plant survival for earlier planting. The lower survival is probably due to the higher soil temperatures and heavy rainfall especially during late August to early September, which enhance damage to seed tubers and plants by diseases and/or soil pests. Plant survival may be promoted by selecting healthy seed tubers, or applying soil fumigation or avoiding waterlogging after heavy rain.

The study also suggests that at higher elevation the biotic stress by tuber-borne or soil-borne pathogens may be lower, because plant stand was higher at higher than at lower elevations, especially in autumn seasons. The small effect of pathogens may be due to lower temperature at higher elevation. This may explain why the cultivar CY56 can be used by farmers in continuous cropping for over 10 years without apparent tuber yield reduction of the crop. On the other hand, the effect of lower density on plant stand was also shown at higher elevation.

The performance of the different plant densities showed that yields per unit area could be increased by increasing density, be it at the expense of individual plant yield. It is necessary to increase the plant density especially at lower elevations where growth vigour is not as strong as at higher elevations in subtropical areas, which is in agreement with the findings of Allen (1978) and Allen and Scott (1980). Our results also showed that it is possible that tuber number per plant did not decline with increasing seed density (hence stem density), while tuber weight was not affected in most cases, which is in agreement with the report by Allen and Scott (1980) for cv. Pentland Crown. It is therefore beneficial for ware potato production. Increased competition may result in indirect soil cooling, beneficial for growth and yield (Ewing and Struik, 1992). Hammes (1985) found a remarkable plasticity and adaptability of the potato plant: total tuber yield was not affected with increasing stem population (from 12 to 24 m^{-2}) although the portion of small tubers increased. Other reports show that the number of stems per plant is constant once a potato crop has been established except possibly at a very high density (30 stems m^{-2}) (Regel and Sands, 1983). The compact soil, the use of whole seed tubers and the scarce rainfall were probably among the main reasons that hampered canopy development at high density treatments.

The lower k-values indicated that crops may have more vertical leaves compared with the crops with a spherical leaf distribution that have k-values of 0.7 (Lövenstein et al., 1992); more solar radiation is intercepted by the crop in the latter case. The strong correlation between total plant dry matter and PAR absorbed by plants indicated the importance of maximizing the leaf canopy cover and duration in the area. The results further supported previous reports (Allen and Scott, 1980; Spitters, 1987; He and Vander Zaag, 1991; Haverkort et al., 1991). Despite the higher rates of photosynthesis in cv. 813-17 than in cv. CY56, the tuber yield of 813-17 was still lower than CY56 in some cases. This can be partly due to the fact that 813-17 had much lower harvest indices than CY56 (data not shown). The total plant photosynthesis rates measured in different planting times and varieties were generally in accordance with their respective growth parameters and yields, which was anticipated.

Conclusions

Earlier planting in spring can promote higher yield at lower elevation but at higher elevation planting time is less critical; in the autumn, suitable planting time was restricted to a limited period both at lower and higher elevations.

Optimal potato planting time not only depends on cultivar and physiological status of the seed tubers, but also on rainfall prior to planting, especially in the autumn seasons.

Denser spacing gave higher yield. The different varieties responded differently at different elevations.

In sub-tropical areas where two crops a year is possible, it is necessary to use cultivars that tuberize early.

Chapter 4

Seed supply of potato to double cropping regions in a sub-tropical, diverse and low-input agro-ecological zone in Sichuan, China

He Wei[1] and Paul C. Struik[2]

Summary

Seed age is affected by conditions during production and storage, therefore it depends on altitude of seed production. Inadequate physiological status of the seed tubers (too young or too old) is often a yield constraint in potato, especially in regions with double cropping. Ten trials were carried out in two years involving three growing seasons to study a practical way of manipulating seed age prior to planting through selection of adequate seed sources to improve potato production in a typical sub-tropical double cropping region. Results showed that for spring crops, seed tubers are required to be older at lower altitude and younger at higher altitude than those commonly used. For the autumn crops, seed tubers should be relatively old both in low and high altitudes. Manipulation of seed sources can be done through selecting products of previous (one to three consecutive crops back) spring or autumn crops produced either in low or high altitudes, or from early harvest of the seed crop. Responses were often cultivar-specific: the yield of the variety with longer dormancy (No. 22-2) was higher at higher altitude when older seed was planted and its variation was larger over different altitudes than for the more adapted variety with shorter dormancy (CY56). More stems and tubers per plant generally contributed to higher yield. The altitude and the season of seed production affected the performance of the seed by influencing seed age and seed health status. Seed health can be restored by multiplying it at high altitude or by regenerating it every consecutive season.
The observed long-term after-effects of seed origins could be associated with effects on seed health. Yield in Sichuan is strongly affected by seed source; optimization of the seed supply system is therefore crucial for yield improvement.

Key words: Seed supply, seed source, physiological age, potato, double cropping, *Solanum tuberosum* L.

Introduction

In many areas of the sub-tropical regions in China, the main potato crop is grown in spring

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and may be followed by a second (autumn) crop and even a third (winter) crop (Wang, 1980). In such cases, the physiological status of the seed tubers at planting is often an important constraint to potato production (Malik et al., 1991). Depending on the season of production, the seed tubers are either too young or too old; both situations give poor plant growth vigour and hence low yields and small tuber size. The physiological status is described in terms of physiological age, and it is modified progressively by increasing chronological age, but also depends on growth history, storage conditions (particularly temperature), and cultivar (Van der Zaag and Van Loon, 1987; Van Loon, 1987; Van Ittersum, 1992a; Ewing and Struik, 1992).

Dormancy and growth vigour of seed potatoes can be manipulated by a haulm application of gibberellic acid of the mother crop, storage temperature regimes (Van Ittersum and Scholte, 1993; Van Ittersum et al., 1993), or treatment of seed tubers (Burton, 1978). Improved methods of storing seed tubers in diffuse light rather than costly cold store can be powerful in prolonging the growth vigour of older seeds (Wiersema and Booth, 1985; Severian et al., 1986; Benz and Fahem, 1988). Temporary warm storage immediately after harvest can shorten dormancy (Van Ittersum, 1992a).

The area under study has different altitudes to plant the crop with specific planting times and seasons, which are primarily determined by prevailing temperatures (He et al., 1997b). The seed flows are very complicated but inadequate to realize high yields (He et al., 1997a). The objective of the study was to analyze the seed flows in the agro-ecologically very diverse potato growing area of Sichuan and to find a practicable way of manipulating seed age and allocating seed lots to different environments to improve potato production in some characteristic zones of the region.

Materials and Methods

Ten trials were carried out at different altitudes, in different seasons and years, with two cultivars. Agronomic details of the 10 trials are shown in Table 1. The variety No. 22-2 was chosen for its characteristically long dormancy and long growth cycle; the mid-early variety CY56 with a shorter dormancy is common in the region. The effects of growing conditions during several generations of multiplication were analyzed by applying treatments explained below. Most trials were laid out as split plots with variety with or without seed status (altitude of previous year's crop) as main plots, and seed origin (previous spring or autumn harvests) as sub-plots. Sub-sub-plots of further seed origin or time of harvest (normal or

Table 1. Details of the experiments (Trials 1 to 10).

Location	Chengdu (104.2° E, 30.6° N, 500 m asl)			
Trial	Trial 1a	Trial 2, 6	Trial 3	Trial 8
Season/Year	Spring '95	Autumn '94	Autumn '95	Spring '95
Planting date (day/month)	9/2	7/9	4/9	10/2
Replications	3	4, 3	4	2
Seed size (g)				
cv. No.22-2	None	Approx. 60	Approx. 60	34-43
cv. CY56	Approx. 31-54	Approx. 50	Approx. 50	31-54
Plant spacing (cm)	30x60	27x60	27x57	30x60
Net plot dimension (m)	1.8x3.0	1.8x3.0	2.3x3.0	1.8x3.0
N-application (kg/ha)	70	70	70	Approx. 60
P_2O_5-application (kg/ha)	50	50	50	Approx. 50
K_2O-application (kg/ha)	None	50	None	None
Harvest (day/month)	10/6	6/12	6/12	10/6
Location	Pengxian (103.7° E, 31.3° N, 1200 m asl)			
Trial	Trial 1b	Trial 4, 7	Trial 9	Trial 5, 10
Season/Year	Spring '95	Autumn '94	Spring '95	Autumn '95
Planting date (day/month)	27/2	17/8	27/2	21/8, 23/8
Replications	4	4, 3	3	4, 1
Seed size (g)				
cv. No.22-2	Approx. 55	Approx. 60	Approx. 50	Approx. 65, 50
cv. CY56	Approx. 50	Approx. 50	Approx. 50	Approx. 55, 45
Plant spacing (cm)	30x57	27x57	30x57	27x57, 28x57
Net plot dimension (m)	1.71x3.0	1.71x3.0	1.14x3.0	1.71x3.0, 1.14/2.28x3.4
N-application (kg/ha)	Approx. 50	Approx. 30	Approx. 30	Approx. 30
P_2O_5-application (kg/ha)	Approx. 50	None	Approx. 50	Approx. 50
K_2O-application (kg/ha)	None	None	None	None
Harvest (day/month)	19/7	10/12	19/7	12/12, 13/12

early) were also included in some trials. The general climatic conditions and cropping systems in the area are described in Chapters 2 and 3.

By varying origins and storage periods the seed quality was manipulated (Table 2), since these factors may provide varying cumulative temperature sums and thus physiological age. For instance, seed tubers for spring 1995 from flows 1, 2, and 3 were old, intermediate and young, respectively (Table 2). In seed flow 2, the autumn crop in 1994 would emerge and mature earlier by about 15 days than the crop from seed flow 3. Consequently, seed tubers for spring 1995 were older in flow 2 than in flow 3 because they had experienced about 15 days × (21-4)°C = 255 degree days more after harvest. Farmers at higher altitude use part of their harvest for seed in a continuous sequence of spring crop, autumn crop, spring crop, etc. So, within each experiment, the starting material of seed tubers used for the production of test material was kept uniform (depending on the experiment either as previous spring or autumn harvests) to allow statistical analysis. Seed tubers were planted whole.

Table 2a. Forms of seed flows used in the experiments, conducted in Chengdu (500 m asl) and Pengxian (1,200 m asl).

Seed flow	Seed age	Production and storage*	Evaluation
1. (old)	++++	93a-94s-----	95s
2. (fairly young)	+++	93a-----94a-	95s
3. (young)	+	93a-94s-94a-	95s
4. (fairly young)	++	93s-----94s-	94a
5. (young)	+	93s-93a-94s-	94a
6. (fairly young)	++	94s-----95s-	95a
7. (young)	+	94s-94a-95s-	95a
8. (young)	+	93s-----94s-94a-	95s
9. (young)	+	93s-93a-94s-94a-	95s
10. (very old)	+++++	94s-94a-----	95a

*: - = short storage at site of production; ----- = long storage at site of production; a = autumn; s = spring.

In trials 6 and 7 (Tables 2, 8 and 9), normal and early (20-30 days earlier than normal) harvest dates of seed tubers tested served as sub-sub-plots. Seed of the subsequent crop was expected to be older at planting for treatments with an early harvest because it was stored longer than the seed of the normal (later) harvest (cf. Van Ittersum, 1992a), and thus it can actually sprout earlier than tubers from a mature crop (Beukema and Van der Zaag, 1990). Moreover, the seed tubers from an immature crop have less virus, fungal and bacterial infections (Beukema and Van der Zaag, 1990).

Table 2b. Seed flows, factors tested and sites of production of seed and test sites for the different experiments.

Trial	Seed flows included	Factors tested	Site of production	Site of evaluation
1a+1b	1-3	One factor: Seed flow.	PX	CD and PX
2	4-5	A: Variety/Altitude in previous spring crop's harvests; B: Previous year's crop.	PX and CD	CD
3	6-7	A: Variety; B: Altitude in previous spring crop's harvests; C: Previous year's crop.	PX and CD	CD
4	4-5	A: Variety/Altitude in previous spring crop's harvests; B: Previous year's crop.	PX and CD	PX
5	6-7	A: Variety; B: Altitude in previous spring crop's harvests; C: Previous year's crop.	PX and CD	PX
6	4-5	A: Variety/Altitude in previous spring crop's harvests; B: Previous year's crop (PX); C: Previous spring crop's harvest time.	PX and CD	CD
7	4-5	A: Variety/Altitude in previous spring crop's harvests; B: Previous year's crop (PX); C: Previous spring crop's harvest time.	PX and CD	PX
8	8-9	A: Altitude in previous autumn crop's harvests; B: Variety/Altitude in previous spring crop's harvests; C: Crop of 2 years earlier.	PX and CD	CD
9	8-9	A: Altitude in previous autumn crop's harvests; B: Variety/Altitude in previous spring crop's harvests; C: Crop of 2 years earlier.	PX and CD	PX
10	6-7, 10	A: Variety; B: Seed flow.	PX	PX

Note: CD = Chengdu; PX = Pengxian; A = main-plot, B = sub-plot and C = sub-sub-plot.

In the experiments, tubers of whole plots were lifted at normal dates. Data on number of plants harvested, number of stems, number of tubers, and fresh tuber weight were recorded. Tuber dry matter content was measured soon after harvest by drying subsamples in an oven at 105 °C for 10 minutes followed by 90 °C until constant weight. Data were analyzed statistically using MSTAT-C and COSTAT. Tables contain P values and LSD-values for comparisons of more than two values or averages.

Results

Trial 1 compares different seed ages at two contrasting altitudes in spring seasons (Table 3). Effects on final plant stands were different for the two sites but correlated closer with yields in Pengxian than in Chengdu. However, effects of seed flow on stem number per plant were similar for both sites: the old seed gave more stems per plant. Final tuber yields were highest from oldest seed (seed flow 1) at lower altitude (Chengdu) and highest from youngest seed (seed flow 3) at higher altitude (Pengxian).

Table 3. Effect of seed source on crop performance. Data of the variety CY56; seeds all derived from Pengxian, crops grown in **spring** season from Feb 9 to Jun 10 (Chengdu) or Feb 27 to Jul 19 (Pengxian), 1995. Trials 1a and 1b.

Treatment: Seed flow[1] /Source	Chengdu (500 m asl)				Pengxian (1200 m asl)			
	Plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Yield (t/ha)	Plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Yield (t/ha)
1. Autumn '93 - Spring '94	95	4.5 a	8.6 a	13.0 a	72 c	4.6 a	8.3 a	6.5 c
2. Autumn '93 - Autumn '94	93	1.3 b	4.2 b	7.4 b	84 b	1.3 b	4.7 b	10.4 b
3. Spring '94 - Autumn '94	74	1.2 b	5.1 b	9.2 b	91 a	1.7 b	4.9 b	12.5 a
Grand mean	88	2.3	6.0	9.9	82	2.5	6.0	9.8
CV (%)	15.7	5.7	9.0	15.4	3.8	23.5	20.1	7.9
LSD (0.05)	ns	0.3***	1.2*	3.4*	5.4***	1.0***	2.1**	1.4***

[1] See Table 2 for seed flow description. ns, *, **, *** stands for non-significant, significant at $P<0.05$, 0.01, and 0.001, respectively.

In Trials 2 and 3 seed tubers varied in physiological status because the previous spring crop was grown at different altitudes (main factor A in Table 4 and B in Table 5), or because these crops were grown from seeds originating from different seasons. Different seed flows or cultivars (A, B and C) had no significant effect on final plant stands. Older seeds (seed grown and stored at lower altitudes) gave higher tuber yields when evaluated at the lower altitude in autumn (in both trials); the effect of the growing season of the previous year's crop (spring or autumn, factor B in Table 4 and C in Table 5) had no effect on yield or yield parameters.

The yield response of variety CY56 to the seed source was similar to the one shown in Trial 1 for evaluation at lower altitude (Table 3). The seed of No. 22-2 derived from previous year's spring crop gave a higher yield than the seed from the autumn crop when it was multiplied in spring at higher altitude (Table 4), whereas the seed from the previous year's

Table 4. Effects of seed source and variety on crop performance in Trial 2; crops grown in Chengdu in **autumn**, from seed harvested in spring '94, from Sep 7 to Dec 6, 1994. CD=Chengdu; PX=Pengxian.

Variety/Altitude in previous spring crop's harvest ('94) (A)	Previous year's crop ('93) (B)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
CY56/Low(CD)	Spring	74	2.2	4.9	8.2
	Autumn	55	2.2	4.2	6.0
	Mean	*64*	*2.2*	*4.5 a*	*7.1 a*
CY56/High(PX)	Spring	59	1.9	3.1	2.6
	Autumn	72	2.2	3.5	5.2
	Mean	*66*	*2.1*	*3.3 b*	*3.9 b*
No.22-2/High(PX)	Spring	63	2.4	2.9	3.1
	Autumn	62	2.6	3.0	2.8
	Mean	*63*	*2.5*	*2.9 b*	*3.0 c*
Averages B	Spring	65	2.1	3.6	4.7
	Autumn	63	2.3	3.5	4.7
Grand mean		64	2.2	3.6	4.7
CV (%)		18.8	19.0	16.9	35.1
LSD(0.05) Main-plot (A)		ns	ns	0.82**	0.65***
Sub-plot (B)		ns	ns	ns	ns
Interaction (AB)		ns	ns	ns	2.62*

Note: ns, *, **, *** stands for non-significant, significant at $P<0.05$, 0.01, and 0.001, respectively.

autumn crop gave a higher yield than the seed from the spring crop when it was multiplied in spring at lower altitude (Table 5). For both varieties, the numbers of stems and tubers per plant were consistently affected by altitudes of previous crops, whereas previous year's seasons did not affect the numbers.

At higher altitude (Tables 6 and 7, Trials 4 and 5) in autumn, such trends still held. The results of both years show that previous year's spring origin generally produced better final plant stands than previous year's autumn origin although there were interactions of the origins with other factors, particularly in variety No. 22-2; very young seeds of No. 22-2 derived from previous high altitude and autumn produced very low plant stands and hence low yield per unit area (Tables 6 and 7). The previous year's crop (factor B in Table 6 and factor C in Table 7) seemed to affect tuber yield for variety No. 22-2 with the longer dormancy: seed grown from the spring crop seed produced much better than seed grown from the autumn crop seed. In CY56 there was (in most cases) an opposite (though non-significant) trend. Again, the numbers of stems and tubers per plant generally correlated with yields, especially when variation was caused by treatments of previous altitudes.

Table 5. Effects of variety and seed source on crop performance in Trial 3; crops grown from seed harvested in spring '95, in Chengdu **autumn** from Sep 4 to Dec 6, 1995. CD=Chengdu; PX=Pengxian.

Variety (A)	Altitude in previous spring ('95) crop's harvest (B)	Previous year's crop ('94) (C)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
CY56	Low (CD)	Spring	78	2.6	7.2	11.0
		Autumn	59	2.8	7.7	8.5
	High (PX)	Spring	62	2.0	5.0	6.4
		Autumn	66	1.9	4.7	7.4
	Mean		*66*	*2.3 b*	*6.1 a*	*8.3 a*
No. 22-2	Low (CD)	Spring	61	3.0	4.8	5.7
		Autumn	85	2.5	4.6	8.3
	High (PX)	Spring	67	2.8	5.1	5.0
		Autumn	60	2.6	4.3	2.5
	Mean		*68*	*2.7 a*	*4.7 b*	*5.4 b*
Averages B	Low (CD)		71	2.7 a	6.1 a	8.4 a
	High (PX)		64	2.3 b	4.8 b	5.3 b
Averages C		Spring	67	2.6	5.5	7.0
		Autumn	68	2.4	5.3	6.7
	Grand mean		67	2.5	5.4	6.9
	CV (%)		15.9	9.8	16.1	16.2
	P or LSD (0.05) Main-plot (A)		ns	*	P<0.08	*
	Sub-plot (B)		ns	*	*	**
	Sub-sub-plot (C)		ns	ns	ns	ns
	Interaction AB		ns	ns	1.3*	ns
	AC		P<0.07	0.3*	ns	ns
	BC		ns	ns	ns	ns
	ABC		16.4**	ns	ns	1.7***

Note: ns, *, **, *** stands for non-significant, significant at P<0.05, 0.01, and 0.001, respectively.

Tables 8 and 9 (Trials 6 and 7) show similar trends for the effects of seed sources (altitude and previous season of production) on yield but only for variety No. 22-2 at both altitudes in autumn: previous spring season's origin gave higher yield. Early harvest of the crop compared with normal (later) harvest in previous spring (factor C) increased yield of the progeny crop at high altitude (Table 9), especially for CY56 that was derived from a previous spring crop grown at low altitude. The yield increases were closely linked with the better plant stands of early harvests, whereas more stems per plant and more tubers per plant sometimes also contributed to the positive effects. The two varieties responded differently in that No. 22-2 with longer dormancy had a more pronounced yield increase at higher altitude when treated with older seed (previous year's source) than CY56.

Table 6. Effects of variety and seed source on crop performance in Trial 4; crops from seed harvested in spring '94, grown in Pengxian in **autumn** from Aug 17 to Dec 10, 1994. CD=Chengdu; PX=Pengxian.

Variety/Altitude in previous spring crop's harvest ('94) (A)	Previous year's crop ('93) (B)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
CY56/Low (CD)	Spring	94	2.3	4.4	13.1
	Autumn	98	2.3	3.5	14.9
	Mean	*96*	*2.3 a*	*3.9 a*	*14.0 a*
CY56/High (PX)	Spring	96	2.0	4.5	10.6
	Autumn	90	1.9	4.0	12.9
	Mean	*93*	*1.9 b*	*4.2 a*	*11.7 a*
No. 22-2/High (PX)	Spring	88	1.8	2.6	10.5
	Autumn	68	1.5	2.3	4.5
	Mean	*78*	*1.6 b*	*2.4 b*	*7.6 b*
Averages B	Spring	92 a	2.0	3.8 a	11.4
	Autumn	85 b	1.9	3.2 b	10.8
Grand mean		89	2.0	3.5	11.1
CV (%)		7.4	20.8	12.8	15.4
P or LSD (0.05) Main-plot(A)		ns	0.3**	0.5***	3.6*
Sub-plot (B)		*	ns	*	ns
Interaction (AB)		10.5*	ns	ns	2.7**

Note: ns, *, **, *** stands for non-significant, significant at $P<0.05$, 0.01, and 0.001, respectively.

Table 10 (Trial 8) shows that seed originating from previous autumn crop's harvest (factor A) at higher altitude (younger seed source) gave more plants producing progeny and higher tuber yield than seed from the lower altitude (older seed source), when evaluated at lower altitude (Chengdu) in spring. In addition, the seed source from the crop (either spring or autumn) that dated back three consecutive seasons (factor C) also had an effect: the younger the source (autumn), the higher the final stands and yields, but only for the seed origin from previous autumn crop's lower altitude's harvest. This long-term carry-over effect of seed source is remarkable and significant. However, the same batch of seed originating from the previous spring crop's harvest (two consecutive seasons earlier, factor B) gave higher final stands and yield for its older source, especially when the autumn '94 harvest came from low altitude (factor A). This effect of factor B was similar in Trial 1 (Table 3), where it was tested at the same altitude (low) and in the same season (spring). Effects of factor A on the numbers of stems and tubers per plant were consistent with its effects on final plant stand and yield; effects of factor B on the numbers of tubers per plant were also consistent with its effects on final plant stand and yield, but the numbers of stems per plant were generally not affected; factor C generally did not affect numbers of stems and tubers per plant.

Table 7. Effects of variety and seed source on crop performance in Trial 5; crops from seed harvested in spring '95, and grown in Pengxiang in **autumn** from Aug 21 to Dec 12, 1995.

