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Agro-ecological zoning of potato

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Summary

In this study, agro-ecosystems suitable for potato are defined on a global scale using recently released detailed data sets on soil (5 x 5 arc minutes pixel grid) and climate (30 x 30 arc minutes pixel grid). The spatial distribution of the length of the growing season, potential tuber yield and water-limited yields of potato are established. Moreover, a detailed climatic characterisation for the regions South Asia and Indonesia is presented as well as a study of the ideal genotype (ideotyping) of potato for these selected regions. Finally, the crucial quality indicators are added of tuber dry matter concentration and tuber number as a function of climatic data of these selected regions. The potential of potato as a crop with a very efficient water use, and the impact of breeding for heat tolerant potato are discussed briefly.

Keywords: potato, *Solanum tuberosum*, agro-ecosystems, GIS, zoning, ideotype, tuber yields, quality, dry matter concentration, tuber number, water use

1. Introduction

The potato chain management study carried out within the framework of the North-South program embodies two parts: the potato production and processing chain and the production and zoning part This study is an integral part of a research project on improved agricultural chain management with special emphasis on the production aspects.

The presented work is an integral follow-up of the potato production and zoning study performed in 1991 by Stol *et al.*[1].

The potato production chain is a sequence of activities in which information is transferred between linked elements. The first step in the sequence is obviously the agro-ecological characterisation for potato production. Locations where potatoes can be grown are determined by matching the climatic characterisation of the zone and the requirements of the potato crop. Potential and water-limited production levels were calculated for all identified areas.

This information is needed to determine what kind of variety (genotype) is best suited (ideal) for the growing conditions: ideotyping. Lateness is the most important feature then because ideotyping means matching the length of the available growing season to the length of the growth cycle of the cultivar.

Next phase in the chain is the production of seed and ware or processing potatoes. Here many cultural practices may be quantified and used to steer the next phase, processing that takes place after storage and transport. Examples are irrigation and nitrogen fertilisation that determine yield, size and dry matter concentration. Other information may be handed on as well such as the regime of chemicals used (*e.g.* special labels or grown organically).

Building on the global study additional work focused on ideotyping and on a more precise zonation of potato for two regions: South Asia and Indonesia. South Asia includes the following countries: Bhutan, Bangladesh, India, Nepal and Pakistan. The spatial and temporal effects of high temperature tolerance and increased temperature requirement are discussed.

Shifts of the growing season as result of temperature tolerance and changed temperature requirement is of particular interest for the potato processing industry. Processes downstream the production chain, storage, transport, processing in factories, are linked to the very first activities of growing and harvesting potatoes. This study analyses the effect of small shifts in temperature tolerance and temperature requirement of cultivar on the suited zone for potato growth (sensitivity analysis).

The objectives of this study, initiated by the North South programme, are:

- To define agro-ecosystems for potato on a global scale using recent datasets on soil (FAO, 1996) and climate (Leemans & Cramer, 1991; Müller, 1996).
- Establish the spatial distribution of the length of the growing season, potential production and water-limited production.
- Provide a more precise climatic characterisation for two regions: South Asia and Indonesia.
- Provide an ideotyping of potato for these selected regions.
- Add quality indicators (tuber dry matter content and tuber number) to these selected regions.

Global climatic data sets used are compared to a selection of local stations, and the consequences for the selection of temperature thresholds is briefly discussed. A world digital elevation map is used to compare with the calculated spatial patterns.

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[1] Part of this integral follow-up is also reported in AB note 151 (Verhagen *et al.*, 1998)

2. Approach

The presented work is a follow-up of the potato production and zoning study performed in 1991 by Stol *et al.* The simulation model as used by Stol *et al.* (1991) was linked to a GIS environment. Updated global data sets and regional data sets were used which allowed a more detailed analysis. In fact, two separate, but closely related studies were carried out:

1. An updated definition of agro-ecosystems for potato on a global scale using recent data sets on soil and climate. Henceforward we refer to this study as the ***'Global study'***.
2. A more detailed additional study for two regions: South Asia and Indonesia. In this study, a more precised climatic characterisation was presented using regional data sets, and details on potato quality were included. Henceforward we refer to this study as the ***'Regional study'***.