Variety (A)	Altitude of previous spring crop's harvest ('95) (B)	Previous year's crop ('94) (C)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
CY56	Low (CD)	Spring	71	2.0	4.3	9.3
		Autumn	87	2.1	3.9	10.1
	High (PX)	Spring	67	1.5	3.8	5.7
		Autumn	74	1.5	3.5	4.7
	Mean		*75 a*	*1.8*	*3.9*	*7.4 b*
No. 22-2	Low (CD)	Spring	85	2.5	3.8	14.5
		Autumn	76	1.7	3.4	12.7
	High (PX)	Spring	58	1.6	3.2	5.6
		Autumn	17	1.3	3.7	1.1
	Mean		*59 b*	*1.8*	*3.5*	*8.5 a*
Averages B	Low (CD)		80 a	2.1 a	3.9	11.6 a
	High (PX)		54 b	1.5 b	3.6	4.3 b
Averages C		Spring	70 a	1.9 a	3.8	8.8 a
		Autumn	63 b	1.7 b	3.6	7.1 b
	Grand mean		67	1.8	3.7	7.9
	CV (%)		14.9	14.8	13.2	12.2
	LSD (0.05) Main-plot (A)		**	ns	ns	*
	Sub-plot (B)		***	**	ns	***
	Sub-sub-plot (C)		$P<0.08$	*	ns	***
	Interaction AB		12.8**	ns	ns	1.0***
	AC		10.9**	*	ns	1.1***
	BC		10.9*	ns	ns	1.1**
	ABC		ns	ns	ns	ns

Note: ns, *, **, *** stands for non-significant, significant at $P<0.05$, 0.01, and 0.001, respectively.

In the same type of trial carried out at higher altitude in spring (Table 11, Trial 9), both factors A and C generally had no effect on tuber yield, but for variety CY56 results were similar to the ones in Trial 1 (Table 3) carried out at the same altitude and in the same season. Likewise, the older source derived from the previous spring crop's harvest (factor B) from lower altitude gave similar plant stands and higher tuber yields for the same variety CY56. The tuber yield of variety No. 22-2 was much higher at higher altitude (Table 11) than at lower altitude (Table 10) from the same seed origins and in the same season. Again for factor A, more stems or tubers per plant were associated with higher yield; for factor B, more stems per plant increased yield; for factor C, there was no relation between the number of stems per plant and tuber yield.

Table 8. Effects of variety and seed source on crop performance in Trial 6; crops from seed harvested in spring '94, and grown in Chengdu in **autumn**, from Sep 7 to Dec 6, 1994.

Variety/ Altitude of previous spring crop's ('94) harvest (A)	Previous year's crop (PX) ('93) (B)	Previous spring crop's ('94) harvest time (C)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
CY56/Low(CD)	Spring	Normal	82	2.1	4.1	7.2
		Early	92	2.2	4.0	7.1
	Autumn	Normal	59	2.1	4.2	7.0
		Early	93	2.3	3.6	8.3
	Mean		*82*	*2.2*	*4.0*	*7.4 a*
No. 22-2/High (PX)	Spring	Normal	81	1.9	2.8	4.0
		Early	79	1.9	2.7	3.5
	Autumn	Normal	53	2.0	2.6	2.0
		Early	64	2.4	3.2	3.7
	Mean		*70*	*2.1*	*2.8*	*3.3 b*
Averages B	Spring		84 a	2.0	3.4	5.5
	Autumn		68 b	2.2	3.4	5.3
Averages C		Normal	69 b	2.0	3.4	5.1
		Early	82 a	2.2	3.4	5.7
	Grand mean		76	2.2	3.4	5.4
	CV (%)		16.0	21.4	19.0	23.2
	Main-plot (A)		ns	ns	ns	P<0.06
	Sub-plot (B)		*	ns	ns	ns
	Sub-sub-plot (C)		*	ns	ns	ns
	Interaction (AB,AC,BC,ABC)		ns	ns	ns	ns

Note: ns, *, **, *** stands for non-significant, significant at P<0.05, 0.01, and 0.001, respectively.

Trial 10 (Table 12), carried out at higher altitude in the autumn season, revealed that the older the seed the higher the yield especially for variety No. 22-2 where the yield variation was larger. The result was opposite to the result found at the same altitude in the spring (Table 3), but consistent with the results of:

1), experiments carried out both at low and high altitudes in autumn (Tables 4, 5, 6 and 7);
2), experiments carried at lower altitude in spring (Table 3);
3), experiments with the variety No. 22-2 in autumn (Tables 8 and 9); and
4), experiments regarding seed source effects in the treatment combination of the previous autumn's harvest at low altitude with the same variety CY56 (Trials 8 and 9, i.e. Tables 10 and 11) in spring.

We observed little variation in tuber dry matter content between altitudes or seasons. The usual range was 18-21% (data not shown).

Table 9. Effects of variety and seed source on crop performance in Trial 7; crops from seed harvested from spring '94, and grown in Pengxian in autumn from Aug 17 to Dec 10, 1994.

Variety/ Altitude of previous spring crop's harvest ('94) (A)	Previous year's crop (PX) ('93) (B)	Previous spring crop's ('94) harvest time (C)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
CY56/Low (CD)	Spring	Normal	74	1.9	3.2	8.3
		Early	86	1.9	3.9	10.3
	Autumn	Normal	70	1.4	2.4	7.8
		Early	93	2.1	3.5	12.0
	Mean		*81 b*	*1.8*	*3.3 b*	*9.6*
CY56/High (PX)	Spring	Normal	96	2.1	4.5	10.2
		Early	95	2.1	4.0	9.6
	Autumn	Normal	97	1.9	3.5	12.7
		Early	98	1.8	3.1	12.0
	Mean		*97 a*	*2.0*	*3.8 a*	*11.1*
No. 22-2/High (PX)	Spring	Normal	88	2.0	2.8	11.1
		Early	98	1.9	2.7	10.8
	Autumn	Normal	76	1.4	1.9	5.9
		Early	82	1.9	2.3	7.4
	Mean		*86 b*	*1.8*	*2.4 c*	*8.8*
Averages B	Spring		90	2.0	3.5 a	10.0
	Autumn		86	1.8	2.8 b	9.6
Averages C		Normal	83 b	1.8	3.0	9.4 b
		Early	92 a	2.0	3.2	10.3 a
Grand mean			88	1.9	3.2	9.8
CV (%)			11.6	21.6	17.1	15.1
P or LSD (0.05): Main-plot (A)			7.1[1]	ns	0.35**	ns
Sub-plot (B)			ns	ns	***	ns
Sub-sub-plot (C)			*	ns	ns	$P<0.07$
Interaction AB			10.1[2]	ns	ns	1.8**
AC			ns	ns	*	1.9*
BC, ABC			ns	ns	ns	ns

[1]$P<0.07$; [2]$P<0.06$.

ns, *, **, *** stands for non-significant, significant at $P<0.05$, 0.01, and 0.001, respectively.

Discussion

In general, plant stands and tuber yields were low (Fig. 1), probably because a) whole seed tubers were planted which have longer dormancy than cut seed tubers, b) spacing (5.6 to 6.5 plants/m^2) was too wide considering the number and size of stems, and c) several other growth factors such as drought and warm temperature were limiting. Higher altitude (squares) gave higher yield than lower altitude (circles) (Fig. 1) as reported and discussed by He et al. (1997a). Tuber yield increased exponentially as final plant stand increased (Fig. 1), but the scatter was large beyond 50% final plant stand, indicating that other factors were

Table 10. Effects of seed source and variety on crop performance in Trial 8; crops grown in Chengdu in **spring** from Feb 10 to Jun 10, 1995.

Altitude of previous autumn crop's ('94) harvest (A)	Variety/ Altitude of previous spring crop's harvest ('94) (B)	Crop of 2 years earlier ('93) (C)	Final whole plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuberized plant stand (%)	Final tuber yield (t/ha)
Low (CD)	CY56/Low	Spring	82	1.3	4.2	73	2.8
		Autumn	75	1.3	4.4	96	4.1
	CY56/High	Spring	79	1.0	2.4	24	0.2
		Autumn	89	1.2	4.2	63	2.5
	No. 22-2/High	Spring	69	1.1	2.9	37	0.3
		Autumn	75	1.0	2.5	38	0.4
	Mean		*78*	*1.1*	*3.4*	*55 b*	*1.7 b*
High (PX)	CY56/Low	Spring	82	1.5	4.6	100	4.9
		Autumn	87	1.7	4.1	100	4.7
	CY56/High	Spring	99	1.8	5.2	100	4.5
		Autumn	92	1.7	4.9	98	4.5
	No. 22-2/High	Spring	87	1.6	4.3	100	2.3
		Autumn	87	1.9	4.3	96	2.3
	Mean		*89*	*1.7*	*4.5*	*99 a*	*3.9 a*
Averages B	CY56/Low		81 ab	1.4	4.3 a	92 a	4.1 a
	CY56/High		89 a	1.4	4.1 ab	71 b	3.0 b
	No. 22-2/High		79 b	1.4	3.5 b	68 b	1.3 c
Averages C		Spring	83	1.4	3.9	72 b	2.5 b
		Autumn	84	1.4	4.0	82 a	3.1 a
Grand mean			83	1.4	4.0	77	2.8
CV (%)			12.3	15.7	23.9	10.7	16.7
P or LSD (0.05): Main-plot (A)			ns	ns	ns	*	*
Sub-plot (B)			0.77[A]	ns	0.79[B]	9.8**	0.77**
Sub-sub-plot (C)			ns	ns	ns	*	*
Interaction AB			ns	0.14**	ns	13.8**	1.08[C]
AC			ns	ns	ns	11.6*	0.71*
BC, ABC			ns	ns	ns	ns	ns

[A]$P<0.07$; [B]$P<0.10$; [C]$P<0.06$.

ns, *, **, *** stands for non-significant, significant at $P<0.05$, 0.01, and 0.001, respectively.

also involved. The extremely low yields in some of the treatments of Trials 5 and 8 were due to the fact that seed tubers were extremely young, resulting in low plant stand and late emergence respectively. The differences in yield between spring and autumn seasons were not so striking as those reported by Susnoschi (1982) and Fahem and Haverkort (1988) where tuber yield was much higher in spring than in autumn (at least for most varieties; Susnoschi, 1982). In these reports seed ages were very different between seasons resulting in large differences in stem numbers per plant; in our experiments the differences were much smaller. More stems or tubers per plant generally increased yield (Figs 2 and 3).

Table 11. Effects of seed source and variety on crop performance in Trial 9; crops grown in Pengxian in **spring**, from Feb 27 to Jul 19, 1995.

Altitude of previous autumn crop's harvest ('94) (A)	Variety/Altitude of previous spring crop's harvest ('94) (B)	Crop of 2 years' earlier ('93) (C)	Final plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Final tuber yield (t/ha)
Low (CD)	CY56/Low	Spring	88	1.5	4.0	11.8
		Autumn	78	1.7	3.7	12.0
	CY56/High	Spring	93	1.3	3.8	6.9
		Autumn	75	1.3	3.8	9.1
	No. 22-2/High	Spring	95	1.6	3.6	13.7
		Autumn	78	1.6	3.4	9.2
	Mean		*85*	*1.5 b*	*3.7 b*	*10.5*
High (PX)	CY56/Low	Spring	78	1.8	4.2	10.1
		Autumn	88	2.5	4.4	12.3
	CY56/High	Spring	90	1.6	4.9	9.6
		Autumn	90	2.0	4.4	11.1
	No. 22-2/High	Spring	82	2.3	4.2	13.0
		Autumn	72	2.3	4.5	11.1
	Mean		*83*	*2.1 a*	*4.4 a*	*11.3*
Averages B	CY56/Low (CD)		83	1.9 a	4.1	11.5 a
	CY56/High (PX)		87	1.5 b	4.2	9.2 b
	No. 22-2/High (PX)		82	2.0 a	3.9	11.8 a
Averages C		Spring	88 a	1.7 b	4.1	10.8
		Autumn	80 b	1.9 a	4.0	10.8
	Grand mean		84	1.8	4.1	10.8
	CV (%)		10.8	15.5	11.1	20.1
	P or LSD (0.05): Main-plot (A)		ns	P<0.10	*	ns
	Sub-plot (B)		ns	0.40[A]	ns	0.67***
	Sub-sub-plot (C)		*	P<0.07	ns	ns
	Interaction AB		ns	ns	ns	0.95**
	BC		ns	ns	ns	2.73*
	AC		9.3*	ns	ns	ns
	ABC		ns	ns	ns	ns

[A]P<0.10. ns, *, **, *** stands for non-significant, significant at P<0.05, 0.01, and 0.001, respectively.

Effects of seed flow observed in our experiments can be summarized as follows:

1) Seed derived from crops grown at low altitude and tested also at low altitude gave poor yield, except when produced in previous spring and planted in autumn of the same year.
2) Seed derived from crops grown at low altitude but tested at high altitude gave good yield, even better than seed derived from crops both grown and tested at high altitude.

3) Seed derived from crops grown at high altitude but tested at low altitude gave poor yield, except after long storage (one season's interval), due to inadequate seed age.
4) Seed derived from crops grown at high altitude and tested also at high altitude gave good yield, except once for cv. No. 22-2, the long dormancy variety.

These effects were generally not affected by the effects of cultivar or the conditions of the seed production of earlier generations. So, the altitude of seed production plays a major role in determining potential performance. But also the season of seed production is important. Both effects probably act through effects on seed age and seed health status. Seed health can be restored by growing seed at high altitude or by regenerating it each season.

Table 12. Effects of variety and seed source on crop performance in Trial 10; crops grown in Pengxian in **autumn**, from Aug 23 to Dec 13, 1995.

Variety	Seed flow	Seed age	Plant stand (%)	Stem (#/pl)	Tuber (#/pl)	Tuber yield (t/ha)
CY56	94s-94a-----	+++	77	4.0	5.2	7.1
	94s-----95s-	++	58	1.8	5.4	5.5
	94s-94a-95s-	+	71	2.0	3.3	4.6
No. 22-2	94s-94a-----	+++	77	4.5	6.7	12.0
	94s-----95s-	++	54	1.0	2.0	5.2
	94s-94a-95s-	+	13	1.3	4.3	0.8

Note: s = spring season/crop; a = autumn season/crop;
-: a short term storage; -----: one season's storage.

Spring crops require relatively old seed at lower altitude even for the mid-early variety CY56 in order to grow shorter. At higher altitude spring crops require relatively young seed in order to let the crop grow longer for better yields (Table 3) (cf. Carls and Caesar, 1979). Seed flow 1 had proper seed age and growth vigour at planting; it should be practised for lower altitudes (< 800 m asl) potato production; seed flow 3 is widely practised for higher altitudes (> 800 m asl) production and should be further promoted there. Both situations of shorter growing period at lower altitude with relatively old seed and longer growing period at higher altitude with relatively young seed make better use of the available solar radiation in terms of photosynthetically active radiation intercepted, hence resulting in higher yields (Table 3).

In the other situations of the spring crop, the observation that variation in status of the seed is still traceable after several multiplications is unique but its explanation is somewhat complex (Tables 10 and 11). At lower altitude, although the seed origins of the previous crop

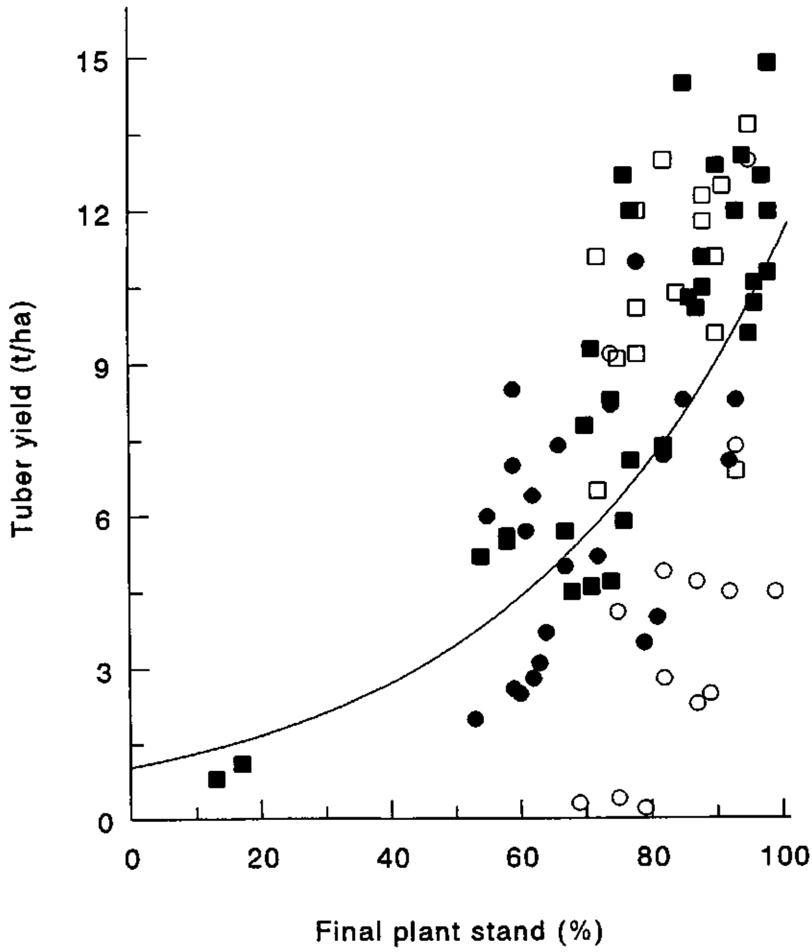

Figure 1. The relation between final plant stand and tuber yield in all experiments combined (n=81). The curve fitting was done after excluding the lowest three open circles.
○ = Chengdu/Spring; ● = Chengdu/Autumn;
□ = Pengxian/Spring; ■ = Pengxian/Autumn.

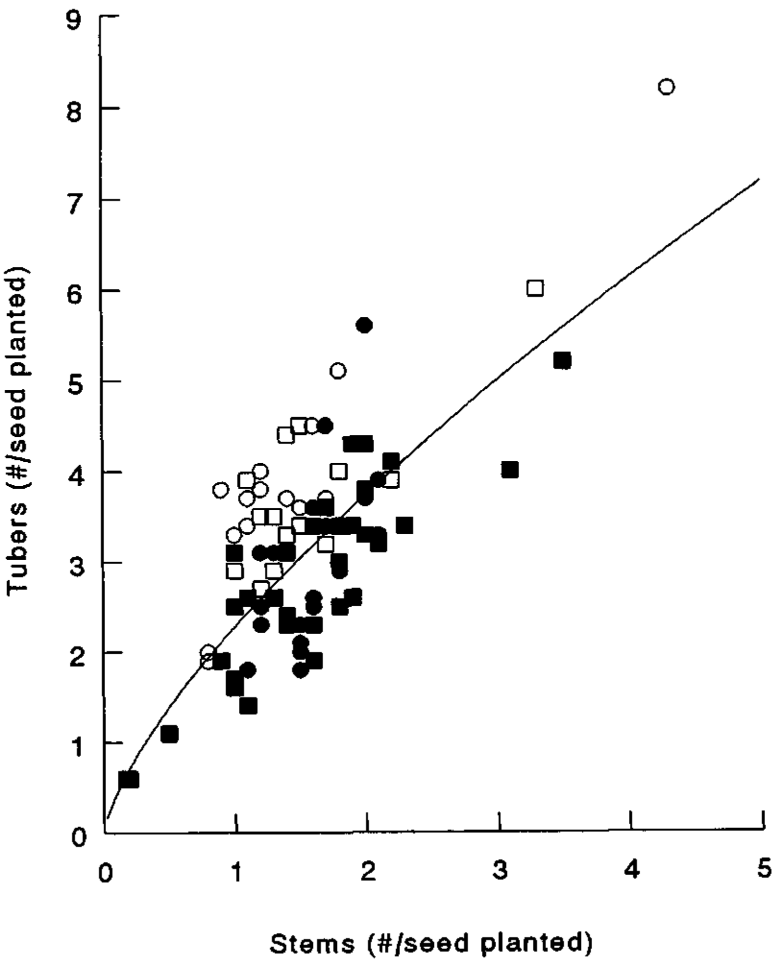

Figure 2. Relation between the number of stems per seed tuber planted and the number of tubers per seed planted (data of all experiments combined).

○ = Chengdu/Spring; ● = Chengdu/Autumn;

□ = Pengxian/Spring; ■ = Pengxian/Autumn.

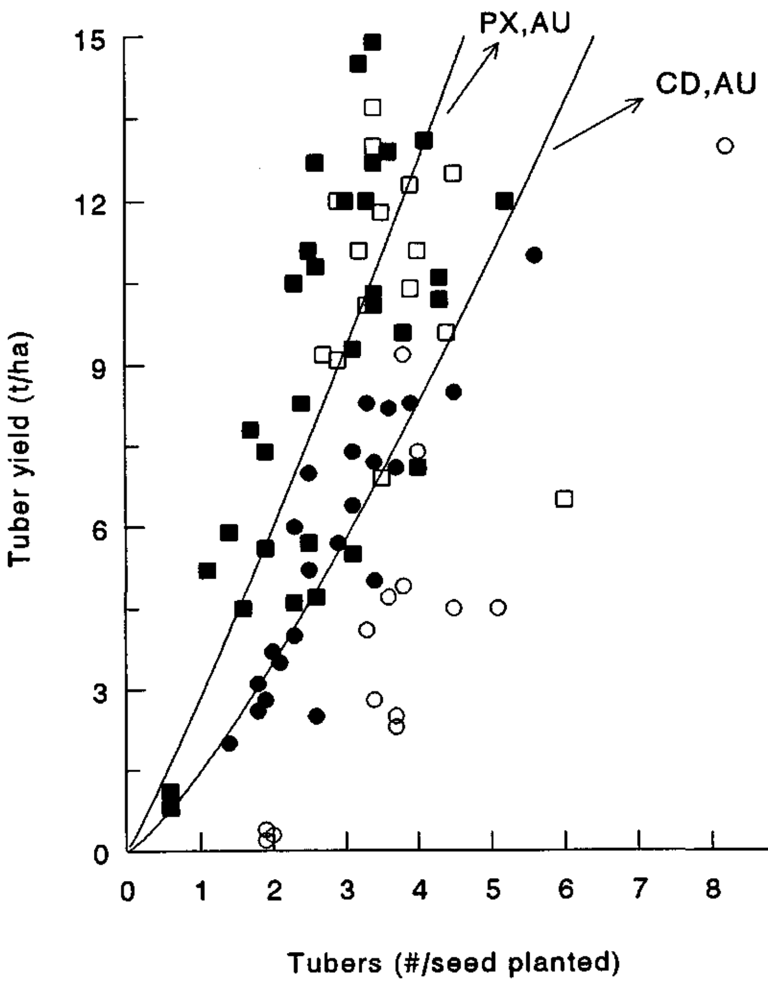

Figure 3. Relation between the number of tubers per seed tuber planted and the tuber yield (data of all experiments combined).

○ = Chengdu/Spring; ● = Chengdu/Autumn;

□ = Pengxian/Spring; ■ = Pengxian/Autumn;

PX, AU = Pengxian/Autumn; CD, AU = Chengdu/Autumn.

(factor A) and of the seed crop three multiplications back (factor C) are required to be younger, the source of the previous two consecutive seasons' multiplication (generations) crops (factor B) is required to be older for better plant stand and higher yield (Table 10). The younger sources of A and C may be necessary for a healthy seed and vigorous growth in combination with the older source of B which may play a key role in determining higher potato production at lower altitude. This was also suggested by Trial 9 (Table 11) at higher altitude where only factor B influenced the seed age to such an extent that it promoted tuber yield, while the younger source in factor C had only a minor influence, i.e. promoted plant stands and tuber yields for No. 22-2.
However, the above mentioned relations can be partly an artifact because other factors such as seed health status may have been involved.

Relating the final plant stands of both seasons to the corresponding yield responses as affected by the different seed sources suggests that different seed sources had no major influences on final plant stands for CY56 but had an effect on No. 22-2 at both altitudes. Probably, the yield increase is due to faster emergence and/or longer canopy duration for crops of No. 22-2 from older sources.

In autumn crops, older seed sources are generally required at both low and high altitudes (Tables 4-9, 12); this can be manipulated by the seed source of the previous crop or even of two multiplications back, especially for the variety with a longer dormancy No. 22-2. This will ensure higher yields in both seasons, because the season has a shorter potato growing period and the soil temperatures early after planting are high causing seed tubers that do not germinate to decay soon or simply to grow out much later. Tuber numbers and stem numbers per seed planted were positively correlated, although spring crops have more tubers at the same number than autumn crops because of the longer and warmer season in spring (Fig. 2). Tuber yield was linked closer to tuber numbers per seed planted in autumn than in spring with higher average tuber weights at the higher altitudes (Fig. 3). Generally, the stem number per plant is variable and is associated with seed age. The season during the cycle of three consecutive multiplications back (spring or autumn-grown, factor C) probably had no effect or much less influence on crop performance in the autumn season than in the spring season (Tables 10 and 11), because previous spring season is supposed to have more temperature sum accelerating crop senescence and increasing seed age thus affecting the autumn crop's performance. Again, other factors may be involved in determining the relations.

The favourable effect of seed source of early harvest of the previous crops of variety CY56 harvested at lower altitude (Tables 8 and 9) on crops grown at the higher altitude is probably attributable to the need for older seed and to a better plant stand in autumn. The positive effect of early harvest may have a function similar to that of early haulm killing of the crop, which can effectively block viruses and other pathogens' infection to the underground tubers in the late season when aphids are flying (Beukema and Van der Zaag, 1990) especially when grown at low altitude, but also enhances the physiological development of the seed. This kind of seed tubers is therefore healthy and of the right physiological age and can make the subsequent crop grow well and have a better plant stand. This is more true for CY56 than for No. 22-2 because the latter could not benefit from manipulation of the seed flows due to its longer growth cycle and dormancy.

The small variation observed in dry matter content is in contrast with the findings of Fahem and Haverkort (1988) who found wide ranges comparing different seasons in North Africa.

Conclusions

The trials have clearly shown that the growing altitudes and seasons during seed production have substantial impact on the physiological status of seed, which subsequently determined tuber yield. The unique ways of seed flows and their effects on potato production have been revealed. The physiological age and health status, together with genetic factors of seed tubers prior to planting are involved interactively.

For spring crops, seed tubers of relatively old age at low altitude and relatively young age at high altitude gave better plant stands and higher tuber yields. For autumn crops, seed tubers of relatively old age both at low and at high altitudes showed better plant stands and higher tuber yields. Seed age can be manipulated by proper selection of seed flows and sources, particularly by selecting the right altitude of seed production.

There are several unique alternatives of manipulating seed source generally; the differences are substantial and long lasting. Therefore, optimization of the seed supply system is crucial for yield improvement in the region.

Chapter 5

Effects of seed tuber weight on potato as influenced by seed origin, plant density and variety under different ecological conditions in Sichuan, China

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Summary

Seed tuber weight affects growth and yield of potato. A study was carried out to investigate these effects and their interactions with effects of the other factors in sub-tropical double cropping systems. When evaluated at constant spacing, seed tuber weight significantly affected tuber yield in all conditions under study although seed origin, variety, altitude and season modified these effects in varying degrees. The effects of seed tuber weight could be attributed to more main stems per plant from heavier seed tubers, resulting in more tubers produced per plant and thus per unit area. Higher plant density also increased yield probably by increasing weight of progeny tubers. This effect can be due to larger canopy cover which cools down the soil and thus enhances partitioning to the tubers. When number of sprouts were set equal per unit area, the effect of weight of seed tubers on final tuber yield per unit area was absent in seed tuber weight range from 22 to 124 g, although lighter seed tubers resulted in lower plant stand and therefore sometimes fewer stems per plant. However, lighter seed tubers tended to increase leaf area per plant thus compensating the lower plant stand, with larger progeny tubers achieved. If calculated at a per stem basis the numbers of tubers produced and the tuber yields were different for the seed weight treatments; these differences were confounded by seed age effects. The number of tubers produced per unit area largely determined plant yield because the varieties used produced few tubers per plant whereas variation was caused by seed weight or seed density. The relation between number of tuber per seed planted and tuber yield was different for the two sites. Higher yields were also associated with higher growth rate of leaves and plants.
The mutual relationships between the yield parameters resulting from the effects caused by the treatments were also discussed.

Key words: Seed tuber weight, seed origin, plant density, yield, tuber number.

Introduction

The size or weight of seed tubers often varies. In association with size or weight, dormancy

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(Burton et al., 1992; Van Ittersum, 1992), number of sprouts and main stems per seed tuber (Allen, 1978; Allen and Wurr, 1992), growth vigour (Van der Zaag and Van Loon, 1987; Van Ittersum et al., 1993), dry matter content (Veerman et al., 1996) and resistance to adverse (both biotic and abiotic) conditions may be different. Within normal ranges of environmental conditions and of physiological age, especially the effect of weight on number of stems per plant is relevant. The number of eyes per tuber increases with tuber weight, though at a decreasing rate and so does the number of sprouts or stems per seed tuber (Allen, 1978). This effect influences the number of tubers produced per plant from seed tubers (Allen, 1978), and the growth pattern and yield of crops grown from these seed tubers. The influence of seed weight therefore depends on plant arrangement and plant density. Practically, the seed rate (weight of seed planted per unit area), i.e. the product of number of seed tubers planted and their average weight, should be determined and knowledge on the effect of seed tuber weight in a specific environment is needed.

In Sichuan, China, the row width is much narrower than in the temperate regions because of shorter growth cycles and hand harvesting. It normally ranges between 50 to 60 cm. Independent of weight, seed quality as affected by different origins can influence the performance of growth and yield (Allen et al., 1992; Wiersema and Booth, 1985; He and Struik, 1997). Seed quality is usually determined by its physiological age and its health status (Wurr, 1978). Seed origin including previous growing (such as location and altitude) and storage conditions largely determines both aspects (Wurr, 1978; Wiersema and Booth, 1985; Burton et al., 1992).

This paper describes research carried out to: 1) quantify the effects of seed tuber weight on crop performance per unit area, in interaction with inherent seed characteristics, seed origin, variety, and environment (season, altitude and planting density); 2) test what effects on plant growth and yield the different seed tuber weights have at a per stem basis under different conditions of seed quality.

Materials and Methods

Table 1 gives an overview of the experimental details and the treatments. The trials were basically set up as factorials in a split-split-plot design, with variety as main factor (A), density as split factor (B) and seed tuber weight as split-split factor (C). Varieties used were CY56 and 813-17 (mid-early) or HH6 and 378711.7 (late). The seed tubers of the varieties of the 1994 and 1995 trials came directly from the crops locally harvested in the previous

Table 1. Experimental details and treatments of the Trials (1 to 10).

Location	Chengdu (104.2°E, 30.6°N, 500 m asl)			
Trial	Trial 1 (and 9)[a]	Trial 2 (and 10)[a]	Trial 3[b]	Trial 4[b]
Season/Year	Spring '94	Spring '95	Autumn '94	Autumn '95
Planting dates (day/month)	Jan 26 (Jan 28)	Jan 23 (Jan 27)	Sep 9	Sep 4
Harvesting (day/month)	Jun 7 (Jun 8)	Jun 9 (Jun 10)	Dec 6	Dec 6
Replications	3 (2)	3 (2)	3	3
Variety	CY56/378711.7	CY56/378711.7	CY56s/CY56a	CY56s/CY56a
Seed tuber weight (g)				
Heavy	96.1±5.6/123.8±4.4	65.5±3.5/76.8±3.4	95.0/117.7	78.8/88.7
Medium	54.9±1.5/81.0±1.8	45.1±1.3/46.5±2.1	39.6/74.0	46.2/43.5
Light	29.8±1.1/42.0±2.7	29.0±0.8/21.5±1.0	19.8/36.5	23.3/16.3
Plant spacing (cm)	60x25, 60x35	60x25, 60x35	60x25, 60x35	57x25, 57x35
Net plot dimension (m)	3.0x3.0 (2.0x1.8)	3.0x2.4 (2.0x1.8)	3.0x2.4	3.0x2.28
N-application (kg/ha)	Approx. 70	Approx. 70	Approx. 70	Approx. 70
P_2O_5-application (kg/ha)	Approx. 50	Approx. 50	Approx. 50	Approx. 50
K_2O-application (kg/ha)	Approx. 50	None	Approx. 50	None
Location	**Liangping (107.8°E, 30.6°N, 750 m asl)**			
Trial	**Trial 5**	**Trial 6**	**Trial 7**	**Trial 8**
Season/Year	Spring '94	Spring '95	Autumn '94	Autumn '95
Planting dates (day/month)	Jan 25	Feb 15	Sep 1	Sep 21
Harvesting (day/month)	Jun 14	Jun 27	Nov 24	Dec 9
Replications	3	3	3	3
Variety	CY56/378711.7	CY56/378711.7	CY56/813-17	CY56/HH6
Seed tuber weight (g)				
Heavy	74.8/75.1	69.1±3.0/71.0±3.1	65.8/65.7	71.5/71.4
Medium	54.9/54.9	48.1±1.7/51.0±2.1	47.4/47.8	45.6/45.6
Light	32.6/33.1	31.1±0.9/31.4±1.3	29.7/29.7	32.0/32.1
Plant spacing (cm)	60x25, 60x35	60x25, 60x35	50x25, 50x30	50x25, 50x30
Net plot dimension (m)	3.33x3.0	3.33x2.4	3.33x1.0	3.33x1.0
N-application (kg/ha)	Approx. 40	Approx. 40	Approx. 40	Approx. 50
P_2O_5-application (kg/ha)	Approx. 40	None	None	None
K_2O-application (kg/ha)	None	None	None	None

[a] Means (n=20) of tuber weights are followed by the SE (after a sign '±'; the other SE values were not measured but have similar values); for Trial 9, cv. CY56, the distances between plants were 29, 17 and 12 cm for the weights of heavy, medium and light, respectively; for cv. 378711.7, those figures were 39, 23 and 19 cm respectively; for Trial 10, cv. CY56, the figures were 28, 18 and 16 cm respectively; for cv. 378711.7, the figures were 36, 26 and 21 cm respectively.
[b] Cv. CY56s and CY56a stand for previous spring and autumn origins of the seed tubers, respectively.

spring of 1993 and 1994 respectively in Pengxian or Liangping. Variety 378711.7 had the right physiological stage prior to planting with sprouting, fairly firm seed tubers compared with cv. CY56 seeds which had longer sprouts and were less firm. The other two varieties had younger seeds. Two seed tuber densities were included: 60x25 or 60x35 cm in Chengdu and in the spring seasons of Liangping; 50x25 or 50x30 cm in the autumn seasons at Liangping. There were three tuber weights (heavy, medium, light) as shown in Table 1, which include the normal weight range in production. These trials were carried out to investigate the effect of different seed tuber weights under constant seed densities for each weight. The variety effect was replaced by seed source effect (seeds from either s: spring or a: autumn crop) in two trials in Chengdu during the autumns of 1994 and 1995.

In two supplemental trials (Trials 9 and 10) in Chengdu, the number of sprouts planted per unit area was kept constant to investigate the effects of seed tuber weight at similar stem number per m^2. To realize this, sprouts were counted on 20 tubers of different weight categories before planting. For CY56, light tubers had on average 1.1, medium tubers 1.5 and heavy tubers 2.6 sprouts per seed tuber; for 378711.7 these figures were 1.7, 2.1, and 3.5, respectively. Distances between plants were adjusted and varied for variety and seed tuber weight to obtain similar sprout numbers per unit area.

The cropping systems and climatic conditions were as described previously (He et al., 1997a; 1997b).

Relatively old seed was used in spring seasons to avoid the effect of too young seed which would not show much effect because of apical dominance. Seed tubers were planted whole. Irrigation was applied 2 to 5 times when needed.

Stem number was recorded by counting the number of above ground possible main stems (omitting the thin ones of less than 5 mm in diameter) of 5 plants per plot; branch number was recorded by counting the branches of more than 2 cm long of 5 plants per plot. Tuber number was counted on the whole plot basis. Canopy cover was measured periodically using a grid (Burstall and Harris, 1983). Light interception f_{int} was recorded by assuming that it is equivalent to the corresponding canopy cover (Beukema and Van der Zaag, 1990; Haverkort et al., 1991). Cumulative absorbed PAR (photosynthetically active radiation) was determined by: $PAR_{abs}=(1-\rho_c)\cdot f_{int}PAR$ (Spitters, 1987), where ρ_c=crop reflection coefficient for PAR often set to be 0.08, and converting global solar radiation data (times 0.5) of local meteorological stations to PAR. Light use efficiency (LUE) was assessed by dividing actual total plant dry weight by total PAR_{abs}. Harvest index (HI) was determined by dividing actual tuber dry weight per plant by actual total plant dry weight, but excluding roots which contributed little to total weight and were difficult to retrieve quantitatively.

Photosynthesis rate of whole plants was measured by labelled isotope ^{14}C according to the method described by Chen (1983). Photosynthesis rate per unit of leaf area was measured by the 'Half leaf method' (Anonymous, 1980), which is based on the concept that plant organic matter produced by photosynthesis, if not translocated outside the leaves, will accumulate inside the leaves, thus increasing the dry matter per area per time interval. About 10 uniform leaves were selected and each was cut into two halves. One half was kept in a dark and humid environment to maintain its respiration but to stop photosynthesis. The other half leaf was kept in-vivo to allow continuous photosynthesis; the veins in petioles were artificially blocked by hot water so that photosynthates accumulated in the leaves. The weight difference of the two half leaves after dividing by their respective areas and the time lapse would serve as an estimation of net photosynthetic rate per unit area.

Growth and yield data were collected and were analyzed statistically using programmes of MSTAT-C and COSTAT. In the tables, different letters indicate significant differences; no letters are placed when treatment effects were not significant. Tables usually only show statistics of main effects since interactions were only relevant in a few cases.

Results

Table 2 shows that in Chengdu (500 m asl) in spring, heavier seed tubers gave higher tuber yields than the lighter ones at both seed densities whereas the plant stands were similar. Numbers of main stems were higher for heavier seeds and numbers of branches per plant were similar. The yield increase of heavier seed tubers was associated with more tubers per plant. Denser spacing also increased tuber yield, but the other growth parameters listed were hardly affected. This suggests that the yield response was associated with differences in average tuber weight. The two varieties had the same seed origin but different plant stands, and responded very differently to the seasons. Tuber yield of variety 378711.7 was significantly lower than of cv. CY56 in spring 1994 while the opposite was true in spring 1995 in Chengdu. This discrepancy could be due to the dry and warm weather during the early spring of 1994. Frequent irrigation was applied, and the crop of 378711.7 grew very vigorously but when it became warmer in May and June this late cultivar had not enough time for tuber bulking. Therefore many light tubers per unit area were produced (data not

Table 2. Effects of seed tuber weight, seed density and variety in Trial 1, grown from Jan 26 to Jun 7, 1994, and Trial 2, from January 23 to June 9, 1995; both spring trials were carried out in Chengdu. All seed tubers were derived from the previous spring crops.

	Plant stand (%)	Main stems (#/pl)	Branches (#/pl)	Tubers (#/pl)	Tuber yield (t/ha)
Trial 1 (1994)[1]					
Seed tuber weight (C)					
Heavy	92	5.0a	8.6	7.9a	10.4a
Medium	91	4.4 b	6.8	6.4 b	8.5ab
Light	91	3.4 c	7.9	5.3 b	6.9 b
Density (B)					
60x25 cm	91	4.3	7.3	6.4	9.7
60x35 cm	92	4.3	8.2	6.7	7.6
Variety (A)					
CY56	85 b	4.3	5.3	7.3	10.8a
378711.7	97a	4.3	10.2	5.7	6.5 b
Trial 2 (1995)[2]					
Seed tuber weight (C)					
Heavy	81	4.5a	3.2	10.1a	15.8a
Medium	75	3.9 b	2.9	10.9a	14.9a
Light	82	3.3 c	3.4	8.4 b	12.0 b
Density (B)					
60x25 cm	80	3.9	2.9 b	9.6	15.8a
60x35 cm	78	3.9	3.4a	10.0	12.7 b
Variety (A)					
CY56	64 b	4.4a	0.9 b	8.3	8.9 b
378711.7	95a	3.4 b	5.4a	11.3	19.6a

[1] Difference of means between varieties for yield was statistically significant at $P<0.07$; difference of means between varieties for branches was significant at $P<0.12$, and interaction between the 3 factors was significant at $P<0.05$.

[2] Difference of means between varieties for plant stand was statistically significant at $P<0.06$; interaction of AxB for branch number at $P<0.05$.

shown) and yield was low; in 1995, temperatures were lower and less irrigation was needed; the canopy of 378711.7 developed normally and bulking started earlier; the crop formed heavier tubers and yield was high. Tuber numbers per plant were consistent with tuber yields for the two varieties.

Table 3 shows results of similar trials carried out in autumn but with only one (early) cultivar with two different seed origins. Effects of tuber weights and densities were similar to those in spring crops. However, older seed resulted in higher plant stands; therefore effects of seed tuber weight and seed source on tuber yield were partly brought about by effects on plant stand, especially in 1994.

The same set of trials was carried out at higher location (750 m asl) (Tables 4 and 5). In spring (Table 4), results showed similar effects of seed tuber weights and densities in that heavier seed tubers generally gave higher yield, but the yield was hardly affected by density

Table 3. Effects of seed tuber weight, seed density and seed source in Trial 3, grown from Sep 9 to Dec 6, 1994, and Trial 4, from Sep 4 to Dec 6, 1995, both autumn trials carried out in Chengdu. Seed tubers were derived either from previous spring or autumn crops as indicated in parentheses.

	Plant stand (%)	Main stems (#/pl)	Branches (#/pl)	Tubers (#/pl)	Tuber yield (t/ha)
Trial 3 (1994)[1]					
Seed tuber weight (C)					
Heavy	80a	3.4a	0.9	4.3a	8.7a
Medium	70 b	2.5 b	1.4	3.8 b	5.8 b
Light	64 b	1.8 c	1.1	3.3 c	4.0 c
Density (B)					
60x25 cm	70	2.5	1.2	4.0a	7.1a
60x35 cm	73	2.6	1.1	3.5 b	5.2 b
Seed source (A)					
CY56 (spring)	85a	2.6	1.2	4.2a	7.6a
CY56 (autumn)	57 b	2.5	1.1	3.4 b	4.7 b
Trial 4 (1995)[2]					
Seed tuber weight (C)					
Heavy	75	3.1a	4.7 a	6.7a	10.1a
Medium	73	2.4 b	3.6 ab	6.2a	8.8a
Light	67	1.8 c	3.0 b	4.9 b	6.2 b
Density (B)					
57x25 cm	68	2.4	3.5	5.9	8.9a
57x35 cm	75	2.4	4.0	5.9	7.8 b
Seed source (A)					
CY56 (spring)	83a	2.44a	3.6	6.0	10.7a
CY56 (autumn)	60 b	2.39 b	3.9	5.9	6.0 b

[1]·Interaction of AxC for plant stands was significant at $P<0.05$; interaction of BxC for branches at $P<0.05$; BxC and AxBxC for tuber numbers at $P<0.01$.

[2]·Difference of means between densities for tuber yield was significant at $P<0.10$ and the interaction of AxC at $P<0.05$; difference of means between seed tuber weights for branches was significant at $P<0.06$ and the interaction of AxB at $P<0.05$.

Table 4. Effects of seed tuber weight, seed density and variety in Trials 5 and 6, crops grown in Liangping, from Jan 25 to Jun 14, 1994 and Feb 15 to Jun 27 (spring crops), 1995, respectively. All seed tubers were derived from previous spring crops.

Seed treatment	Trial 5, 1994			Trial 6, 1995			
	Stand (%)	Tubers (#/pl)[1]	Yield (t/ha)	Stand (%)[2]	Main stems (#/pl)[3]	Tubers (#/pl)	Yield (t/ha)
Tuber weight (C)							
Heavy	93	13.1a	12.6	94a	5.3a	19.4a	13.3a
Medium	93	11.1ab	12.4	87 b	4.5 b	15.8 b	12.0a
Light	91	8.9 b	11.6	82 b	3.6 c	11.5 c	8.0 b
Density (B)							
60x25 cm	91	10.8	12.9	84	4.5	15.2	11.3a
60x35 cm	94	11.3	11.4	92	4.5	15.9	10.1 b
Variety (A)							
CY56	87 b	13.1a	10.4 b	76 b	4.6	14.1 b	8.4 b
378711.7	98a	9.0 b	13.9a	99a	4.4	17.0a	13.8a

[1]·F tests between weights significant at $P<0.08$; between varieties at $P<0.06$; [2]·interaction of AxC was significant at $P<0.01$; [3]·AxC at $P<0.01$;

treatments. Variety 378711.7 consistently gave higher plant stands and yields than cv. CY56 in both years. It also shows a longer dormancy and requires a longer growing period to tuberize. Hence it could make better use of the long growing period under the cooler conditions of the higher elevation. There was a tendency that the effect of seed tuber weight on yield was reduced at the higher location, especially in Trial 5 (spring season, Table 4). Table 5 shows results from trials in autumn. The yields were affected by seed tuber weights in both years. The effects of seed tuber weights and densities were similar to those in Chengdu in autumn, but the plant stands and yields were higher.

Table 5. Effects of seed tuber weight, seed density and variety in Trials 7 and 8, crops grown in Liangping, from Sep 1 to Nov 24, 1994 and Sep 21 to Dec 9 (autumn crops), 1995, respectively. All seed tubers were derived from previous autumn crops. Data on tuber number were not recorded for Trial 7.

Seed treatment	Trial 7, 1994		Trial 8, 1995			
	Stand[1] (%)	Yield[2] (t/ha)	Stand (%)	Stems (#/pl)	Tubers (#/pl)	Yield (t/ha)
Tuber weight (C)						
Heavy	81	14.1a	91	4.7a	7.5a	10.4a
Medium	82	12.9a	92	3.5 b	6.4 b	8.5 b
Light	80	10.9 b	90	2.8 c	5.5 c	6.8 c
Density (B)						
50x25 cm	76 b	13.0	91	3.7	6.5	8.8
50x30 cm	86a	12.3	92	3.5	6.5	8.3
Variety (A)[3]						
CY56	82	13.1	92	3.2 b	7.3a	9.2a
813-17/HH6	79	12.2	90	4.0a	5.7 b	7.9 b

1. Interactions of BxC and AxBxC were significant at $P<0.05$.
2. Interaction of BxC significant at $P<0.01$.
3. The variety 813-17 was replaced by the variety HH6 in 1995.

Seed tuber weight, plant density and variety effects usually did not interact. In a few trials relevant interactions occurred for plant stands: a), in a spring trial in Liangping (Table 4) the effect of seed tuber weight on plant stand was only significant in cv. CY56; b), in the autumn trial in Liangping (Table 5), a significant three way interaction occurred for plant stand.

There were no differences in tuber yield between seed tuber weights in the trials in which the number of sprouts per m^2 was kept constant for all seed tuber weights (Table 6), although there were differences in tuber numbers per plant, plant stands and numbers of main stems, which were similar to the differences in previous trials. Again, the same conflicting trends of the cultivar effects were shown for both trials.

Table 6. Effects of seed tuber weight and variety in Trial 9, crops grown from Jan 28 to Jun 8, 1994, and Trial 10, grown from Jan 27 to Jun 10, 1995; both trials were supplementary, in Chengdu (spring season), with more or less fixed numbers of sprouts/m². All seed tubers were derived from previous spring crops.

	Plant stand (%)	Main stems (#/pl)	Branches (#/pl)	Tubers (#/pl)	Tuber yield (t/ha)
Trial 9, 1994[1]					
Seed tuber weight (B)					
Heavy	88	5.3	6.9a	6.5a	6.5
Medium	87	5.0	4.7 b	3.9 b	6.7
Light	79	3.9	4.7 b	3.9 b	6.6
Variety (A)					
CY56	74 b	5.0	3.2 b	6.7	10.5a
378711.7	95a	4.5	7.7a	2.8	2.7 b
Trial 10, 1995[2]					
Seed tuber weight (B)					
Heavy	81a	4.9a	4.2a	11.9a	16.0
Medium	75 b	4.5a	2.3 b	10.1a	17.8
Light	69 c	3.0 b	3.5ab	8.6 b	16.1
Variety (A)					
CY56	56 b	5.0a	0.6	8.2	10.9 b
378711.7	93a	3.3 b	6.1	12.2	22.3a

1. Differences of means between varieties for plant stands and for yield were significant at $P<0.10$ and $P<0.08$, respectively.

2. Difference of means between varieties for yield significant at $P<0.09$; interactions of AxB for plant stands and tuber numbers at $P<0.05$.

Tuber numbers and tuber yields per stem (results not presented) did not differ between the seed tuber weight treatments in the spring seasons, but the tuber number per stem increased while the yields per stem still remained the same as the seed tuber weight decreased in the autumn seasons, under the same seed density conditions (Tables 2 to 5); the yields per stem increased as the seed tuber weight decreased, although the tuber numbers per stem remained similar in the spring seasons when fixed numbers of sprouts per unit area were planted (Table 6).