2.1 Database

2.1.1 Climatic data

Global weather data set

Both for the *global study* and the *regional study*, we used long-term weather data from two sources. Leemans & Cramer (1991) published a 30 x 30 arc minutes pixel grid on a global scale with long-term average monthly data of cloudiness, temperature and precipitation. The degree of cloudiness was used to calculate solar radiation. As the model uses daily data as input, we needed to interpolate the monthly averages. For radiation and temperature this was a straight-forward procedure. For the distribution of precipitation an intermediate step was needed in the statistical distribution of the monthly total rainfall over the total number of days that it rained. These rainy days, however, are not mentioned in the databases of Leemans & Cramer (1991). Therefore they were derived from the number of rainy days of 1272 meteorological stations compiled by Müller (1996) and subsequently translated to the 30 x 30' grid.

Global soil data set

The water availability used in the *global study* is based on the FAO soil map published on CD-ROM (FAO, 1996). This map classifies the soil types of the world based on a pixel grid of 5 x 5 arc minutes. We used three texture classes to determine the water holding capacity of the soil. Even within the small 5 x 5 arc minute pixel several soil types may be present. Therefore water-limited yield was calculated using weather data from the 30 x 30 grid as a weighted average based on the relative proportion of each soil type per 5 x 5 pixel.

Regional data set

For the *regional study*, for the regions South Asia and Indonesia, we used additional information from the METEO database of Plant Research International. This contains two sources: first, the long-term Climatic Data from the FAOCLIM Global Weather Database (FAO, 1990); second: the Handbuch ausgewählter Klimastationen der Erde (Müller, 1987).

2.1.2 Elevation data

For the *regional study*, we used also the digital elevation model (DEM) GTOPO30, resulting from a collaborative effort led by the staff at the U.S. Geological Survey's EROS Data Center in Sioux Falls, South Dakota, see Figures 1 and 2. Elevations in GTOPO30 are regularly spaced at 30 arc seconds (approximately 1 kilometre).