The photosynthesis measurements reflected that higher plant photosynthesis rate was found in plants from heavier seed tubers (Table 7) and heavier seed tubers tended to have slightly higher photosynthesis per unit of leaf area as well (Table 8). Stems contributed only little to plant photosynthesis although trends were similar to those in leaves (Table 7).

Table 9 summarizes the results on total cumulative absorbed PAR (ΣPAR_{abs}) in MJ/m², LUE in g/MJ and tuber harvest index (HI) in g/g obtained in Chengdu. These three parameters jointly determine tuber (dry) yield (g/m²). Generally, variation in ΣPAR_{abs} accounted to a

Table 7. Photosynthesis rate per plant measured in Chengdu, spring, 1994, in CO_2 mg/hr/plant, using labelled isotope ^{14}C. CY56 was tested on May 19 when light intensity was 0.292 kW/m^2; and 378711.7 on April 27 with 0.694 kW/m^2. All seed tubers were derived from previous spring crops.

Variety	Seed weight	Leaves	Stems	Total plant
CY56	Heavy	8.5	1.0	9.5
	Medium	6.3	0.5	6.8
	Light	5.7	0.6	6.3
378711.7	Heavy	42.9	6.0	48.9
	Medium	30.4	4.6	35.0
	Light	33.2	5.6	38.8

Table 8. Photosynthesis (P) rate per unit of leaf area using the 'Half leaf method' measured in Chengdu, May 3 (spring), 1995. The rate included respiration, in kg DW/ha/hr, or mg DW/dm^2/hr. Light intensity was approx. 0.5 kW/m^2. All seed tubers were derived from previous spring crops.

Variety	Seed weight	P rate
CY56	Heavy	6.5
	Medium	5.0
	Light	4.8
	Mean	*5.5*
378711.7	Heavy	8.9
	Medium	9.3
	Light	6.9
	Mean	*8.4*

large extent for variation in yields within varieties (Tables 2 and 5) for the trials in which seed densities were set equal. For the supplemental trials (where stem densities were set similar) that was not the case: in spring 1994, differences in LUE were also relevant and consistent with differences in photosynthesis. Differences in yield between varieties were mainly explained by both differences in intercepted PAR and in harvest index. Harvest indices as influenced by seed tuber weight and seed density, varied over seasons and years, particularly between varieties in spring 1994. The total ΣPAR_{abs} in autumns were much lower due to the shorter growing season and lower solar radiation levels. However, the LUEs were higher than in spring, supporting other results (Kooman and Rabbinge, 1995; He et al., 1997a).

Table 9. Effects of seed tuber weight, seed density and variety or seed source on ΣPAR_{abs} (MJ/m^2), LUE (g DM/MJ) and HI (g/g, dry weight basis) in Trials 1 through 4, 9 and 10, all in Chengdu. Seed tubers were derived either from previous spring crops (s) or autumn crops (a) as indicated in parentheses.

Treatment	Spring, 1994			Spring, 1995		
	ΣPAR_{abs}	LUE	HI	ΣPAR_{abs}	LUE	HI
Tuber weight						
Heavy	211	2.47	0.41	169	2.42	0.81
Medium	197	2.46	0.36	160	2.45	0.80
Light	175	2.38	0.34	138	2.30	0.79
Density						
60x25 cm	208	2.45	0.39	173	2.46	0.78
60x35 cm	180	2.47	0.35	139	2.31	0.83
Variety						
CY56 (s)	154	2.34	0.60	95	2.33	0.83
378711.7 (s)	234	2.53	0.23	217	2.31	0.84
	Autumn, 1994			Autumn, 1995		
Tuber weight						
Heavy	57	4.30	0.73	97	3.31	0.64
Medium	42	4.05	0.70	81	3.45	0.64
Light	29	4.71	0.60	62	3.14	0.65
Density						
60x25 cm	50	4.06	0.71	86	3.25	0.65
60x35 cm	35	4.39	0.70	74	3.34	0.64
Seed source						
CY56 (s)	50	4.50	0.69	105	3.21	0.65
CY56 (a)	34	4.00	0.71	56	3.43	0.64
	Spring[1], 1994			Spring[1], 1995		
Tuber weight						
Heavy	167	1.95	0.41	169	2.45	0.81
Medium	189	2.02	0.36	195	2.39	0.80
Light	177	2.25	0.34	175	2.44	0.79
Variety						
CY56(s)	152	2.30	0.60	137	1.99	0.83
378711.7(s)	198	1.24	0.23	223	2.54	0.84

[1] Trials 9 and 10 (supplementary trials).

Discussion

When evaluated in the same spacing, weight of seed tubers had significant effects on tuber yield under all conditions, i.e. the heavier the seed tubers the higher the yield (Fig. 1). There were interactions with effects of variety or seed origin and with density, mainly in the autumn seasons. Such interactions were associated with differences in plant stands and differences in numbers of main stems per plant emerged (quadrant I, Fig. 1). Number of

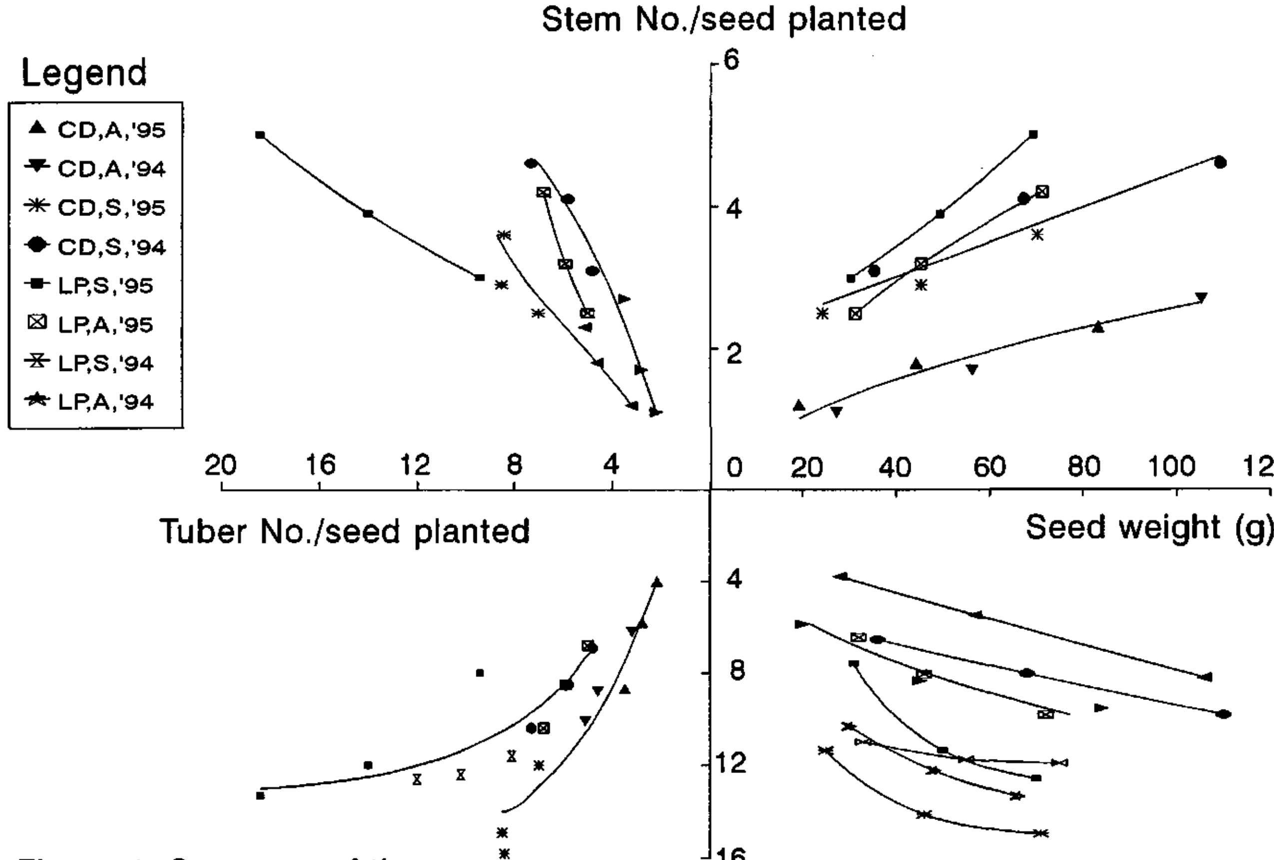

Figure 1. Summary of the relationship between the the growth parameters.

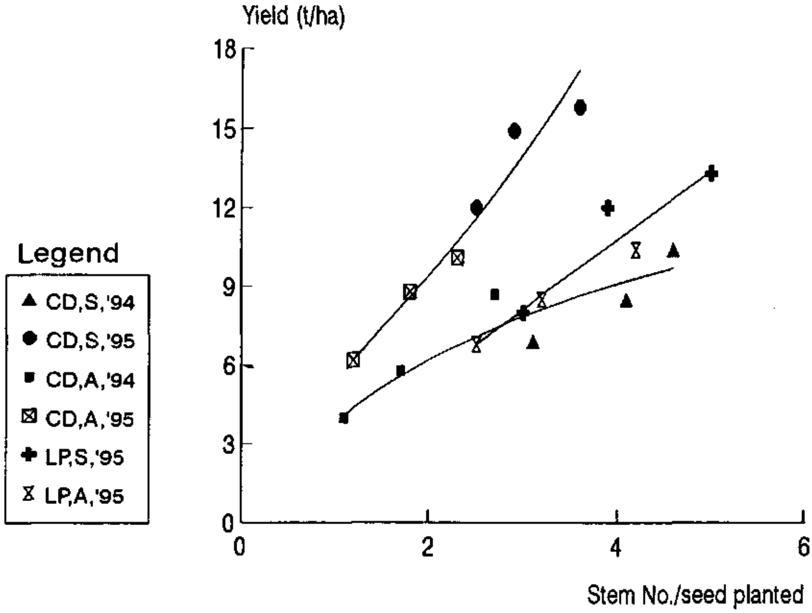

Figure 2. Relationship between tuber yield and number of stems per seed tuber planted.

stems produced per seed tuber planted and seed weight correlated closely within both seasons across both years, indicating that seed age was primarily determining the effect (quadrant I, Fig. 1). Numbers of tubers per plant correlated closely with number of stems per plant within one year for both years across both seasons (quadrant II, Fig. 1). This may indicate that the relationship is independent of environmental factors. Tuber yield increased as number of tubers per seed planted increased with data within each location falling on the same line (quadrant III, Fig. 1), indicating the site-specific association with differences in duration of canopy cover and hence in solar radiation intercepted by the crop. Tuber yield increased as seed tuber weight increased (quadrant IV, Fig. 1), but the response differed for each experiment, because of differences in relations discussed before.

Heavier seed tubers normally have more sprouts which can develop into more stems and produce more stolons and progeny tubers (Allen, 1978); this mechanism is illustrated in Fig. 2. The relationship was modified by season indicating the major role of seed age and by location. The difference of yield between the two seed sources (autumn or spring seeds in Trials 3 and 4) was mainly caused by their effects on plant stand, which was consistent with previous results (He and Struik, 1997).

However, when calculated per stem under the same seed densities, there were no differences in the numbers of tubers produced and tuber yields obtained between the seed weight treatments evaluated in the spring seasons when old seed tubers were used, indicating the additive effects of the different stems after the end of dormancy and apical dominance; the fact that lighter seed tubers produced more tubers per stem evaluated in the autumn illustrates the partial dormancy and the apical dominance of the seed when young seed tubers were used. The fact that the yields per stem increased as the seed tuber weight decreased in the spring seasons with fixed numbers of sprouts per unit area of planting, further indicated that leaf area per stem or per plant from lighter seed tubers probably expanded to compensate for their lower plant stand or main stems per plant to intercept more radiation for the similar tuber yields as from the heavier seed tubers.

Better plant stands and higher yields by heavier seed tubers were also associated with higher photosynthesis at both leaf and plant level (Tables 7 and 8) and higher light use efficiency, probably due to better basis in the heavier tubers such as more moisture conservation and more resistant to adverse soil environment, which could ensure better plant establishment hence enabling better plant growth in the rest period. The lower yield from the wider spacing could be also attributed to more exposure of soil surface during the early growing stages that raised soil temperature in later growing period, which may impede plant growth.

When numbers of sprouts (and probably subsequently developed stems) were set equal per unit area, the effects of seed tuber weights on cumulative PAR_{abs} and final tuber yield were absent (Tables 6 and 9), indicating the importance of stem numbers per unit area in determining yield. Yields were similar even though lighter seed tubers produced fewer main stems per plant, probably because they increased leaf area per stem as compared with heavier seed tubers. This resulted in similar values of cumulative PAR_{abs} for the different weights of seed tubers (Table 9). Apparently, the larger tuber sizes resulting from lighter seed tubers are mainly determining the differences in tuber yields, although the lower plant stands also partly contributed in the trial of 1995. Furthermore, light use efficiencies at similar stem densities from lighter tubers were higher in many cases (Table 9). Less inter-plant competition in lighter seed-tuber treatment could explain the results. Wiersema claimed that sprout number per unit area is not a proper density parameter when seed tuber weight falls below 20 g, since stem number per m^2 (in one year), early canopy cover, and tuber yield were lower from the lighter seed tubers (Wiersema, 1989). In our study the range in seed tuber size was from 21.5 to 124 g.

It has also been shown that the effects of seed tuber weight depend on the weight range and on environment (Wiersema, 1989; Lommen and Struik, 1994). The effect of variety was not only strong on cumulative PAR_{abs} but also on harvest index which reflects the degree of induction to tuberization. The induction is primarily genetically governed. Tuber yield correlated negatively with duration of seed tuber dormancy, in a way depending on seed tuber weight; the heavier the seed tubers, the less variable seed dormancy and seed vigour (Van Ittersum and Struik, 1992).

Conclusions

When evaluated at constant spacing, seed tuber weight significantly affected tuber yield in all conditions under study. Higher plant density also increased yield probably by increasing weight of progeny tubers.

When number of sprouts were set equal per unit area, the effect of weight of seed tubers on final tuber yield per unit area was absent in seed tuber weight range from 21.5 to 124 g.

When calculated per stem the numbers of tubers produced and the tuber yields obtained were different for the different seed weight treatments; this effect depended on the physiological status of the seed.

Chapter 6

Effects of cutting seed tubers on potato growth and yield in a double-cropping region of sub-tropical China

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Summary

In the potato double-cropping region of sub-tropical China, delayed plant emergence caused by the use of young and unsprouted seed tubers is an important yield constraint in short growing seasons. Cutting of seed may contribute to reducing the problem. Six field experiments were conducted at three locations (around 30° N) differing in altitude (500, 750, and 1200 m asl), in both spring and autumn seasons in 1994 and 1995. The experiments were laid out with variety or seed source as the main-plot, and seed cutting treatments as sub-plot. The sub-plot factor consisted of three levels: whole-seed tuber, once-cut (cut into two tuber pieces), and twice-cut (into three tuber pieces), planted at similar seed rate per hill for each treatment. Cutting generally promoted plant emergence and increased stem numbers per plant in comparison with the whole seed tuber per unit seed weight planted. Cutting also spread a wilting disease probably caused by *Pseudomonas solanacearum*, especially at lower altitude, thus limiting productivity. The spread of this pathogen during cutting is difficult to control without chemicals. Varieties differed in their resistance to the disease. Cutting effects interacted with variety effects, but more strongly in autumn than in spring, probably due to the shorter growing season, other choice of variety, and the disease severity.

Key words: cut seed tuber pieces, whole seed tuber, potato, yield, sub-tropics.

Introduction

Cutting of seed tubers into pieces prior to planting is a common practice in some areas such as North America and parts of Spain (Allen et al., 1992). It is also important in some Asian countries such as India (Shashirekha and Narasimham, 1989) and China. In the double potato cropping regions of Southwest China, a varying portion of the seed tubers for the spring crop comes from the previously harvested autumn crop, and seed tubers for the autumn crop mostly come from the previous spring crop. Delayed plant emergence from the young,

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unsprouted still dormant seed tubers is often a problem. Plant growth from the young whole seed tubers is more vigorous than that of old seed (after long-term storage of 6 to 8 months) derived directly from earlier seasons, but is still suboptimal. The tuber yields are therefore relatively low with either too young or too old seed. This problem commonly exists in the double-cropping regions of the country (Li, 1979).

Therefore, it is necessary to have a simple and effective method to solve the problem of seed tuber age both for spring and autumn crops. Foliage spraying of a plant growth regulator (PP333) to suppress abundant haulm growth was effective (Cao and Jiang, 1989) but may not be practical or environmentally safe. Temporary warm storage immediately after harvest can shorten seed dormancy (Van Ittersum, 1992) and can be used to improve the status of young seeds. The possibility to increase tuber yield through improved seed flow management shows promising (He and Struik, 1997). Cutting seed tubers into pieces is another practical alternative in the area. It is observed that cutting seed tubers into pieces prior to planting promotes both plant emergence and plant growth, but a strong interaction exists between treatment and variety (cf. Beukema and Van der Zaag, 1990). It seems that farmers use a smaller amount of seed when cutting is applied, compared with planting whole seed tubers. However, it is not yet clear what specific effects cutting of seed tubers has on potato growth and yield, in the different environments and seasons of southwest China, when using local degenerated seed under practical conditions.

Materials and Methods

Six field experiments were conducted at three locations with different altitudes (Chengdu, 500 m asl; Liangping, 750 m asl; and Pengxian, 1200 m asl) all in Sichuan, including both spring and autumn seasons in 1994 and 1995. The latitude of the locations is approximately 30° N. The experiments were arranged in a split-plot design, with variety and seed source as the main plot, and seed cutting treatments as sub-plot, with 2 to 4 replications. The sub-plot factor consisted of three levels: whole-seed tuber, once-cut (into two tuber pieces), and twice-cut (into three tuber pieces).

Relatively uniform (from 40 to 60 g) seed tubers were selected to be cut into two or three pieces, i.e. once-cut or twice-cut from a whole tuber. Cuts were made longitudinally. Whole-seed tubers, once-cut and twice-cut tubers were planted entirely per hill at the same seed rate for each treatment. Plot sizes varied over experiments from 2.4 to 5.4 m^2 and plant densities from 5.56 to 6.43 plants/m^2. Minimum amounts of fertilizers and manure were applied into the fields prior to planting. In the spring season, the seed of previous spring or autumn crops was used, while in autumn, the seed was all derived from the previous spring season. Varieties used were CY56 (mid-early), Mira (mid-late), CIP-24 (late), 378711.7 (late; introduced from CIP, the International Potato Center) and No. 22-2 (late; bred from true potato seed from CIP).

Details regarding weather and soil were described in previous papers (He et al., 1997a; 1997b). Plants were harvested at maturity. Yield parameters and disease incidences were recorded. Data were processed statistically using MSTAT-C and COSTAT. Percentage data were transformed before analyzing.

Results

Expt 1 conducted in Chengdu in spring shows that the variety × cutting interaction was only significant for plant stand (Table 1). Cutting seed tubers promoted plant emergence at 51 DAP and significantly increased final plant stand and stem number per hill. However, tuber number and tuber yield per unit area or per hill were reduced by cutting, though not significantly so, due to significantly lower average tuber weight. There were also differences in plant emergence and stem number per hill between varieties and/or seed sources; the younger the seed tubers, the later the plant emergence and the lower the stem number. No apparent disease incidences were observed in this experiment.

When a similar trial was conducted the following year (Expt 2, Table 2), no significant interactions were found. Cutting seed tubers slightly increased plant emergence at 49 DAP, increased stem numbers per hill significantly, and slightly increased tuber specific gravity. The other yield parameters including tuber weight (not shown) were not affected by cutting. The differences in plant emergence between the seed sources can be explained by the differences in variety and origin determining length of dormancy. For example, CY56 had the youngest seed with the latest emergence, lowest stem and tuber numbers and largest tubers, resulting in the lowest final yields. Symptoms of bacterial wilt (*Pseudomonas solanacearum*) were observed at 103 DAP and higher in cut treatments than in crops from whole seed tubers in cv. CY56, with no apparent differences between the treatments in the other two seed sources. The incidence of late blight (*Phytophthora infestans*) was negligible.

In Expt 3 (Table 3), which was conducted in Chengdu in autumn, significant interactions between variety and seed treatment were found for all parameters except tuber dry matter concentration. In general, cutting once significantly enhanced plant emergence even at 20

Table 1. Effects of cutting seed tubers on tuber yield parameters; crop grown in Chengdu, *spring*, from Feb 1 to Jun 13, 1994, Expt 1.

Treatment[1] Variety (A) Cutting of seed (B)	Plant emergence (51 DAP)[2] (%)	Final plant stand (%)	Stem number[3] (#/hill)	Tuber number (#/hill)	Tuber yield (t/ha)	Tuber yield (g/hill)	Tuber weight (g)
A CIP-24s	85	100	6.7 a	8.3	14.3	245	29
CY56s	69	96	4.0 b	10.2	15.0	266	26
CY56a	30	96	2.3 c	8.1	15.9	283	35
B Whole	52	95 b	3.9 b	9.5	17.2	309	33 a
Once cut	61	98 a	4.3 ab	8.4	13.7	241	29 b
Twice cut	70	100 a	5.0 a	8.7	14.3	245	28 b
Grand mean	61	98	4.4	8.9	15.0	265	30
CV(%) (B)	16.0	2.4	15.4	16.1	18.0	19.8	9.1

Table 2. Effects of cutting seed tubers on tuber yield parameters, crop grown in Chengdu, *spring*, from Feb 9 to Jun 10, 1995, Expt 2.

Treatment[1] Variety (A) Cutting of seed (B)	Plant emergence (33/49 DAP)[2] (%)	Final plant stand (%)	Stem number (#/hill)	Tuber number[4] (#/hill)	Tuber yield (t/ha)	Tuber yield (g/hill)	Tuber specific gravity (%)
A CIP-24s	57/100 a	93	7.0 a	11.3 a	13.1	251	1.090
CY56a	0/55 b	95	2.1 c	6.0 b	9.9	188	1.089
378711.7s	79/99 a	95	3.8 b	11.3 a	17.2	325	1.088
B Whole	48/79	92	3.1 c	9.4	14.0	273	1.087
Once cut	43/89	97	4.4 b	9.2	13.1	244	1.090
Twice cut	44/86	95	5.4 a	10.0	13.0	246	1.090
Grand mean	45/85	94	4.3	9.5	13.4	254	1.089
CV(%) (B)	12.1/7.7	6.8	10.9	13.0	11.9	10.8	0.3

[1]All interactions in Tables 1 and 2 are non-significant at $P<0.05$ except for plant stand in Table 1; s or a following the variety names means the seed is derived from previous spring or autumn crop, respectively. [2]DAP=days after planting. Different letters in a column within a factor means significantly different at (at least) $P<0.05$, except [3]within factor B at $P<0.08$ and [4]within A at $P<0.12$.

Table 3. Effects of cutting seed tubers on tuber yield parameters, crop grown in Chengdu, *autumn*, from Sep 15 to Dec 7, 1995, Expt 3.

Variety (main-plot) (A)	Cutting of seed (sub-plot) (B)	Plant emergence (20 DAP)[1] (%)	Final plant stand (%)	Stem number (#/hill)	Tuber number (#/hill)	Tuber weight (g)	Tuber yield (t/ha)	Tuber yield (g/hill)	Tuber dm % (%)
No. 22-2	Whole	17	78	2.8	3.7	24	4.4	90	18.9
	Once cut	41	80	2.9	3.0	19	3.1	58	20.1
	Twice cut	21	39	1.9	1.9	14	0.7	26	21.2
	Mean	*27 c*	*66 b*	*2.5*	*2.9 c*	*19 b*	*2.7 c*	*58 c*	*20.1*
CY56	Whole	72	88	2.0	3.9	39	8.4	150	19.7
	Once cut	70	70	2.8	4.0	18	3.2	72	20.0
	Twice cut	68	87	2.6	3.8	17	3.6	66	19.9
	Mean	*70 b*	*81 a*	*2.4*	*3.9 b*	*25 a*	*5.1 b*	*96 b*	*19.9*
378711.7	Whole	72	88	2.2	5.9	26	8.7	154	18.3
	Once cut	93	92	2.9	7.8	17	7.9	133	18.3
	Twice cut	98	91	3.7	8.1	14	6.6	113	19.5
	Mean	*88 a*	*90 a*	*2.9*	*7.3 a*	*19 b*	*7.7 a*	*133 a*	*18.7*
Average	Whole	*54 b*	*85 a*	*2.3 b*	*4.5*	*30 a*	*7.2 a*	*131 a*	*19.0 b*
	Once cut	*68 a*	*80 ab*	*2.9 a*	*5.0*	*18 b*	*4.7 b*	*88 b*	*19.5 ab*
	Twice cut	*62 ab*	*72 b*	*2.7 ab*	*4.6*	*15 c*	*3.6 c*	*68 c*	*20.2 a*
	Grand mean	61	79	2.6	4.7	21	5.2	96	19.6
	CV(%) A	9.6	11.5	21.0	15.4	12.0	28.4	25.9	11.3
	CV(%) B	14.2	10.0	16.2	11.3	8.5	11.8	10.1	4.3
	P or LSD (0.05) A	9.2***	13.7*	ns	0.9***	3.3*	1.9**	32.5**	ns
	P or LSD (0.05) B	11.0*	9.9$^{P<0.09}$	0.4*	ns	1.8***	0.6***	9.9***	0.9*
	P or LSD (0.05) A×B	19.1*	16.0**	0.8**	3.3***	3.2***	1.1***	17.2**	ns
	Interaction A×B	*	**	**	***	***	***	**	ns

Different letters in a column within a factor means significantly different at least at $P<0.05$. [1]DAP=days after planting. *, **, and *** means significant F test at $P<0.05$, 0.01, and 0.001, respectively. All the varieties came from the previous spring crop.

DAP, stem numbers per hill, tuber dry matter concentration, and decreased average tuber weight; cutting twice decreased final plant stand at least in No. 22-2; both cutting treatments reduced yield parameters significantly, with the more cuts the lower average tuber weight and the lower tuber yield. The interactions were mostly reflected in the much lower values of the twice-cut treatment for plant stand, stem number and tuber yield (t/ha) in variety No. 22-2. The incidence of bacterial wilt was observed mid-late in the growing period (at 54 DAP) and was higher in cut treatments than for whole seed tubers, especially in cv. CY56.

At higher altitude in Expt 4 (Table 4) in autumn, significant interactions occurred only in plant emergence and stem numbers per hill. Cv. Mira gave earlier emergence, many more stems and tubers per hill, and higher tuber dry matter concentration, thus producing significantly higher tuber yields than variety 378711.7. Cutting significantly promoted earlier emergence, induced more stems and tubers per hill to develop, increased tuber dry matter concentration, and slightly increased tuber yield. There was no cutting treatment effect in plant emergence for cv. Mira and only twice cut apparently increased stem numbers per plant for cv. 378711.7 (data not shown). The incidence of bacterial wilt was slightly higher in cut treatments than in the crops from whole seed tubers for Mira. In 378711.7 no symptom of bacterial wilt was visible.

At even higher altitude in Pengxian, spring (Expt 5, Table 5), significant interaction occurred only for plant emergence (69 DAP). Tuber yields from seeds of previous autumn origin were higher than those from seeds of spring origin for CY56, due to the better plant stand and the larger tubers, even although these yields had to be realized with fewer stems per hill. Variety 378711.7 gave the highest yield (30.9 t/ha) because almost all growth and yield parameters were more favourable than for the other two treatments. Cutting significantly promoted earlier emergence, higher plant stand, more stems or tubers per plant, but still tended to have lower yields than the whole seed tubers. There were no cutting treatment effects on plant emergence in cv. CY56a and 378711.7; the main cutting treatment effect was expressed mainly in cv. CY56s both at 40 DAP and 69 DAP, with no cutting effects for CY56a and 378711.7s (data not shown), but there might have been an effect especially for CY56a between 40 and 69 DAP which was missed. The incidence of bacterial wilt was observed at 69 DAP to be slightly higher in cut treatments than when using whole seed tubers in variety CY56, with no incidence at all in variety 378711.7.

In autumn in Pengxian (Expt 6, Table 6), significant interactions occurred in plant stand, tuber weight and tuber yield per unit area. CY56a performed better than No. 22-2 for all

Table 4. Effects of cutting seed tubers on tuber yield parameters, grown in Liangping, *autumn*, from Sep 21 to Dec 9, 1995, Expt 4.

Treatment[1] Variety (A) Cutting of seed(B)	Plant 80% emergence (DAP)[2]	Final plant stand (%)	Stem number (#/hill)	Tuber number (#/hill)	Tuber yield (t/ha)	Tuber yield (g/hill)	Tuber weight (g)	Tuber dm % (%)
Mira	17.0 b	79	6.6 a	10.0 a	8.3 a	173 a	18	20.8 a
378711.7	24.1 a	79	2.2 b	5.1 b	4.2 b	88 b	23	17.0 b
Whole	23.7 a	78	3.4 b	5.6 b	5.7	121	29	17.7 b
Once cut	19.0 b	79	4.5 a	7.8 a	6.6	139	17	20.8 a
Twice cut	19.0 b	81	5.3 a	9.2 a	6.4	131	14	18.2 b
Grand mean	20.6	79	4.4	7.5	6.2	131	20	18.9
CV(%) (B)	4.6	3.1	15.8	19.7	19.7	19.0	76.9	5.8

Table 5. Effects of cutting seed tubers on tuber yield parameters, crop grown in Pengxian, *spring*, from Feb 27 to Jul 19, 1995, Expt 5.

Treatment[1] Variety (A) Cutting of seed (B)	Plant emergence[2] (40/69 DAP)(%)	Final plant stand (%)	Stem number[3] (#/hill)	Tuber number (#/hill)	Tuber yield[4] (t/ha)	Tuber yield (g/hill)	Tuber weight (g)	Tuber dm % (%)
CY56s	21/78 b	68 b	3.6 a	6.1 b	5.7 c	149 c	25 b	18.8
CY56a	1/100 c/a	91 a	2.6 b	5.7 b	14.3 b	270 b	48 a	19.8
378711.7s	78/99 a	94 a	3.4 ab	10.9 a	30.9 a	562 a	52 a	19.5
Whole	27/81 b	79	2.8 c	7.0	18.7 a	371 a	52 a	19.3
Once cut	34/98 a	86	3.2 b	7.2	15.3 b	297 b	39 b	18.9
Twice cut	38/99 a	88	3.6 a	8.6	16.9 ab	314 b	34 b	19.9
Grand mean	33/93	84	3.2	7.6	17.0	327	42	19.4
CV(%) (B)	20.3/8.0	10.6	11.4	20.0	15.4	16.9	14.0	5.9

[1]All interactions in Tables 4 and 5 are non-significant except those of plant emergence and stem number per plant in Table 4 and plant emergence (at 69 DAP) in Table 5; s or a means the seed is derived from previous spring or autumn, respectively; the seeds in Table 4 all came from previous spring crop. [2]DAP=days after planting. [3]Significant at $P<0.07$ within factor A; [4]at $P<0.06$ within factor B.

Table 6. Effects of cutting seed tubers on tuber yield parameters, grown in Pengxian, *autumn*, from Aug 22 to Dec 12, 1995, Expt 6.

Variety (main-plot) (A)	Cutting of seed (sub-plot) (B)	Plant emergence[1] (47 DAP) (%)	Final plant stand (%)	Stem number (#/hill)	Tuber number (#/hill)	Tuber weight (g)	Tuber yield (t/ha)	Tuber yield (g/hill)	Tuber dm % (%)
No. 22-2s	Whole	56	69	1.4	3.2	39	5.3	125	16.7
	Once cut	77	61	1.9	3.0	46	5.3	139	17.6
	Twice cut	71	51	1.7	2.7	32	2.8	86	17.7
	Mean	*68 b*	*61 b*	*1.6 b*	*3.0 b*	*39 a*	*4.5 b*	*117 b*	*17.3 a*
CY56a	Whole	91	79	1.7	4.3	37	7.8	158	15.4
	Once cut	100	69	2.1	4.9	30	6.5	146	15.9
	Twice cut	100	86	2.0	5.5	27	8.2	147	16.3
	Mean	*97 a*	*78 a*	*1.9 a*	*4.9 a*	*31 b*	*7.5 a*	*150 a*	*15.8 b*
Average	Whole	*73 b*	*74*	*1.5 b*	*3.7*	*38 a*	*6.6*	*142*	*16.0 b*
	Once cut	*89 a*	*65*	*2.0 a*	*4.0*	*38 a*	*5.9*	*142*	*16.7 a*
	Twice cut	*86 a*	*69*	*1.8 a*	*4.1*	*29 b*	*5.5*	*117*	*17.0 a*
	Grand mean	83	69	1.8	3.9	35	6.0	134	16.6
	CV(%) A	11.5	14.0	9.7	14.4	23.0	19.7	28.1	5.2
	CV(%) B	9.3	11.8	11.9	23.8	14.1	20.2	18.7	2.5
	P or LSD (0.05) A	**	*	*	**	$P<0.11$	**	$P<0.12$	*
	P or LSD (0.05) B	10.8***	ns	0.23**	ns	5.4**	ns	ns	0.5**
	P or LSD (0.05) A×B	ns	15.1*	ns	ns	7.7*	1.9*	ns	ns
	Interaction A×B	ns	*	ns	ns	*	*	ns	ns

Different letters in a column within a factor means significantly different at least at $P<0.05$; s or a means the seed is derived from the previous spring or autumn crop, respectively. [1]DAP=days after planting. *, **, and *** means significant F test at $P<0.05$, 0.01, and 0.001, respectively.

parameters except for tuber weight and tuber dry matter concentration. In comparison with whole seed tubers, cutting significantly promoted earlier plant emergence, increased stem numbers per hill and tuber dry matter concentration, but produced slightly lower plant stands and slightly lower tuber yields. Cutting twice also resulted in smaller tubers. Twice cutting treatment decreased plant stand in variety No. 22-2; tuber yield (t/ha) was decreased by cutting twice in No.22-2s while it was increased in CY56a. The incidence of bacterial wilt was slightly higher in cut treatments than in crops from whole seed tubers in CY56a. No incidence was found in variety No. 22-2.

It was observed that tuber yields were positively correlated to canopy cover regardless of the cutting treatments and variety or seed source treatments for the experiments.

Discussion

Cutting generally promoted earlier plant emergence, especially in autumn and at higher altitudes, and increased stem number per hill, confirming previous reports (e.g. Allen and Wurr, 1992). Cutting seed tubers early (5 to 15 days before planting) is more effective in promoting earlier emergence than cutting immediately before planting (Chase et al., 1988; 1990; Vander Zaag and Demagante, 1989; Beukema and Van der Zaag, 1990). Cutting of the seed tuber is believed to break the dormancy imposed by the apical bud on many eyes, probably aided by wound-induced gibberellins (Rappaport and Sachs, 1967). The earlier emergence by cutting is also believed to be attributed to the result of stimulation of interior physiological activity due to more oxygen being available on the cut surface (Li, 1979). When calculated at a per cut piece basis, the stem and particularly the tuber numbers were generally lower than for the whole seed tuber treatment, which is logical given the smaller size of the seed reserves. Surprisingly, cut pieces gave higher final tuber dry matter concentration or tuber specific gravity especially in autumn, probably due to earlier maturity of the progeny tubers.

In practice in China, it is observed that cutting seed tubers gives good yield, where pathogen infection due to cutting is naturally scarce (at high altitude). This is because farmers plant more cut pieces than whole tubers. Our study confirms the advantages of cutting seed tubers at suitable conditions. Farmers at intermediate altitudes (e.g. in Pengxian, 1200 m asl) cut seed tubers into smaller pieces, hence more pieces per tuber than at higher altitude (> 1500 m asl), which is a practicable measure that enhances the effect of cutting seed tubers to produce more stems in comparison with fewer cut pieces per tuber (Allen and Wurr, 1992) and also saves seed. At higher altitudes (e.g. 1500 m and above), the smaller cut pieces and their progeny plants may not tolerate the adverse influences of drought or frost.

However, cutting generally did not give higher final tuber yield than planting of whole seed tubers confirming other early reports (e.g. Khan and Ahmad, 1979; Satjadipura, 1988; Singh, 1993). Cut seed-tuber pieces tended to be infected by diseases (believed to be bacterial wilt, *Pseudomonas solanacearum* based on the typical symptoms), especially at lower altitudes, eventually leading to yield reduction, even though the plant stand could be increased, compared with the whole seed tubers. Incidence of *Pseudomonas solanacearum* is frequent in the sub-tropics (e.g. Vijayakumar et al., 1985; Hide and Lapwood, 1992) and tropics (e.g. Satjadipura, 1988) by using cutting and by using infected seed sources. *Erwinia carotovora* is another commonly reported harmful bacterium associated with cutting both in warm and cool regions (e.g. Shumaker and Weingartner, 1973; Shashirekha and Narasimham, 1989; Gudmestad et al., 1988; Wastie et al., 1994). The fungus *Fusarium solani* was identified as the causal pathogen to cut piece decay (e.g. Sinha et al., 1982; Borborua, 1984).

Therefore, the process of cutting is supposed to be well implemented by, for example, chemical sterilizing of the cutting knife and cut pieces or by letting the pieces form a layer of suberin to prevent invasion of pathogens and evaporation, prior to planting, especially at lower altitudes where temperature is so high that pathogens multiply fast. This is not feasible in this part of China. There is no report yet on practical or widely-used methods to solve the problem in the area.

The occurrence of bacterial wilt in the area is primarily related to warm temperature and levels of resistance of variety, and is observed to be irregular in the past; damage by *Pseudomonas solanacearum* can be severe (He et al., 1994). It is probably the major concern for the cutting practice in the area. The other bacterial pathogens and fungi may also be involved, since treatments of some chemicals (antimicrobiocides or fungicides) showed effectiveness in varying degrees to control the pathogens or to increase emergence or yield (e.g. Sinha et al., 1982; Borborua, 1984; Chase et al., 1990; Tariq et al., 1995). Resistance or tolerance to bacterial wilt was found in CIP-24, No. 22-2, and especially 378711.7 which is probably even immune to the disease. Mira and especially CY56 were susceptible to the disease and special care needs to be taken, because of the wide use of these two cultivars in the area.

The effects of cut treatments were dependent on variety or seed source, associated with their effects on dormancy and seed vigour. Variety 378711.7 performed well (average yield 30.9 t/ha) both for the whole seed tuber (33.8 t/ha) and cutting treatments (average 29.4 t/ha), in spring at high altitude. Nearly all growth parameters recorded were favourable.

The interactions between seed treatment and variety or seed source were found mostly in plant emergence or final plant stand. Cutting seed significantly promoted plant emergence even in the older seed (cv. CY56s) in Pengxian, spring 1995 (data not shown), illustrating the status of apical dominance of the whole seed tuber; there was probably some effect of cutting on plant emergence between 40 DAP and 69 DAP for CY56a (which was not recorded) due to its physiological status. Likewise, cutting seed significantly increased plant stand even in the older seed source of CY56 in Chengdu, spring 1994 (data not shown). In autumns, however, cutting slightly reduced plant emergence (Table 3) in cv. CY56, due to more disease infection than in spring (He et al., 1997b); cutting had no effect on cv. Mira (data not shown), indicating the easy breaking of the dormancy of this cultivar as has been observed earlier (Wang Jun, personal communication, 1990). There were more parameters that showed interactions in autumn than in spring, due to the shorter growing season, different cultivar choice, and the difference in disease incidence.

Conclusions

Cutting had consistent physiological effects on promoting plant emergence and increasing stem numbers per unit weight of the seeds.

Cutting tended to increase disease infection mainly by causal agents of wilt, especially at lower altitude, thus reducing yields.

Both effects depend on the genotype and the origin of the seed.

Chapter 7

Effects of row-ratios and plant densities in potato-maize intercropping in sub-tropical China

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Summary

Intercropping of potato with maize (with maize planted later than potato) is a common practice in spring crops in southwestern sub-tropical China, but optimal plant arrangement is still a matter of debate. Six experiments were conducted at three altitudes in two years to evaluate the current intercropping system for possible further improvement of yield. Two row-ratios, two potato plant densities and two varieties or seed sources of potato were used for five experiments; in the sixth experiment maize density was varied. Higher total yield was found when one row of maize was alternated with two rows of potato (R1) than with two rows of maize (R2). The competition effects found in the study were in descending order: on maize imposed by potato, on potato imposed by maize, and both inter- and intra-plant competition on maize or potato. The relatively weak competition indicates that planting dates of the two species can be more closely synchronised and the densities of both species can be further increased in the current intercropping system, to achieve a more efficient use of space and time. It is necessary to use varieties that are adapted and can minimize the competition effects.

Key words: potato, maize, intercropping, canopy cover, row-ratios, plant density.

Introduction

Intercropping of potato (*Solanum tuberosum* L.) and maize (*Zea mays* L.) is a common practice in spring crops in Sichuan as well as in other regions of southwestern sub-tropical China (Lai and Wen, 1990; Liu and Midmore, 1990), where the progress of temperature over time allows more solar radiation to be utilized by the crop per unit land area to produce higher (intercrop) yield annually. The intercropping is practised also because maize grain is an important source of feed for livestock and poultry. The most common advantages of this intercropping system are complementarity of resource use between component crops,

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improved efficiency of use of both space and time, and reduced pest and disease incidence (Midmore, 1990).

Research has been focused on how to find a compromise in the interspecific competition in various situations in the tropics (e.g. Vander Zaag and Demagante, 1990); for the sub-tropics it has recently been reviewed by Liu and Midmore (1990). The share a species acquires in the total leaf area of the vegetation or the relative leaf cover is supposed to be the main determinant of its competitive ability (Spitters, 1984; Kropff, 1988).

The maize plants will shade potato plants once they have reached a certain size. In addition to effects on production, less light interception by the potato crop delays and prolongs stolon initiation slightly (Struik, 1986; Midmore et al., 1988) but does not reduce stolon number (Struik, 1986). Tuber initiation occurs over a very short period and variation in level of radiation affects final number of tubers largely only during this period (O'Brien et al., 1993). These findings may be relevant to the practice of intercropping of potato with maize in the sub-tropics in China.

In China, broad strip-cropping (4 rows of potato:4 rows of maize) is believed to be appropriate for highly fertile soils and narrow strip-cropping (2:2) is more favourable on soils of moderate or low fertility (Lai and Wen, 1990). It is not clear yet whether this narrow strip-cropping is appropriate in southwest China or whether it has to be improved in view of different previous reports (Liu and Midmore, 1990; Vander Zaag and Demagante; Batugal et al., 1990). We studied effects of row-ratios and densities of component crops in narrow strip-cropping of potato and maize, which is commonly practised in sub-tropical China. Investigation of competition effects between potato and maize in this paper is primarily focused on light energy and not on other relevant resources, such as water and nutrients.

Materials and Methods

Six experiments were conducted at three locations with different altitudes (Chengdu, 500 m asl; Liangping, 750 m asl; and Pengxian, 1200 m asl), all in spring seasons in 1994 and 1995. The latitude of the locations is approximately 30° N. Five experiments were arranged in multi-split plots, with variety or seed source as the main plot, row-ratio of potato in combination with maize as sub-plot, and potato density as sub-sub-plot; experiments contained two or three replications. A minimal amount of N and P fertilizers and manures were applied to the experimental fields before planting. Potatoes were planted between

January and February; maize was planted into the prepared rows from March to April depending on weather and altitude. The varieties chosen were local or newly released ones. The seed tubers of potato came from crops grown during the previous spring or autumn. For maize the hybrid Chengdu-13 was used.

In the first five experiments (Tables 1 to 5), there were two row-ratios: 1) two rows of potato alternated with one row of maize (Ratio-1); 2) two rows of potato with two rows of maize (Ratio-2). Within-row distances of potato were set to 0.25 m (D1) or 0.35 m (D2). Row distances were always 0.5 m for both species. Maize density was set constant at 5.25 plants per m^2, with within-row distance adjusted accordingly for each row-ratio, two plants per hill. Plot size was 4×3.5 m^2 with a little variation among the locations. Potato seed tubers (approx. 50 g) were planted whole.

In the sixth experiment (Table 6), within-row distance of maize was varied: D1=0.25 m, D2=0.40 m and D3=0.55 m; between-row distance was 1.6 m. Two rows of potato were evenly and alternately planted between the single maize rows. So the average potato between-row distance was 0.80 m with a within-row distance of 0.23 m, keeping a constant potato density. The seed tubers were cut into small pieces (approx. 15 g each) immediately before planting. The above treatments were chosen to test the current farmer's practice.

The two crop species were harvested separately at their respective maturities. Three potato fresh yields were calculated: a) potato yield per plant; b) the "gross" yield per ha calculated by multiplying plant yield by plant density by area occupied by total crop (including maize); c) the "net" yield (t/ha), calculated by multiplying plant yield by plant density by area occupied by potato only. The "net" yield is calculated because it may indicate competition effects (if any); it is higher than the "gross" yield which has more practical implications. Maize yields either per unit area or per plant were expressed as sun-dried kernel with approximately 93% dry matter content. The calculation of maize yield per m^2 gives relevant practical sole information. Maize yield per hill may illustrate the competition effects.

Leaf canopy was measured using methods and concepts described by Burstall and Harris (1983), Beukema and Van der Zaag (1990) and Haverkort et al. (1991). Other experimental details regarding meteorology and soil components in the area were as described in previous papers (He et al., 1997a; 1997b). Data were processed statistically by programmes of MSTAT-C and COSTAT. Percentage data were transformed into arcsine square root when necessary before analyzing. Coefficients of variation (%) were calculated by ($\sqrt{}$Error

MS)/Grand mean×100, from the ANOVA tables for separate factors.

Results

Yield parameters

Maize yields per unit area and per plant were significantly different between row-ratios but not between potato densities at Chengdu in 1994 (Expt 1, Table 1). The maize plant stands were nearly 100% (data not shown) while the potato plant stands differed slightly among treatments. Tuber yield per plant, tuber number per plant, and average tuber weight were increased by lower potato density but were not affected by row-ratio. Higher potato plant density and Ratio-1 gave significantly higher "gross" tuber yields and slightly (non-significantly) higher "net" yields. The row-ratio effects on tuber yields per ha were opposite to the effects on maize yields. Significant interactions were found between the factors density and row-ratio only for maize yields and tuber yield per plant. Coefficients of variation were generally higher in the main-plot factor row-ratio (Table 1). Tuber yields of cv. HH6 were extremely low (average 1 t/ha) and data were not presented in the table.

The experiment conducted the following year at the same location (Expt 2) showed that there was neither yield difference between row-ratios nor between densities for maize (Table 2); maize plants generally grew more vigorously and the yields were higher than in the previous year. The two origins from the same variety CY56 differed in that the spring origin gave significantly higher values of all potato yield parameters than did the autumn origin. Similar to Expt 1, both "gross" and "net" potato tuber yields were higher for denser and Ratio-1 treatments. The trend of tuber numbers per plant between densities and row-ratios was noticeably different from Expt 1. All interactions were non-significant.

When conducted at an intermediate altitude for Expts 3 and 4 (Tables 3 and 4), performance became more variable as indicated by higher coefficients of variation. Tuber yields were generally low at the location, whereas the maize yields were intermediate. In 1994 (Table 3), the potato density treatments had the same effects on tuber yields as previously described experiments (Tables 1 to 2) but also had a significant influence on maize yields: the denser potato crop resulted in a higher maize yield; the row-ratios affected maize yields as was also observed in the other experiments (Tables 1 and 2) but had an opposite effect on "net" tuber yield. Cv. HH6 generally yielded more at this location than cv. CY56. In 1995 (Table 4), only potato plant stands and tuber yield per plant were influenced in a way similar to those

Table 1. Effects of intercropping in Expt 1 with potato cv. CY56 planted on January 27 and harvested on June 14, and maize planted on March 31 and harvested on July 27, 1994, in Chengdu.

Treatment[A]	Maize yield[B] (kg/m^2)	Maize yield[C] (g/hill)	Potato Stand (%)	Tuber yield (g/pl)	Tubers (#/pl)	Av. tuber weight[D] (g)	Tuber gross yield[E] (t/ha)	Tuber net yield (t/ha)
D1 (50×25cm)	0.19	72	94	256 b	4.7 b	54 b	10.5 a	17.8
D2 (50×35cm)	0.19	74	95	309 a	5.1 a	61 a	9.5 b	16.2
Ratio-1 (2P:1M)	0.15 b	55 b	97	290	5.3	56	12.0 a	18.0
Ratio-2 (2P:2M)	0.23 a	91 a	92	274	4.6	59	8.0 b	16.0
Interaction D×R:	*	*	ns	*	ns	ns	ns	ns
CV(%) Density:	4.3	4.6	7.9	4.4	5.2	8.1	8.3	9.1
Ratio:	27.9	27.5	15.1	15.1	22.0	7.2	11.8	10.2

[A] D=potato plant density while the gross maize plant density remains constant at $5.25/m^2$; R=row-ratio; the potato seed tubers originated from the previous autumn; tuber yield of the variety HH6 was too low (1 t/ha) and its data set was not included in this table; different letters in a column for treatments indicate differences of means at least significant at $P<0.05$. * means significant at $P<0.05$; ns means non-significant. [B-E] All at $P<0.09 \sim 0.11$ for factors R (Ratio), R, D, and D respectively; maize yield refers to sun-dried grain and potato to fresh.

Table 2. Effects of intercropping in Expt 2 with potato planted on February 11 and harvested on June 29, and maize planted on March 28 and harvested on July 24, 1995, in Chengdu.

Treatment[A]	Maize yield (kg/m^2)	Maize yield (g/hill)	Potato Stand (%)	Tuber yield (g/pl)	Tubers[B] (#/pl)	Av. tuber weight[C] (g)	Tuber gross yield[D] (t/ha)	Tuber net yield[E] (t/ha)
D1 (50×25cm)	0.28	108	83 b	200	6.5	30	7.4	12.6
D2 (50×35cm)	0.30	114	90 a	196	5.8	33	6.1	10.4
Ratio-1 (2P:1M)	0.29	110	90	192 b	5.9 b	32	7.7 a	11.5
Ratio-2 (2P:2M)	0.29	113	83	204 a	6.4 a	31	5.7 b	11.4
S1 (CY56a)	0.31	118	79 b	140 b	4.8 b	29 b	4.3 b	7.2 b
S2 (CY56s)	0.27	105	94 a	256 a	7.5 a	34 a	9.2 a	15.7 a
CV(%) D:	10.6	10.9	6.5	17.8	11.2	9.3	22.4	23.1
R:	29.7	34.7	7.3	2.5	3.7	6.0	10.0	9.0
S:	11.4	10.3	0.4	5.8	10.1	3.2	11.5	12.1

[A] D=potato plant density while the gross maize plant density remains constant at $5.25/m^2$; R=row-ratio; S=seed source; different letters in a column for treatments indicate differences of means at least significant at $P<0.05$. All interactions are non-significant. CY56a and CY56s means previous autumn and spring origin respectively; maize yield refers to sun-dried grain and potato to fresh. [B~E] All at $P<0.08$ for factors R (Ratio) & S (Seed source), S, S, and S respectively.

Table 3. Effects of intercropping in Expt 3 with potato planted on January 25 and harvested on June 18, and maize planted on April 14 and harvested on August 12, 1994, in Liangping.

Treatment[A]	Maize yield[B] (kg/m^2)	Maize yield[C] (g/hill)	Potato Stand (%)	Tuber yield[D] (g/pl)	Av. tuber weight (g)	Tuber gross yield[E] (t/ha)	Tuber net yield[F] (t/ha)
D1 (50×25cm)	0.50 a	188 a	82	84	29	3.3 a	5.7 a
D2 (50×35cm)	0.45 b	169 b	86	81	28	2.3 b	4.1 b
Ratio-1 (2P:1M)	0.44 b	168 b	82	76	27	2.8	4.3 b
Ratio-2 (2P:2M)	0.50 a	188 a	86	89	30	2.8	5.6 a
V1 (CY56a)	0.46	175	81 b	67 b	28	2.2 b	3.9 b
V2 (HH6a)	0.48	181	87 a	97 a	28	3.4 a	5.9 a
CV(%) D:	11.3	10.9	10.0	11.3	11.5	11.9	13.7
R:	13.7	11.7	12.6	22.5	17.6	26.9	24.9
V:	13.7	11.2	3.2	30.3	10.4	29.1	25.8

[A] D=potato plant density while the gross maize plant density remains constant at $5.25/m^2$; R=row-ratio; seeds of both varieties originated from previous autumn. All interactions are not significant; different letters in a column for treatments indicate differences of means at least significant at $P<0.05$. [B–F] All at $P<0.08$ for factors R (Ratio), R, V (Variety), V, and R & V respectively; maize yield refers to sun-dried grain and potato to fresh.

Table 4. Effects of intercropping in Expt 4 with potato planted on February 15 and harvested on July 13, and maize planted on April 15 and harvested on August 22, 1995, in Liangping.

Treatment[A]	Maize yield[B] (kg/m^2)	Maize yield[C] (g/hill)	Potato Stand[D] (%)	Tuber yield[E] (g/pl)	Av. tuber weight (g)	Tuber gross yield (t/ha)	Tuber net yield (t/ha)
D1 (50×25cm)	0.43	162	80 b	55 b	41	2.1	3.6
D2 (50×35cm)	0.43	162	89 a	69 a	38	2.0	3.5
Ratio-1 (2P:1M)	0.40	152	87	60	39	2.3	3.5
Ratio-2 (2P:2M)	0.47	172	83	65	40	1.8	3.6
V1 (CY56a)	0.40 b	151 b	81 b	22 b	36	0.7 b	1.2 b
V2 (HH6a)	0.46 a	173 a	88 a	103 a	43	3.4 a	5.9 a
CV(%) D:	11.4	11.6	12.2	26.2	31.3	29.7	30.8
R:	24.4	24.4	10.6	36.7	30.7	39.3	39.6
V:	10.4	8.9	6.9	55.0	26.1	55.8	53.1

[A] D=potato plant density while the gross maize plant density remains constant at $5.25/m^2$; R=row-ratio; seeds of both varieties originated from previous autumn; different letters in a column for treatments indicate differences of means at least significant at $P<0.05$. All interactions are not significant. [B~E] All at $P<0.08$ for factors V (Variety), V, V, and D (Density) respectively; maize yield refers to sun-dried grain and potato to fresh.

described for the previous experiments, while the other parameters remained unaffected. Cultivar effects at this site were consistent over the two years (Tables 3 and 4). All interactions were non-significant in both years.

At higher altitude for Expts 5 (Table 5), the potato density treatments had similar effects on maize yields (no difference) as in Tables 1, 2 and 4 and potato yields (higher yields from denser spacing) as in Tables 1 to 4, but had a different effect on tuber numbers per plant compared with the previous experiment (Table 1). Row-ratio treatments had similar effects on maize yields as the experiments (Tables 1, 3 and 4), and had similar effects on tuber yields as observed in the previous experiments (Tables 1 and 2), but had different effects from experiment in Table 3 where "net" tuber yield was higher in Ratio-2 than in Ratio-1. There was also the same effect of row-ratio on tuber number per plant (Table 5) as in Table 1. The two seed origins of the same variety CY56 showed similar effects on tuber numbers per plant and tuber yields as in the previous experiment (Table 2). The effects of the seed origins on average tuber weights are contrasting for the two altitudes. Maize yields were notably higher than at the lower altitude (Tables 1 and 2). All interactions were non-significant except for maize yields in R×S ($P<0.05$).

The higher maize density resulted in higher maize yield per unit area but a lower yield per maize plant in Expt 6 (Table 6). However, the densities had no clear effect on potato yields. During the second half of the growing season, potato suffered from the attacks of late blight (*Phytophthora infestans*) and the pest 28-spot beetle (*Epilachna niponica* Lewis), thus maturing earlier than usual.

Canopy development

Potato plant height reached the maxima of 0.3 ~ 0.5 m and maize up to 1.9 ~ 2.7 m, the higher the altitude the higher the plant. Figure 1 refers to Expt 1 (Table 1) and it shows different treatment effects of density and row-ratio on leaf canopy development over time for potato and maize. The differences of potato yield parameters (Table 1) were in accordance with the differences of potato leaf canopy development in the first part of the growing period. Ratio-2 gave slightly higher maize canopy cover than ratio-1 most of the time and this trend is also consistent with maize yields. The difference in canopy cover between varieties was large (not shown) and that between densities small. Maize canopy covers did not differ significantly between any treatments for different growing periods either averaged over the two potato varieties or with only cv. CY56, with an exception of a significantly higher canopy

Table 5. Effects of intercropping in Expt 5 with potato planted on February 28 and harvested on Jul 20, and maize planted on April 9 and harvested on September 2, 1995, in Pengxian.

Treatment[A]	Maize yield[B] (kg/m^2)	Maize yield[C] (g/hill)	Potato Stand (%)	Tuber yield (g/pl)	Tubers[D] (#/pl)	Av. tuber weight[E] (g)	Tuber gross yield (t/ha)	Tuber net yield (t/ha)
D1 (50×25cm)	0.55	217	88	255	7.7 a	38 b	9.8 a	16.8 a
D2 (50×35cm)	0.57	225	98	250	6.6 b	43 a	8.2 b	14.0 b
Ratio-1 (2P:1M)	0.54 b	216 b	94 a	257	7.3 a	40	10.6 a	15.9
Ratio-2 (2P:2M)	0.58 a	225 a	91 b	249	7.0 b	41	7.4 b	14.9
S1 (CY56a)	0.55	219	89	256	4.7 b	55 a	8.7	14.9
S2 (CY56s)	0.56	222	96	249	9.6 a	26 b	9.3	15.9
CV(%) D:	4.6	4.2	14.6	7.9	11.4	5.6	11.1	16.3
R:	1.3	1.1	0.6	4.7	3.5	10.1	7.6	11.1
S:	1.8	2.3	10.9	7.8	18.6	6.8	4.2	4.2

[A] D=potato plant density while the gross maize plant density remains constant at $5.25/m^2$; R=row-ratio; S=seed source; different letters in a column for treatments indicate differences of means at least significant at $P<0.05$. [B,C] All interactions in the table are non-significant except R×S ($P<0.05$) for the two yields. [D] $P<0.07 \sim 0.09$ for factor D (Density), R (Ratio), and S (Seed source). CY56a and CY56s means previous autumn and spring origins respectively; maize yield refers to sun-dried grain and potato to fresh.

Table 6. Effects of intercropping in Expt 6 with potato planted on February 14 and harvested on July 20, and maize on April 9 and harvested on September 2, 1995, in Pengxian.

Maize density[A]	Maize yield (kg/m^2)	Maize yield (g/hill)	Av. tuber weight[B] (g)	Tuber gross yield (t/ha)	Tuber net yield (t/ha)
D1 (1.6×0.25 m)	0.40 a	161 c	28 b	8.5	12.7
D2 (1.6×0.40 m)	0.32 b	205 b	32 a	8.0	11.9
D3 (1.6×0.55 m)	0.27 c	240 a	30 ab	8.2	12.3
CV (%)	6.7	6.9	5.6	3.5	3.4

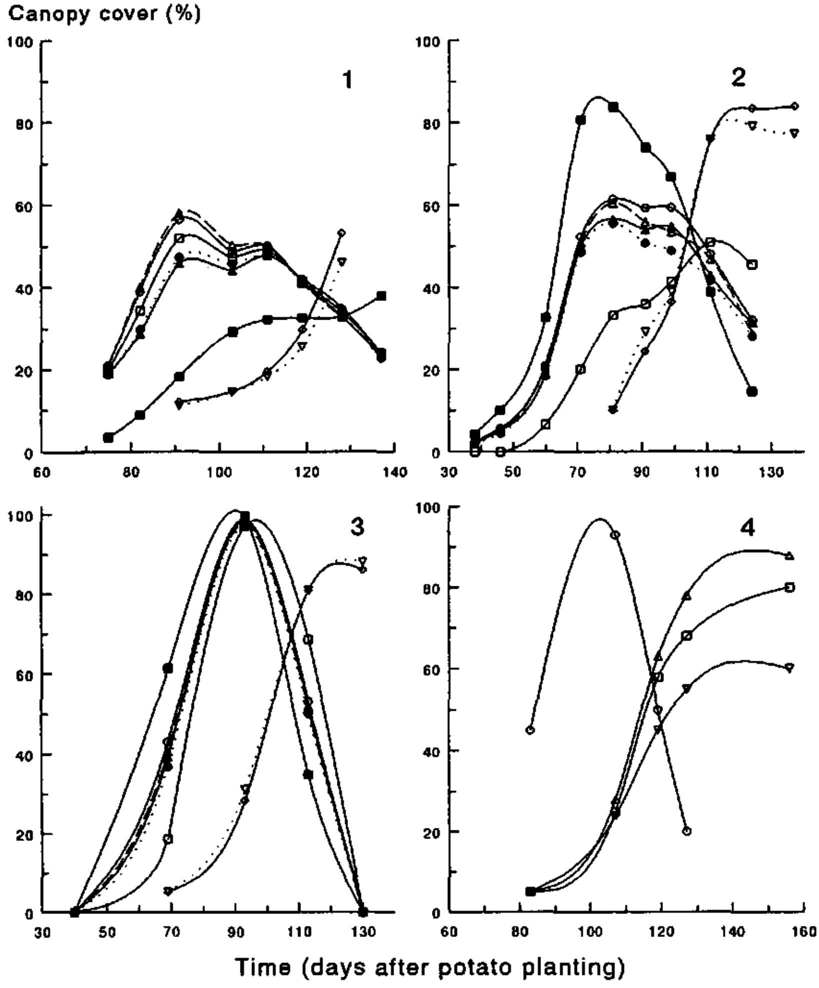
[A] Potato plant density remains constant at $5.43/m^2$; [B] $P<0.09$. Different letters in a column indicate differences of means significant at $P<0.01$. Maize yield refers to sun-dried grain and potato to fresh.

cover when intercropped with cv. HH6 than with cv. CY56 for the last data recording (128 days after potato planting). Maize canopy cover caught up with potato canopy during later potato growth.

Figure 2 relates to Expt 2 (Table 2), again the difference in canopy cover between varieties was large; similar trends as in Figure 1 were found for the other two treatments but with smaller differences. Maize canopy did not differ much between row-ratios. Figure 3 for Expt 5 (Table 5) shows similar trends as Figures 1 and 2 but with smaller differences between density and row-ratio treatments for potato and row-ratios for maize. Figure 4 for Expt 6 (Table 6) shows that maize canopy overlapped with potato canopy during relatively late growing period of potato, and that the denser the maize spacing the higher the canopy cover in the later growth period of maize. The larger maize canopy at the higher densities is in agreement with the higher maize yield per unit area (Table 6). There was no clear trend of effect of maize density treatments on potato yields.

Total potato and maize yields

Table 7 shows that total "gross" yields of both species ranged from 3.67 to 7.14 t/ha for dry matter production or from 18.4 to 35.7 t/ha for the equivalent tuber fresh yields. The higher potato or maize densities gave consistently higher total dry and fresh yields than lower densities across all experiments. R(atio-)1 (i.e. the higher proportion of gross potato population) generally gave yields similar to R2. R(atio-)1 gave higher yields than R2 in Expt 2 due to higher "gross" potato yield of R1 than of R2 (Table 2), whereas R2 gave higher yields than R1 in Expts 3 and 4 due to higher maize yields of R2 than of R1 (Tables 3 and



Leaf canopy cover over time of treatments of potato density, row-ratio and potato variety or seed source; Figure 1 for Expt 1, 2 for Expt 2, 3 for Expt 5, and 4 for Expt 6. The density and row-ratio treatments are only for V1 (cv. CY56) in 1, and they are averaged over both seed sources for 2 and 3. Maize was planted at 63, 45, 40 and 54 days after potato planting for 1, 2, 3, and 4, respectively.

For Figure 1, 2 and 3:

Potato			Maize
○ = D1	△ = R1	□ = V1/S1	▽ = R1
● = D2	▲ = R2	■ = V2/S2	◇ = R2

For Figure 4: ○ = Potato; Maize: △ = D1 (5.0 pl/ m^2); □ = D2 (3.1/ m^2); ▽ = D3 (2.3/ m^2)

Table 7. Data on total intercropped potato and maize yields.

Experiment/Location/ Year/Treatment	Total dry matter yield (t/ha)[1]	Equivalent tuber fresh yield (t/ha)[2]
Expt 1 (Table 1, Chengdu 1994)		
D1 (50×25 cm)	3.87	19.4
D2 (50×35 cm)	3.67	18.4
R1 (2P:1M)	3.80	19.0
R2 (2P:2M)	3.74	18.7
Expt 2 (Table 2, Chengdu 1995)		
D1 (50×25 cm)	4.08	20.4
D2 (50×35 cm)	4.01	20.1
R1 (2P:1M)	4.24	21.2
R2 (2P:2M)	3.84	19.2
S1 (CY56a)	3.74	18.7
S2 (CY56s)	4.35	21.8
Expt 3 (Table 3, Liangping 1994)		
D1 (50×25 cm)	5.31	26.6
D2 (50×35 cm)	4.65	23.3
R1 (2P:1M)	4.65	23.3
R2 (2P:2M)	5.21	26.1
V1 (CY56a)	4.72	23.6
V2 (HH6a)	5.14	25.7
Expt 4 (Table 4, Liangping 1995)		
D1 (50×25 cm)	4.42	22.1
D2 (50×35 cm)	4.40	22.0
R1 (2P:1M)	4.18	20.9
R2 (2P:2M)	4.73	23.7
V1 (CY56a)	3.86	19.3
V2 (HH6a)	4.96	24.8
Expt 5 (Table 5, Pengxian 1995)		
D1 (50×25 cm)	7.08	35.4
D2 (50×35 cm)	6.94	34.7
R1 (2P:1M)	7.14	35.7
R2 (2P:2M)	6.87	34.4
S1 (CY56a)	6.86	34.3
S2 (CY56s)	7.07	35.4
Expt 6 (Table 6, Pengxian 1995)		
D1 (1.6×0.25 m)	5.42	27.1
D2 (1.6×0.40 m)	4.58	22.9
D3 (1.6×0.55 m)	4.15	20.8

[1] Total potato and maize dry matter yield is calculated by addition of the maize sun-dried and potato fresh yield after multiplying with their respective dry matter content of 93% and 20%.
[2] The yield is calculated by the total dry matter yield divided by potato dry matter content of 0.20.

4). In Expt 5, R1 gave higher yields than R2, due to the greater "gross" potato yield increase in R1 than maize yield increase in R2 (Table 5). V1 gave higher yields than V2 in Expt 1 (data not shown) in Chengdu, whereas in Liangping V2 gave higher yields than V1 in Expts 3 and 4 due to both higher "gross" potato and maize yields (Tables 3 and 4). S2 always gave higher yields than S1 at both altitudes in Expts 2 and 5, the difference mainly being proportional to their respective "gross" potato yields (Tables 2 and 5).

Discussion

Effects of density and row-ratio on potato

Under intercropping conditions, denser potato planting increased both "gross" and "net" tuber yields at all altitudes (Tables 1 to 5), which is consistent with the authors' previous results under potato monocropping systems (He et al., 1997a), illustrating the density tolerance of the potato and the possibilities for yield increase under the intercropping conditions. The effects of row-ratios did not differ on potato yield on "net" area basis (which is a reasonable reference) under constant maize density under most conditions of Expts 1 to 5 (Tables 1 to 5). The overall higher tuber yields under the intercropping conditions for Expts 1 and 2 in Chengdu (Tables 1 and 2) in comparison with the adjacent fields' yields of sole crops would indicate the favourable cooling effect of shading on tuber bulking, which compensated and masked the unfavourable effect of lower light interception also due to shade. The shade to potato by R2 is expected to be greater than by R1. The discrepancy in the effects on tuber number per plant of both density and row-ratio treatments in Table 2 and density treatments in Table 5 in comparison with the more logical result shown in Table 1 (the lower the shade, the higher the number of tubers produced per plant) is probably associated with their respective lower potato plant stands so that more light could be intercepted per plant. The potato plant stand tends to correlate negatively to its plant density (He et al., 1997b) rather than to maize shading (Tables 1, 2 and 5).

The intercropped potato crop was not much affected by varying the maize density (Table 6), partly due to the severe late blight and 28-spot beetle (*Epilachna niponica* Lewis) attacks during the second half of the growing period, which can be seen in Figure 4 in which potato leaf canopy development had a prompt decline when maize canopy increased. It is also likely that the degree of inter-specific competition was not as strong as that reported by Vander Zaag and Demagante (1990) who observed that planting maize within 30 days after planting potato can significantly reduce potato yield due to maize's shade. Shade late in the season is also less likely to effect significant reductions in carbon assimilation, since all leaves are old by then, and photosynthetic capacity declines with leaf age (Vos and Oyarzún, 1987). The maize planting density ($40 \sim 53 \times 10^3$ ha^{-1}) when intercropped with potato in farmer's field in southwest China is far less than the reported density treatments ($56 \sim 83 \times 10^3$ ha^{-1}) (Vander Zaag and Demagante, 1990) of the intercropping with double- or single-row beds. Competition in intercropping or strip-cropping with maize in the tropics can be stronger than in the sub-tropics since potato yield is reduced when there is shading by maize limiting photosynthesis of the potato crop (cf. Batugal et al., 1990). Moreover, the favourable soil cooling effect (mean daytime soil temperature < 25°C) on potato plant emergence (Sale, 1979; Midmore, 1992) due to shade (Midmore et al., 1988; Midmore, 1990) is not found in areas where the temperature is already below that value (He et al., 1997b). So, both options of the row-ratios in our study, which are commonly practised by farmers are practicable. The maize planting density can be further increased while maintaining the potato yield based on the above analysis. The influences of the density and row-ratio treatments on tuber yields can be attributed to the differences in potato canopy cover, which is shown in Figures 1 to 3. The results further confirm previous extensive researches on the effects of density in potato mono-cultures (e.g. Allen and Scott, 1980; Spitters, 1987; Haverkort et al., 1991; He et al., 1997b) as well as in intercropping situations (e.g. Vander Zaag and Demagante, 1990).

Effects of density and row-ratio on maize

In all trials conducted, potato competed with maize differently when the two crops' row-ratios were varied. The effects were closely associated with the differences of the effects on canopy developments of both species (Figures 1 to 3). This indicates that the two species compete to intercept solar radiation during early growth. The stronger competition effects between the two species shown in Tables 1 and 5 than those shown in Table 2 are explained by the larger overlap of the two species shown in Figures 1 and 3 than in Figure 2. The competition imposed by potato for irradiance interception is more important than a possible cooling effect, because maize is a heat tolerant C_4 plant. The increase in maize yield with increasing potato density, observed in Expt 3 (Table 3), is in contradiction to the other experiments, and cannot be accounted for.

There was also an obvious intra-specific competition within the maize crop depending on the different maize densities (Table 6). However, maize yield per unit area still increased as the maize density increased.

Effects of variety and seed source

The varieties differed among each other in their yield components and also contributed to the variation in competition between the two species. The differences in canopy covers were mostly due to the differences of the varieties or seed sources among the three treatments (Figures 1 to 4). The performances were also influenced by different environments: the lagging behind of potato canopy progress from the autumn origin in comparison to the spring origin (Figure 3), which resulted in similar maize yields for both origins (Table 5) suggests that the competition effect imposed by potato to maize is also weak, since shading by potato at early stages of maize growth is supposed to be important for maize establishment. There is apparently some period of early stages of both species in which there is "wasted" resource of solar energy to be utilized (Harris, 1990).

The spring origin had higher tuber yields than the autumn origin especially at lower altitude (Table 2), which confirms previous findings (He and Struik, 1997). At higher altitude, the potato yields from the autumn origin is expected to be close to those from the spring origin, if the potato's growing period were as usually longer than in the present experiment (Table 5), as is proved by He and Struik (1997).

Interactions of the factors

Interactions were rare in the experiments and in relation to maize yield that existed mainly in potato density×row-ratio (Table 1) and row-ratio×potato seed source (Table 5). This indicates that the effects of row-ratio treatments on maize yield are dependent on either the density or the seed source, whereas potato yield parameters are affected independently by the individual factors. The fact that interactions between the treatments were rare provides more freedom to manage the intercropping systems with respects to the density, row-ratio and variety or seed source.

Total potato and maize yield

The higher total yields of combinations of both potato (Expts 1 to 5) and maize (Expt 6) per unit area due to an increase in potato or maize density are resulting from combined yield effects on both potato and maize. The difference in total yields between R1 and R2 is associated with the yield of both crops, but particularly of potato, indicating the importance of the potato component in the intercropping system. This is further shown by the effects of varieties or seed sources. The average total yields of both crops in all experiments are higher than previously found in Asia (Liu and Midmore, 1990; Vander Zaag and Demagante, 1990). In the present intercropping (relay cropping) systems, possible shortening of the combined growing period of the two crops is not a priority, because the two crops can not be planted one after another. Legumes and some vegetables can be planted between the maize plants after potato is harvested. So, in order to increase the total yields it is necessary to increase the densities of both crops or of one of them.

Influence of altitude

Maize yield increased while potato yield fluctuated as altitude ascended. R2, i.e. the higher proportion of maize, consistently gave higher maize yields but tended to reduce potato yield compared to R1 across the three different altitudes. Potato plant density treatments generally resulted in similar maize yields and consistently gave not only higher potato yields but also higher total yields in the higher density treatment at all three altitudes. Altitude also interacted with the effects of potato variety and of seed source. These results provide clear potential to manipulate the combined yields or the component yields according to specific desires, under intercropping conditions across all altitudes.

Implications for production

Since potato "net" yield is not affected by the current row-ratio practices by farmers, they can choose either way according to their specific desire for potato or maize produce. Besides, there must be possibilities for both species to further increase the planting densities and to narrow the planting dates of both species, in order to achieve higher yields of both or higher total yield at the acceptable expense of the other. Therefore, either the Land Equivalent Ratio (LER) or the Area×Time Equivalency Ratio (ATER; Hiebsch and McCollum, 1987) or both can be improved. The competition effects found in the study are in descending order: on maize imposed by potato (especially when potato emerges early and grows vigorously), on potato imposed by maize, and both inter- and intra-plant competition on maize or potato.

Conclusions

The planting of the two species can be further synchronised and the density of both species can be further increased compared to the current intercropping system at all altitudes studied, in order to achieve a more efficient use of space and time. However, it is necessary to use varieties that are adapted and can minimize the competition effects.

Appendix

Effects of potato-maize intercropping on land equivalent ratio (LER)

The main purpose of the paper was to investigate the effects of row-ratio, potato density and variety or seed source in the current intercropping systems, rather than to do more, e.g. to test the potato yield advantage over the sole crop. However, comparing the intercrop potato yield or the combined yield with the sole crop yield would provide further information. These comparisons can only be made based on estimates of the sole potato yield (generally higher than the intercropped gross and lower than the net potato yield) and sole maize yield (generally higher than the intercropped maize yield), avoiding unrealistically high estimations of the land equivalent ratios (LERs).

Materials and Methods

Land equivalent ratio (LER) was calculated following the method described by Midmore (1990). Data for sole potato and maize yields were collected from adjacent fields or estimated based on local yield levels.

Results

The land equivalent ratios (LER) in the table range from 0.91 to 1.78, and show the same effects and trends as observed for combined yields between each pair of treatments within each experiment except in comparing row-ratios in Chengdu 1994 (Expt 1), yet with only a slight difference. The higher potato or maize densities gave consistently higher LER than lower densities in all experiments. R(atio-)1 (i.e. the higher proportion of gross potato population) gave higher LER than R2 in Expt 2 due to higher "gross" potato yield of R1 than of R2 (Table 2), whereas R2 gave higher LER than R1 in Expts 3 and 4 due to higher maize yields of R2 than of R1 (Tables 3 and 4). In Expt 5, R1 gave higher LER than R2, due to the greater proportion of "gross" potato yield increase in R1 than maize yield increase in R2 between the two row-ratios (Table 5). V1 gave higher LER than V2 in Expt 1 (data not shown) in Chengdu, whereas in Liangping V2 gave higher LER than V1 in Expts 3 and 4 due to both higher "gross" potato and maize yields (Tables 3 and 4). S2 always gave higher LER than S1 at both altitudes in Expts 2 and 5, the difference mainly being proportional to their respective "gross" potato yields (Tables 2 and 5).

Table. Data of the effect of intercropping potato and maize on overall LER.

Experiment/Location/ Year/Treatment	LER (Land equivalent ratio)[1]
Expt 1 (Table 1, Chengdu 1994)	
D1 (50×25 cm)	1.36
D2 (50×35 cm)	1.30
R1 (2P:1M)	1.32
R2 (2P:2M)	1.34
Expt 2 (Table 2, Chengdu 1995)	
D1 (50×25 cm)	1.51
D2 (50×35 cm)	1.43
R1 (2P:1M)	1.57
R2 (2P:2M)	1.37
S1 (CY56a)	1.28
S2 (CY56s)	1.66
Expt 3 (Table 3, Liangping 1994)	
D1 (50×25 cm)	1.37
D2 (50×35 cm)	1.15
R1 (2P:1M)	1.20
R2 (2P:2M)	1.31
V1 (CY56a)	1.16
V2 (HH6a)	1.35
Expt 4 (Table 4, Liangping 1995)	
D1 (50×25 cm)	1.17
D2 (50×35 cm)	1.16
R1 (2P:1M)	1.14
R2 (2P:2M)	1.21
V1 (CY56a)	0.91
V2 (HH6a)	1.42
Expt 5 (Table 5, Pengxian 1995)	
D1 (50×25 cm)	1.78
D2 (50×35 cm)	1.68
R1 (2P:1M)	1.83
R2 (2P:2M)	1.63
S1 (CY56a)	1.69
S2 (CY56s)	1.75
Expt 6 (Table 6, Pengxian 1995)	
D1 (1.6×0.25 m)	1.55
D2 (1.6×0.40 m)	1.42
D3 (1.6×0.55 m)	1.40

[1] LER was calculated by adding up the ratios between intercropped yields and respective sole crop's yields.

Discussion

Potato yields under intercropping conditions are not reduced and even increased, and total yields of both component crops are much higher than in sole potato cropping (cf. He et al., 1997a; 1997b; He and Struik, 1997). The benefit of the current practice of intercropping potato with maize is further proved by the fact that LER values exceeded 1.00 (Table 7). The highest LERs (range 1.63 ~ 1.83) were found when normal potato and high maize yields were achieved in Expt 5 (Table 5), which are higher than the findings of Batugal et al., 1990; Vander Zaag and Demagante, 1990. LERs below 1.00 occurred only in varieties unadapted to specific conditions (data not shown). Lower LERs in Liangping than in the other locations were due to its generally lower tuber yields rather than to reduced maize yields, which resulted from some unfavourable environmental conditions (particularly poor soil physical conditions). Another experiment conducted in Chengdu in 1995, resulting in lower tuber yields and lower maize yields showed LER values ranging from 1.01 to 1.25 (complete data not presented), again due to unfavourable soil conditions. The variation of LER is dependent on specific competition effects which results from different potato plant densities, row-ratios, and potato varieties or seed sources. Generally, R1 gave higher total yield and LER than R2, which contrasts the findings of Liu and Midmore (1990).

Conclusions

Intercropping maize and potato gives a yield advantage for potato, as well as for the total yield of the component crops across the altitudes.

Chapter 8

Diseases and pests in potato production in Sichuan, China

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Summary

It is important to know the specific disease and pest status of potato production, especially in the warmer regions. A series of studies, including general field surveys, phyto-pathological tests and estimation of yield losses, was conducted in Sichuan, China. In general, potato viruses, late blight and bacterial wilt were the most important diseases. Seed tubers and plants were generally infected with viruses, which reduce production. A regular late blight epidemic every season causes severe yield loss. Incidence of bacterial wilt occurs irregularly. The severity of the three diseases was closely associated with season, altitude, seed age, variety and agronomic practices such as cutting of seed tubers. Genetic resistance, especially to late blight and bacterial wilt, was found. Parasitic nematodes also proved detrimental. Defoliation by 28-spot beetle was severe in certain circumstances in the area. Various possible approaches to control diseases and pests are discussed.

Key words: disease, pest, potato, yield, altitude, control, Sichuan.

Introduction

The potato is prone to more than 100 diseases caused by bacteria, fungi, viruses, viroids or mycoplasmas, but fortunately relatively few cause serious damage in any one growing area (Hide and Lapwood, 1992). Potato fields are also inhabited by many different insects and mites (Raman and Raddcliffe, 1992). Little systematic knowledge is available on potato disease and pest damage in Sichuan. Previous chapters have shown that potato yields in Sichuan are often low. The reasons for this are complicated, but factors definitely include infection by various potato diseases, and probably to a lesser extent pests.

The primary reason for low yields is the wide use of degenerated seed tubers. Degeneration is mainly caused by various viruses. PSTV presumably also occurs in the southern highlands

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of Sichuan, since the typical symptom, i.e. the spindle tuber, has been observed. The cool climate is suitable for the viroid. A seed potato production system to supply high quality seeds is lacking.

Phytophthora infestans is the causal agent of potato late blight that may have a devastating effect on the crop depending on weather and susceptibility of cultivars grown. Late blight is usually the most important disease wherever potatoes are grown (Hide and Lapwood, 1992). In China, some research work has been carried out on the disease but it is restricted to the identification of different races of the pathogen and of the corresponding genes responsible for resistance or susceptibility in potato. Applied research has mainly been focused on the selection of varieties that show horizontal resistance to the pathogen; incidentally, some work has been done on chemical control.

Bacterial wilt caused by *Pseudomonas solanacearum* is sometimes severe in the region. Determination of biovars (biotypes) of *Pseudomonas solanacearum* has been carried out and the biovar II (i.e. Race 3 in most cases) proves to be the dominant strain in China (He et al., 1983). Further understanding of the disease in the main potato producing areas is needed.

Potato viruses, late blight and bacterial wilt are the three important diseases in Sichuan. More information on their occurrence, epidemiology and yield effects, as well as on certain other pests, in relation to environmental conditions would contribute to the understanding of the problem and thus would provide a basis for further improvement of potato production. Therefore, an attempt was made to collect the necessary information.

Materials and Methods

General. Copies of a questionnaire on overall view on potato production and diseases were sent to the agricultural bureaus of some 30 counties in Sichuan, with relatively large potato growing areas. During May to July, 1990, 24 villages of 10 counties were selected for a field survey of potato diseases and pests, and to interview farmers and local agro-technicians. Samples of leaves and tubers were taken back to the laboratory for analysis. Some of the work was done in 1994 and 1995.

Identification of Potato Viruses. Potato leaves with virus symptoms were carefully sampled from the selected localities and tested in the laboratory by Enzyme-Linked Immuno-Sorbent Assays (ELISA). Antisera of PVX, Y, S, A, M and PLRV were kindly provided by Prof.

Zhang Heling, Nei-Meng-Gu (Inner-Mongolia) University.

Classification of P. solanacearum. Bacterial wilt infested plants were identified and their tubers were brought to the lab. The strains of *Pseudomonas solanacearum* were purified from the isolates of the pathogen using TZC (tetrazolium chloride) media at 28°C for 48 hours. For long term storage, the cultures of strains were maintained as suspensions in distilled water in capped test tubes under room conditions. The determination of biovars was carried out following the tests proposed by Hayward (1964), i.e. the response to oxidation (or not oxidation) of the 6 carbohydrates, namely cellobiose, dulcitol, lactose, sorbitol, maltose, and mannitol.

Late blight. Estimates were made of the rate of incidence, time of occurrence and spread, yield loss, and the factors that influence severity of the disease were assessed.

Identification of nematodes. Samples of soil, tuber and root of potato were isolated and examined under binoculars to identify the species and to count the numbers per unit of volume or weight of each sample.

Identification of other bacteria and fungi. Tuber samples collected were planted in pots in a net house and infected plants were chosen to identify the pathogens.

Observation of insects. Presence of insects was recorded based on the survey in different production areas and by visual observation in farmers' fields.

Results and Discussion

In the Sichuan province, the major potato cultivars are Epoka, Mira (introduced from Poland and the former GDR, respectively, in the 1950's), Nowa Huta, locally bred CY56 and Liangsu 97, plus several minor local ones. Most varieties are degenerated due to infection of viruses and other pathogens. A seed production system providing clean seed is simply lacking in most areas. Viral diseases, late blight and bacterial wilt are the major biological constraints, and farmers and local agricultural extension workers are familiar with them. Farmers are eager to acquire new resistant and adapted varieties to replace the old ones that have been mixed and are degenerated.

Late Blight. Late blight (*Phytophthora infestans*) is the most important and widely spread disease in the province, followed by viruses, bacterial wilt, pests, and other minor diseases. Late blight usually reduces tuber yield by 10-30%. However in 1990, there was a severe late blight epidemic in many parts of Sichuan, especially in the western basin, followed by the east, probably due to heavy rainfall and low temperatures in March and April. Potato yield loss was estimated to be 60% in the Sifang county, and 30% in the Pengxian county. Late blight epidemic was advanced by 10-15 days in most areas of the Sichuan basin. The earliest record of occurrence in the east was even on March 28. The severity of late blight was found to be related to the use of seed tubers that had been multiplied locally and continuously for over 15 years without any crop rotation or regional crop diversity due to land shortage and lack of knowledge; environmental factors such as higher altitude and higher humidity enhanced the disease. Application of fungicides was effective but is not common in the region.

The incidence of late blight is heavier in spring crops (Feb-Jul) than in autumn crops (Sep-Dec). There were only slightly infested plants in autumn crops in the east but more infection in the west basin.

In southern Sichuan (Liangshan region) there is only one potato crop per year (Mar-Sept) when it is grown in the highland (1,500-3,200 m asl). There the epidemic is normally later (June-July) and its severity depends on the year.

Viruses and Viroids. Symptoms of viruses were frequently observed, mainly mosaic and leaf roll. Presence of PSTV was also noted in the southern highland (Liangshan region), especially in the open pollinated true seed progenies of cultivar 'Kuannae' that used to be brought from Inner-Mongolia. The results of Enzyme-Linked Immuno-Sorbent Assays (ELISA) showed that at least infection with PVX, Y, S, M and PLRV occurred (Table 1). It seems that both PVS and PVM were either absent, or present simultaneously in the cool climate conditions, since the two viruses are closely related (Raman and Radcliffe, 1992). It was also noted, e.g. in the cases of PVS, PVM and PVY, that the seemingly healthy plants were not necessarily actually infected with less virus than the seemingly infected plants. Spindle tuber caused by viroids was also observed. The disease can cause severe secondary symptoms on the plants (Hide and Lapwood, 1992). Some samples from the eastern and southern highland of Sichuan proved virus-free.

Records on aphids abundance using yellow pan traps showed that the peak of the aphid (*Myzus persicae*) population in a mountain area (around 1500 m asl) was during early May in the spring potato crop. The infection level of viruses in potato leaves was not closely related to tuber yield under field conditions, thus other factors may have more influence on

Table 1. Summary of the virus infection of 107 farmers' fields in the major potato growing areas of the Sichuan province, 1990.

County	Fields sampled	ELISA results				
		PVX	PVY	PVS	PLRV	PVM
		---------------------(% samples infected)--------------------				
Wenchuan	19 H*	26	11	63	26	53
	I*	16	26	58	11	58
Wanxian	23	26	39	17	35	9
Liangshan	9	33	78	22	44	0
Pengxian	16	69	38	6	.**	0
Sifang	16	63	31	0	.	6
Xuyong	20	95	35	5	.	0
Guling	4	100	0	0	.	0
Total	107	50	34	19	33	12

*. H, seemingly healthy plants; I, seemingly virus-infected plants. **. No data taken.

the yield (He et al., 1991).

Bacterial Wilt. The potato bacterial wilt caused by *Pseudomonas solanacearum* is another disease that was first observed at the end of 1970's and showed severe epidemic in the early 1980's, but somehow gradually decreased its severity over the last 10 years, especially in the west part of the basin. In the past, farmers planted cv. Epoka at low elevation (500 m asl) in spring, and then brought the harvested seed tubers to high elevation (1200 m asl) to grow the crop in the following autumn to have a better seed age in autumn. That practice has been stopped after they had access to the earlier cultivar CY56 which can be grown in both seasons at the high altitude. This may explain why the disease gradually decreased there, because the pathogen which is easily multiplied in warm weather is difficult to spread under cool conditions (cf. Hide and Lapwood, 1992).

Our preliminary results of classification of biovars of *Pseudomonas solanacearum* showed that strains were assessed as biovar V, and biovar III. Biovar V (Race 4) was previously found by He et al. (1983). The strain produced acid from lactose, maltose, cellobiose and mannitol, but not from dulcitol and sorbitol. They reported that the strain of biovar V from mulberry is only weakly virulent on eggplant and potato and not on tomato, pepper, peanut, or tobacco. Biovar II, i.e. Race 3 in most cases, was considered to be the dominant strain in China (He et al., 1983).

Table 2 summarizes the general trend of performance of the three main diseases averaged for the seasons, altitudes, seed ages and varieties in the potato crop, which is taken from the "seed supply" experiment. There was a slightly higher incidence of late blight in spring but there were no differences for the other two diseases between the spring and autumn seasons. Late blight epidemics were more severe at high than at low altitude due to lower temperature and higher humidity there; no differences in virus symptoms were found between the altitudes within this range. Plants were more infected by bacterial wilt at low than at high altitude. Older seed generally resulted in more infection by late blight and viruses in the progeny plants but in less symptoms of bacterial wilt. Variety No. 22-2 showed far more resistance to all the diseases than cv. CY56. Cutting seed tubers without chemical sterilizing has been shown to be inducive to infection with bacterial wilt both for cut pieces and plants grown from them. Lower plant stand in autumn than in spring is probably also partly accounted for by effects of other bacterial and fungal air-borne pathogens and soil-borne pests. Differences in plant stands between crops grown from seeds previously harvested, at high or low altitudes and spring or autumn seasons, were both caused by diseases and seed dormancy status; for example, in variety No. 22-2 plant emergence and plant stand can be low due to the long dormancy of the seed tubers. In cv. CY56, interaction existed between effects of season and site of seed origin.

Table 2. General severity of the diseases averaged for seasons, altitudes, seed age and varieties in the potato crop.

	Late blight	Virus	Bacterial wilt
Spring	++	+	+
Autumn	+	+	+
Low (500 m asl)	±	+	++
High (1200 m asl)	++	+	+
Young seed	+	+	++
Old seed	++	++	+
Cv. CY56	+++	+++	++
Variety No. 22−2	−	+	−

Note: The severity of disease increases from ± up to +++; − means no incidence at all.

Other bacteria and fungi. The bacterial disease *Erwinia* spp. was identified once from tuber samples collected in spring 1994. No fungal diseases such as stem canker (*Rhizoctonia solani*) were found in the samples.

Possible control strategies for the above diseases may be in general the development of resistant cultivars and cultural or biological control. Intercropping and rotation for example effectively reduce bacterial wilt Race 3 (biovar II), but hardly reduce Race 1 (biovar III) which also affects many other crops and weeds (especially *Solanaceae*). There are also interactions between strains of the pathogens, hosts and environments.

28-spot beetle. Defoliation by the pest 28-spot beetle (*Epilachna niponica* Lewis) was sometimes very severe, especially in dry conditions. The resulting tuber yield loss was substantial. It is probably the most important potato insect pest that defoliates leaves of the crop in China. Chemical control of the pest is effective.

Nematodes. Parasitic nematodes were found in all soil samples collected from the different places of potato fields (Table 3). Root-knot nematodes (*Meloidogyne* spp.) were found in six samples with variable numbers. They occur more commonly in warm, light, wet soils, and certain species cause severe damage locally (Evans and Trudgill, 1992). *Pratylenchus* spp., *Helicotylendus* spp. and *Aphelenchoides* spp. were found in relatively large numbers in the samples. Cyst nematodes (*Globodera pallida* and *G. rostochiensis*) were not found; they usually occur in more temperate regions. Hardly any parasitic nematodes were found in tuber samples from Pengxian.

Table 4 only shows the result of samples found with parasitic nematodes. No nematodes were found in tuber samples from any of the different altitudes tested in spring. Chemical treatment (a locally produced biocide) seemed to have effects on controlling the presence of nematodes in a rotated crop field. In a piece of land that was never cropped to potato, no nematodes were found, either treated or non-treated with the chemical on soil before planting, indicating that the presence of nematodes was closely related to crop rotation.

Also in autumn, no nematodes were found in tuber samples of the tests of Table 5. The special nematodes, i.e. bacterial feeders (*Rhabditoidea* spp.) were found in large numbers in some non-chemical treated root and soil samples (Table 5).

In general, the parasitic nematodes were found in variable numbers and some of them

Table 3. Different parasitic nematodes observed in soil samples at the three elevations both in experiments and in practice of the potato crop in spring, 1994.

Parasitic nematodes	Pengxian (1200 m asl)			Lingping (750 m asl)	Chengdu (500 m asl)	
	A	B	C		A	B
Meloidogyne spp.	186	+	42	–	77	+
Pratylenchus spp.	72	+	+	+	176	+
Helicotylendus spp.	+	+	–	262	+	–
Aphelenchoides spp.	+	+	+	–	26	–
Rotylenchulus spp.	+	–	–	–	+	–
Rotylenelms spp.	–	–	–	–	+	–

Note: The figures in the table are numbers of nematodes per 500 ml in volume of soil sample; + means < 10; – means none. The soil samples were randomly taken, labelled with A, B or C. Nearly no parasitic nematodes were found in tuber samples from Pengxian.

Table 4. Presence of different parasitic nematodes observed at three elevations both in experiments and in practice of the potato crop in spring, 1995.

Parasitic nematodes	Mianning (2200 m asl)	Pengxian (1200 m asl)		Chengdu (500 m asl)
	Sl	T/Sl	C/Sl	C/Sl
Meloidogyne incognita	25	–	5	25
Pratylenchus spp.	15	–	–	–
Trichodorus spp.	–	5	5	–
Ditylenchus dipsaci	15	–	–	10
Trlenchus spp.	–	–	–	5

Note: Sl=Soil; T=Treatment with chemical; C=Control without chemical. The figures in the table are numbers of nematodes per 500 ml in volume of soil (Sl) samples; – means none. No parasitic nematodes were observed in the other samples of both tuber and soil (see text).

Table 5. Different parasitic nematodes observed at three elevations both in experiments and in practice of the potato crop in autumn, 1995.

Nematodes	Pengxian (1200 m asl)		Lingping (750 m asl)		Chengdu (500 m asl)		
	RT	Sl	RT	Sl	C/RT	C/Sl	T/Sl
Meloidogyne incognita	–	40	–	25	–	–	25
Pratylenchus spp.	–	5	–	110	–	125	10
Ditylenchus dipsaci	–	15	–	30	–	5	105
Bacteria-vorous nematode	15	–	300	230	67	–	–

Note: Sl=Soil; T=Treatment with chemical; C=Control without chemical. The figures in the table are numbers of nematodes per 500 ml in volume of soil (Sl), or 50 g roots (RT), samples; – means none. No parasitic nematodes were observed in the other samples (see text).

reached damaging population densities. It is easier to control cyst nematodes that have a narrow host range by the crop rotation than to control nematodes with a wide host range (such as *Meloidogyne* spp.) (Evans and Trudgill, 1992). In northwestern America the population density of *M. hapla* is greatly decreased by cereals (Evans and Trudgill, 1992). This may indicate the possible control of *Meloidogyne* spp. by means of agronomic measures such as intercropping potato with maize. Use of resistant cultivars may be an alternative.

It is important to have a disease- and pest-free environment for potato production, yet it takes time to achieve that, mainly because of the technical and socio-economical situation in the area. Storing potatoes always involves risks and improvement in storage technology is needed to avoid catastrophes as well as the smaller but more continuous losses which amount annually to a significant proportion of world production (Hide and Lapwood, 1992). Agronomic (non-chemical) control of diseases may include proper rotation, intercropping, i.e. by means of physical barriers and diverse hosts (Potts, 1990; Midmore, 1988), roguing, biological control, early haulm killing for seed tubers, storage, rapid multiplication techniques, use of true (botanical) seed (TPS), etc. The combination of the use of resistant cultivars and integrated management may be most effective (Hide and Lapwood, 1992; Raman and Radcliffe, 1992).

Conclusions

Seed tubers and plants were systematically infected with viruses, which limited production; there was a regular late blight epidemic every season that causes severe yield loss; bacterial wilt occurred irregularly but it can also be devastating to the crop.

The performance of the three diseases was closely associated with season, altitude, seed age and seed history, variety and agronomic practice (e.g. cutting of seed tubers). Varietal resistances to the diseases, especially to late blight and bacterial wilt, were found.

Parasitic nematodes were found in variable numbers. Defoliation by 28-spot beetle was sometimes severe.

Chapter 9

General discussion and conclusions

Yield gap analysis

'Potential' and attainable yields using local seeds at different elevations and in different growing seasons suggest that the present actual yields in the area can be improved substantially, especially at lower altitudes. Higher 'potential' and actual yields were obtained at higher altitudes where temperatures are lower and seed age is generally more suitable at planting. Low actual yields are directly caused by the short duration of the canopy cover. A number of important biotic and abiotic factors presented in the thesis is involved in determining this short canopy duration. Moreover, light use efficiency often proved to be suboptimal. Understanding the values of both total canopy duration and light use efficiency and how to improve them are of practical importance.

The simple model is easy to use; it clearly illustrates and quantifies the main aspects of crop production. Moreover, the estimates of crop yield obtained with simple models are often more reliable than the estimates from the complicated models (Beukema and Van Der Zaag, 1990). The model indicates that the low solar radiation level in Chengdu or at even lower altitude is a major yield limiting factor. This low radiation level is associated with poor light interception. The combination of these negative factors can only partly be solved by agronomic measures. At higher altitudes, crops perform better because light intensity increases and light interception increases at the same time, until altitude becomes so high that yields become limited by the low temperature, first because temperatures only allow one growing season per year, later because temperatures become an actual growth limiting factor.

Planting time

The purpose of choosing optimal planting time at a specific location is to find the growing period where available solar radiation can be utilized to the maximum considering total light interception, maximum light use efficiency and optimal dry matter distribution. Temperature is a main factor in this respect. In practice, however, the earliest possible planting time is necessary because other crops or a second potato crop need to be planted in the same field. Planting too early can lead to soil compaction in the subsoil, cold, cloddy, dry, nitrogen deficient soils in the ridge, delayed and reduced emergence, reduced leaf growth (Allen and

Scott, 1992), and in autumn low plant stand (Chapter 3), hence reducing yield. The effect of planting time is also associated with seed tuber age, i.e. the sprout number and size on the tubers at planting. The use of polythene film to cover the soil is an attempt to increase the soil temperature, to advance sprouting, emergence and early leaf cover and thus to increase yield (Allen and Scott, 1992). This technique is common in the highlands of Sichuan.

Seed quality

The seed age is believed to be one of the most important issues for production in double cropping regions. In practice, the problems associated with inadequate physiological age are not well appreciated nor sufficiently solved. In fact, the entire study reported in this thesis shows the relevance of seed age; the topic becomes most evident in Chapters 4, 5 and 6 and to a lesser extent in Chapters 3 and 7. It is shown that seed age determines growth and yield and is affected by conditions during production and storage; too young seed is the main problem in the area, but generally the young seed outyielded the old seed at higher altitude (1200 m asl) where the growing period is longer (Chapter 4); this was not the case for the variety No. 22-2 with a very long dormancy.

<u>Seed origin and flow</u>

Seed age can effectively be manipulated through selecting seed tubers derived from certain altitudes or seasons. The large variation of seed age that affects plant growth and yield is caused primarily by differences in accumulated temperature sum. This sum is different for the various seed flows, since conditions during growth, dates of harvest and conditions during storage of the consecutive progenies differ. Inconsistent effects of different seed sources have been reported (Allen et al., 1992). However, the research reported in Chapter 4 clearly shows that manipulation of seed sources can effectively be done through selecting progenies of previous spring or autumn crops produced either at low or hight altitudes, or from an early harvest of the seed crop. During the course of seed production, seed health can also become an issue, but it is not yet clear in what specific ways. Chapter 8 already indicated that the occurrence and severity of diseases were also different for the different environments. However, the involvement of the diseases that may affect the seed qualities used in Chapter 4 can be secondary and needs to be further looked at.

Seed tuber weight

The size or weight of seed tubers often varies in practice. The effects of seed tuber size on tuber yield, in association with seed dormancy and apical dominance, were investigated under the different ecological conditions (Chapter 5). When evaluated at constant spacing, seed tuber weight significantly affected tuber yield in all conditions under study. Higher plant density also increased yield, probably by increasing the average weight of progeny tubers. When numbers of sprouts per unit area were set equal, the effect of weight of seed tubers on final tuber yield per unit area was absent in the seed tuber weight range studied. This indicates that the number of sprouts planted is a crucial factor, even more so than the number of eyes planted (cf. Allen and Wurr, 1992). It also shows the effect of using lighter (smaller) seed tubers, as the seed rate from the lighter ones can be lower (Allen and Wurr, 1992), but further study is needed to assess the effect on yield in different conditions. When calculated per stem the numbers of tubers produced and the tuber yields differed between the seed weight treatments; effects depended on the seed dormancy status: tuber number per stem increased as seed tuber weight decreased when the seed tubers used were younger. The leaf area per stem or per plant from lighter seed tubers probably increased to compensate for their lower plant stands, or lower numbers of main stems per plant, thus resulting in similar tuber yields compared to heavier seed tubers. Results also indicate the need to study in a quantitative way the effects of cutting the large young seed tubers to break dormancy and apical dominance.

Seed-tuber cutting

Chapter 6 evaluated a practical way of breaking dormancy and apical dominance in the double cropping area, i.e. cutting seed tubers into pieces. This practice is also common in some temperate regions probably mainly for the purpose of saving seed. Cutting generally promoted plant emergence and increased stem numbers per plant in comparison with the whole seed tuber per unit seed weight planted. Cutting also spread a wilting disease, probably mainly caused by *Pseudomonas solanacearum*, especially at lower altitude.

Seed density

Seed or plant density is an important aspect of crop production; it is often inadequate in the warmer regions. Effects of seed or plant density were studied in combination with the effects of planting time (Chapter 3), seed tuber weight (Chapter 5), or intercropping with maize

(Chapter 7). Denser spacing up to 10 (Chapter 3) or 8.0 (Chapters 5 and 7) seed tubers/m^2 consistently increased tuber yields compared to lower densities down to 4.2 (Chapter 3), 4.8 (Chapter 5) or 5.7 (Chapter 7) seed tubers per m^2; average densities in farmers' fields are about 5.0 seed tubers per m^2. This increase of yield is attributed to a larger canopy cover intercepting more light, more stems and hence more progeny tubers, without apparently reducing average tuber weight. The seed density effect is ultimately determined by stem density and numbers of branches per stem; both parameters are mainly influenced by the product of seed number and average weight or size per unit area, seed age, genotype, and several other environmental factors such as temperature and rainfall. The sprout numbers prior to planting can serve as an early predictor of stem density (Chapter 5) (cf. Allen and Wurr, 1992). Final plant stand was reduced by higher seed density in most experiments (Chapters 3, 5 and 7), probably due to higher humidity within the canopy of the higher seed density treatments (cf. Allen and Scott, 1992). The increase of yield by the experimental higher seed densities (Chapters 3, 5 and 7) and the weak inter-plant competition (Chapter 7) show that the current seed density in practice can be increased considerably to achieve a higher yield.

Intercropping

In Chapter 7, the current intercropping system was evaluated. Higher total yield of combined potato and maize was obtained when two rows of potato were alternated with one row of maize than when two rows of potato were alternated with two rows of maize. The relatively weak competition between the two crops indicates that planting dates of the two species can be more closely synchronised and densities of both species can be further increased in the current intercropping system at all altitudes studied, to achieve a more efficient use of space and time. Based on well-estimated sole potato yields and sole maize yields to calculate the land equivalent ratio (LER), it was shown that intercropping maize and potato gives a yield advantage for potato, as well as for the total yield of the component crops for all the altitudes in the study. The increase in total yield can also partly be attributed to disease control by the spatial arrangement (Potts, 1990; Midmore, 1990).

Diseases and pests

As shown in Chapter 8, seed tubers and plants were systematically infected with viruses, which limited production; there was a regular late blight epidemic every season that caused severe yield loss; bacterial wilt occurred irregularly and it can also be devastating to the crop. The severity of the three main diseases was closely associated with season, altitude, seed age and seed history, variety and agronomic practice (e.g. cutting of seed tubers). Varietal resistances to the diseases, especially to late blight and bacterial wilt, were found. Parasitic nematodes were found in variable numbers and their role in affecting plant growth and yield was not yet clear. Defoliation by 28-spot beetle was sometimes severe. The influences of diseases were also shown to be closely associated with the agronomic measures relating to planting time (Chapter 3), seed density (Chapters 3, 5 and 7), and cutting of seed tubers (Chapter 6).

Other important aspects

Sprouting prior to planting and storage. The sprouting status of the seed tubers prior to planting is not given priority in this thesis, as there were unsprouted young seed tubers in several chapters (e.g. Chapter 4). There are several methods to have seed tubers with sturdy sprouts before planting, such as choice of a short dormancy variety, seed treatment with various chemicals or heat and cold shocks. The most important practical and environmentally safe method to break the dormancy or to advance seed vigour may be to give the seed tubers a period of warmth, as intensively studied by Van Ittersum (1992). There is a need to develop a more specific way to do so in this double cropping area of Southwest China, as this method has never been practised by the farmers.

Final remarks

This thesis provided a systematic agronomic study on potato production in a characteristic ecological region, where there has been little formal research done before. A number of important specific aspects has been effectively unravelled, though most of them may seem within the framework of basic applied research. All agronomic measures studied aimed at maximizing leaf canopy cover, since the leaf area index (LAI) is less than 3.5 in most cases. The light use efficiency (LUE) varied in the studies and needs to be further investigated for various conditions, because of its importance in yield determination, and its significance to trace stress factors and suboptimal agronomic measures. Most agronomic effects identified in this thesis have a physiological basis and manifest themselves consistently despite the influence of agro-ecological factors also varied in these experiments. Sometimes they were overruled by other effects, which need more careful attention.

Field experiments have their own niche in understanding crop production to further improve yield from a point of view of the ecosystems, even though existing knowledge on plant physiology may already provide some basic insight. The results presented can serve as a basis for further modelling, for further improvement of crop growth, and for developing ideotypes, which include characteristics such as short dormancy and rapid tuber bulking.

Summary

1. Introduction

Currently potato occupies an annual hectarage of 3.0 to 3.2 million ha in China, of which 40% is grown in the sub-tropical southwest mountain areas at different altitudes, in different seasons, and intercropped with maize or in sole cropping. Potato in China is a low input crop and the average yield is low. Little was done on crop physiology, production ecology and agronomy in the area compared with activities in the temperate regions and in the tropics. The reasons why the yields are low and the relative importance of the yield reducing and limiting factors are practically unknown. However, it was already ascertained that poor seed quality and inadequate seed management were among them.

The objectives of this study were: 1) To analyze and describe in a quantitative way the growth and characteristics of potato grown at different altitudes both for spring and autumn crops in Sichuan, China. 2) To investigate and evaluate quantitatively the effects of seed quality, and the effects of cultural practices related to seed management for different cultivars, under the different agro-ecological conditions in the double cropping area.
The results gained can serve as a basis for further crop improvement.

2. Yield potential and yield gaps

Yields were higher at higher elevation. The spring crops showed higher yields but had lower light use efficiencies than the autumn crops, especially at higher altitudes. In spring the gaps between actual and "potential" yields were mainly due to long periods of insufficient canopy cover and low light use efficiency. These physiological constraints were associated with drought and heat stresses at the low elevations, lack of fertilization, and occurrence of biotic stresses. The lower yields of the autumn crops can also be attributed to the short growing season resulting in low levels of accumulated light interception.

3. Planting time

In practice, planting time should be as early as possible because other (or second potato) crops are to be planted in the same piece of land. Earlier planting in spring increased yield at 500 m asl; at 1200 m asl effects on yield were absent. In autumn, effects of planting time on yield were generally absent at all elevations, although plant stands at early planting were consistently and often severely reduced. Best planting time in autumn seems to be immediately after the late summer heavy rainfall. Optimal planting time depended on cultivar and dormancy of the seed tubers used.

4. Seed quality

Seed tubers normally used in Sichuan are systematically degenerated but in varying degrees. However, the effects of the use of infected seed on yield and its interactions with other agronomic measures (e.g. the seed source) was not studied. Effects of seed age and other seed characteristics, however, are also relevant, and were investigated in detail.

4.1 Seed age, seed origin and seed flow

Seed age is important for production in double cropping regions. In many parts of this study the issue of physiological age proved to be important. Generally, young seed outyielded old seed at higher altitude (1200 m asl) where there is a longer growing period, but this is not the case in the variety No. 22-2 which has a very long dormancy. For spring crops, seed tubers are required to be older at lower altitude and younger at higher altitude than those commonly used. For autumn crops, seed tubers should be relatively old both at low and high altitudes. Manipulation of seed sources can be done through selecting progenies of previous (one to three consecutive crops back) spring or autumn crops produced either at low or high altitudes, or from an early harvest of the seed crop. The observed long-term after-effects of seed origins may have been associated with effects on seed health.

4.2 Seed tuber weight

Heavier seed tubers produced higher tuber yields under all conditions. When numbers of sprouts were set equal per unit area, the effect of weight of seed tubers on final tuber yield per unit area was absent. When calculated per stem the numbers of tubers produced and the tuber yields were different for the different seed weight treatments; effects depended on seed status; tuber numbers per stem increased as seed tuber weight decreased when the seed tubers used were younger.

4.3 Cutting of seed tubers

Cutting of seed tubers generally promoted plant emergence and increased stem numbers per plant in comparison with the whole seed tuber, per unit seed weight planted; cutting also spread a wilting disease probably mainly caused by *Pseudomonas solanacearum*, especially at lower altitude.

5. Seed density

The different trials on seed or plant density effects in combination with planting time, seed tuber weight and intercropping showed that the denser spacing up to 10 seed tubers/m^2 consistently increased tuber yields. Plant stand was reduced by higher seed density in most experiments, though not at the expense of yield.

6. Intercropping

Higher total yields of the combined potato and maize crops were obtained when one row of maize was alternated with two rows of potato than when two rows of potato were alternated with two rows of maize. Results suggest that planting dates of the two species can be more closely synchronised in the current intercropping system at all altitudes, to achieve a more efficient use of space and time.

7. Diseases and pests

Viruses and late blight occurred regularly, but bacterial wilt occurred irregularly. These three diseases caused severe yield loss. Their occurrence depended on season, planting time, altitude, seed age, seed density and seed history, variety and agronomic practice (e.g. cutting of seed tubers). Varietal resistances to the diseases, especially to late blight and bacterial wilt, were found. Parasitic nematodes were found in variable population densities and their effects on yield were not clear. Defoliation by 28-spot beetle was sometimes severe.

8. Final conclusions

Several practical aspects in relation to crop production have been unravelled and some effects of the most important agronomic measures have been clarified. The study has thus provided some basic information necessary to improve crop management in these complex agro-ecological conditions.

Samenvatting

1. Inleiding

Jaarlijks worden in China 3,0 - 3,2 miljoen hectares aardappel verbouwd. Veertig procent daarvan wordt geteeld in het subtropische, zuidwestelijke berggebied. De aardappels worden in dat gebied verbouwd op verschillende hoogtes, in verschillende seizoenen en al dan niet in mengteelt met maïs. De aardappelteelt wordt gekenmerkt door lage inputs en lage gemiddelde opbrengsten. Er is niet veel bekend omtrent de gewasfysiologie, de productie-ecologie en de agronomie van de aardappel in dit gebied, zeker niet in vergelijking met de kennis over de aardappelteelt in de gematigde of de tropische gebieden.

De oorzaken van de gemiddeld lage opbrengsten en het relatieve belang van de verschillende opbrengstlimiterende en opbrengstkortende factoren zijn nog goeddeels onbekend. Voor aanvang van deze studie was evenwel reeds duidelijk dat de pootgoedkwaliteit (zowel de fysiologische kwaliteit als de gezondheid van het pootgoed) van groot belang was.

De doelstellingen van het in dit proefschrift beschreven onderzoek waren:

1. Het geven van een (zoveel mogelijk kwantitatieve) beschrijving en analyse van de groeikarakteristieken van het aardappelgewas op verschillende hoogtes, zowel bij voorjaarsteelt als bij najaarsteelt in Sichuan (China).
2. Het onderzoeken van de effecten van pootgoedkwaliteit en van de teeltmaatregelen die met pootgoedgebruik te maken hebben voor verschillende rassen en onder de uiteenlopende agro-ecologische condities in dit teeltgebied.

De resultaten kunnen bijdragen aan een verdere verbetering van de aardappelteelt in Sichuan.

2. Opbrengstmogelijkheden

Opbrengsten waren hoger op grotere hoogtes dan op lagere hoogtes. In de voorjaarsteelt werden hogere opbrengsten gerealiseerd dan in de najaarsteelt, maar de lichtbenuttingsefficiënties waren lager, vooral op grotere hoogtes. In het voorjaar was het verschil tussen werkelijke opbrengsten en potentiële opbrengsten vooral te wijten aan de lange periodes met onvoldoende lichtonderschepping en de lage lichtbenuttingsefficiëntie. Deze fysiologische beperkingen werden vooral veroorzaakt door droogte- en hittestress op lagere hoogtes, en door nutriëntengebrek en biotische stress. De relatief lage opbrengsten in de herfstteelt waren deels ook te wijten aan het (te) korte groeiseizoen.

3. Planttijdstip

In de praktijk geldt dat het planttijdstip zo vroeg mogelijk gekozen moet worden om het mogelijk te maken op hetzelfde perceel nog een ander (of een tweede aardappel-) gewas te verbouwen. Vroeger planten bleek in het voorjaar op 500 m boven de zeespiegel (bzs) te leiden tot een hogere opbrengst. Op 1200 meter bzs werd geen opbrengsteffect gevonden. In de herfstteelt waren op alle hoogtes de effecten meestal afwezig, hoewel vroeg planten wel leidde tot een (soms veel) minder goede opkomst. Het beste poottijdstip in de herfst leek onmiddellijk na de regenval in de nazomer te zijn. Optimale pootdata hingen echter af van het gebruikte ras en van de fysiologische toestand van het gebruikte pootgoed.

4. Pootgoedkwaliteit

Het pootgoed dat normaal gesproken in Sichuan wordt gebruikt is gedegenereerd, zij het in variabele mate. In het onderzoek kon bij gebrek aan voldoende schoon pootgoed niet worden nagegaan hoe het gebruik van besmet pootgoed de opbrengst en de effecten van allerlei teeltmaatregelen op de opbrengst beïnvloedt. Ongeacht deze artefact is het effect van leeftijd en andere eigenschappen van pootgoed relevant.

4.1. Fysiologische leeftijd, herkomst en pootgoedstromen

Fysiologische leeftijd is belangrijk in gebieden met meer dan één teelt per jaar. Het thema fysiologische leeftijd bleek in veel deelstudies in dit proefschrift relevant te zijn. In het algemeen bleek relatief jong pootgoed hogere opbrengsten te geven dan oud pootgoed bij teelt op grotere hoogte (1200 m bzs), dus in gebieden met een relatief lang groeiseizoen. Dit effect werd echter niet waargenomen bij het ras No. 22-2, dat een zeer lange kiemrust heeft. In de voorjaarsteelt moet het pootgoed op geringere hoogte jonger en op grotere hoogte juist ouder zijn dan gebruikelijk. Door de juiste herkomsten en de juiste condities voor de nateelten van herkomsten te selecteren (daarbij lettend op hoogte van de teelt, het seizoen waarin het gewas wordt geteeld en de oogstdatum van het pootgoed) kan pootgoed van een goede fysiologische kwaliteit worden verkregen. Sommige van de lange-termijn effecten van de factor herkomst kunnen te maken hebben gehad met verschillen in gezondheid van het pootgoed.

4.2. Pootgoedgewicht

Zwaarder pootgoed geeft hogere opbrengsten dan lichter pootgoed onder alle onderzochte omstandigheden. Bij gelijke aantallen geplante spruiten per oppervlakte-eenheid werden de effecten van pootgoedgewicht niet meer waargenomen. De knoltallen en de knolopbrengsten per stengel waren verschillend voor de verschillende potergewichten, maar de effecten hingen af van de fysiologische leeftijd. Knoltallen per stengel namen toe bij een toename van het potergewicht indien de poters jonger waren.

4.3. Het snijden van pootgoed

In het algemeen had het snijden van het pootgoed een positief effect op de opkomst en op het aantal stengels per poter ten opzichte van ongesneden poters, tenminste als de vergelijking werd gemaakt bij gelijk pootgoedgewicht. Het snijden leidde echter tot verspreiding van een verwelkingsziekte die waarschijnlijk door *Pseudomonas solanacearum* werd veroorzaakt. Dit effect was vooral op geringere hoogte aanwezig.

5. Plantdichtheid

In de proeven waarin plantdichtheid al dan niet in interactie met andere factoren werd onderzocht, bleek dichter planten tot een waarde van 10 poters per m^2 te leiden tot hogere opbrengsten. De plantdichtheid was bij hogere poterdichtheden meestal lager, zij het dat dit effect niet ten koste van opbrengst ging.

6. Mengteelt

Een plantverband met twee rijen aardappel afgewisseld door één rij maïs gaf in mengteeltsituaties hogere totaalopbrengsten dan een plantverband met twee rijen aardappel afgewisseld met twee rijen maïs. De verkregen resultaten suggereren dat de plant- en zaaidata van de beide gewassen dichter bij elkaar kunnen liggen dan in de praktijk thans gangbaar is. Sneller na elkaar planten kan een betere benutting van ruimte en tijd geven.

7. Ziekten en plagen

Virussen en *Phytophthora* kwamen regelmatig voor, maar het vóórkomen van ziekte als gevolg van de *Pseudomonas*-bacterie was onregelmatig. Deze drie ziekten gaven alle ernstige opbrengstverliezen. Het vóórkomen ervan hing af van het teeltseizoen, het poottijdstip, de hoogte, de fysiologische leeftijd van de poters, de poterdichtheid en de poterherkomst, maar ook van het gebruikte ras en de teelttechniek (bijvoorbeeld het al dan niet snijden van het pootgoed). Rassen verschilden in resistentie tegen deze ziekten, vooral tegen *Phytophthora* en *Pseudomonas*. Er werden ook parasitaire nematoden aangetroffen. De dichtheden daarvan varieerden en de effecten op de opbrengst bleven onduidelijk. In een aantal gevallen werd ernstige ontbladering door de kever *Epilachna niponica* Lewis waargenomen.

8. Slotconclusie

Het in dit proefschrift beschreven onderzoek heeft inzicht gegeven in een aantal praktische aspecten van de aardappelteelt en heeft de effecten van enkele belangrijke teeltmaatregelen inzichtelijk gemaakt. Daarmee heeft het onderzoek bijgedragen aan kennis die nodig is om de teelttechniek onder deze complexe agro-ecologische condities te optimaliseren.

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Curriculum vitae

He Wei was born in Yaan, Sichuan, China, on January 20, 1960. He finished secondary and high school education at the Chengdu No. 8 Middle School in 1977, and graduated from the Sichuan Agricultural University in 1983, with a Bachelor degree in Agronomy. Since then, he has been working at the Crops Institute of the Sichuan Academy of Agricultural Sciences on a national sweet potato breeding programme for the first three years, followed by a project on rapid multiplication of virus-free potato seed. In 1987, he was granted a scholarship from the International Potato Center (CIP) and studied at the University of the Philippines in Los Baños (UPLB), and obtained the degree of Master of Science in Horticulture in 1989, with a major in crop physiology and a minor in plant breeding. His MSc thesis was entitled "Potato (*Solanum spp.*) apical and sprout cutting production and their agronomic potential as transplants", and was written under the guidance of Dr. Peter Vander Zaag. Since 1990, he has been involved in the CIP-China project on potato germplasm evaluation for Southwest China and later in the CIP-China project on TPS (true potato seed) in the same region. Since 1993 he has been working on the research described in this thesis within the framework of a sandwich programme of the Wageningen Agricultural University.