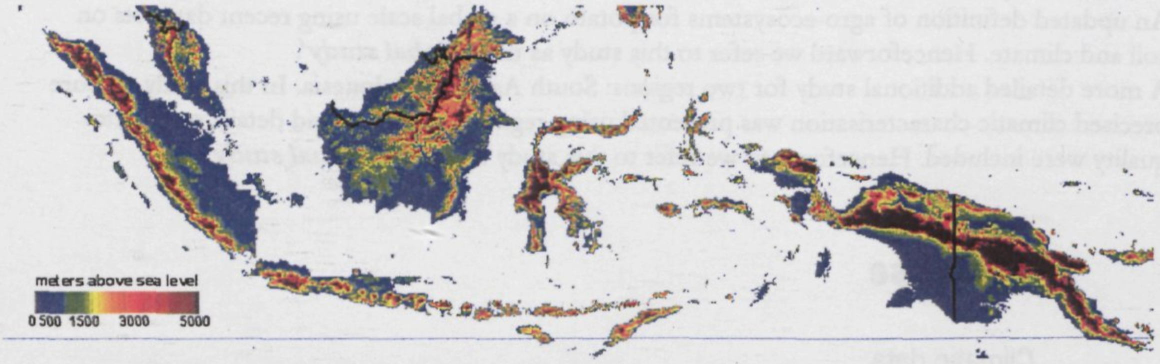

Figure 1. *Elevation data Indonesia (meters above sea level).*

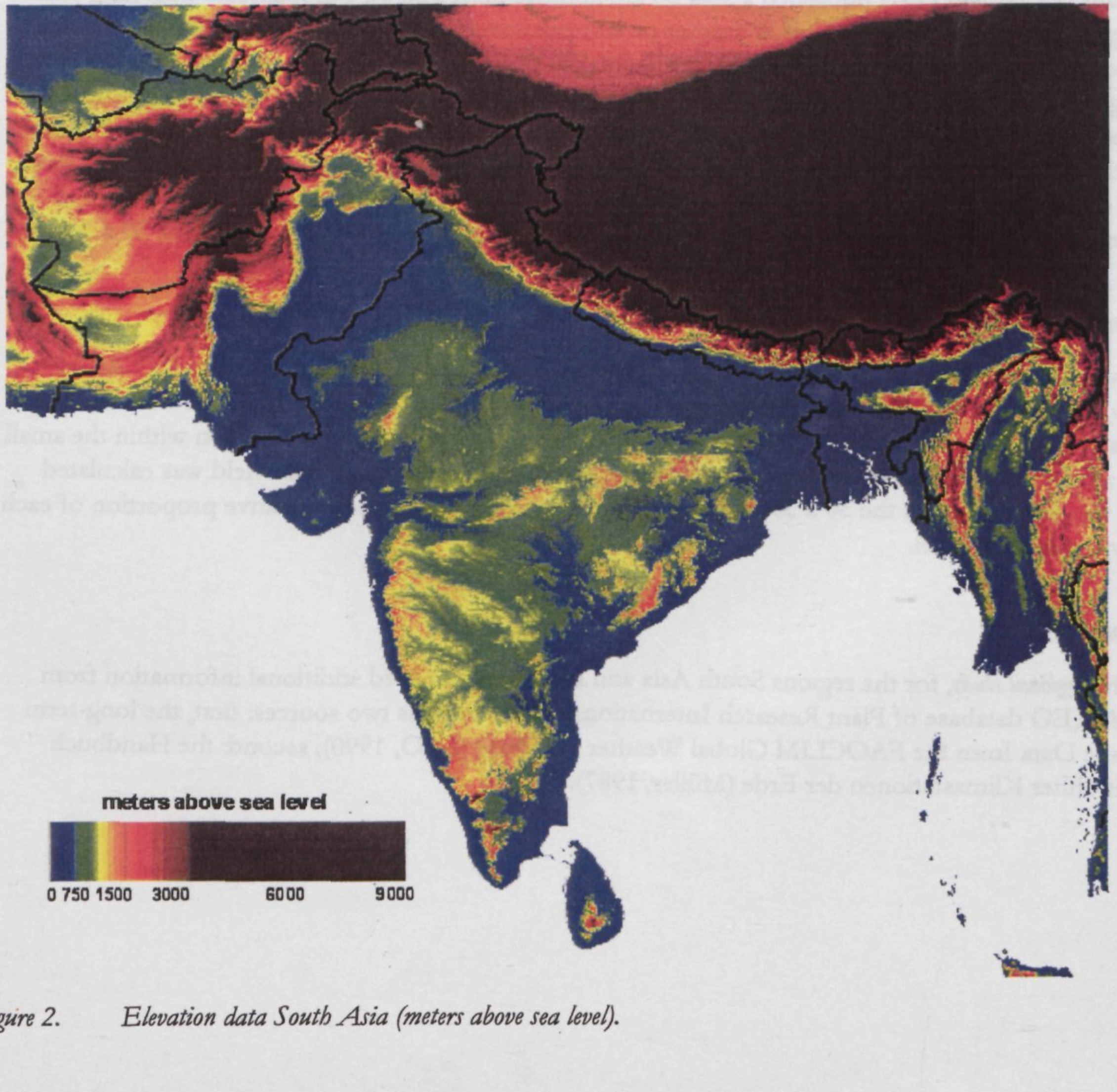

Figure 2. *Elevation data South Asia (meters above sea level).*

2.2 Methodology

To allow comparison between the present study and the study of Stol *et al.* (1991), we tried to use the same simple crop growth model as in 1991 as integrally as possible; for a detailed description of the model we refer to Stol *et al.* (1991). Some adaptations, however, were needed; these are presented below.

2.2.1 Temperature tolerance levels for potato

Stol *et al.* (1991) defined the temperature window suited for potato growth as the period in which the daily minimum temperature is higher than 5°C and the daily maximum temperature is lower than 28°C. In the present study, these thresholds could not be used, as the new global dataset only contains daily mean temperature values and not the necessary daily minimum and maximum temperature values.

For this reason, in the agroecological zone study potato production was defined between a lower threshold of an average temperature of 5 °C and an upper threshold of an average temperature of 21°C. This selection was made via an iterative process using expert judgement of potato producing regions in the world. Next, in the ideotyping approach as part of the *regional study*, the same temperature window was used as a reference.

In the *regional study* the effect of relaxing the upper temperature threshold on the growing season was explored using three upper temperature limits: 21, 24 and 27°C, the lower temperature threshold remained 5°C. The *regional study* focuses on tropical areas, hence loosening of the lower temperature thresholds was not considered.

A certain amount of heat expressed in accumulated temperature (a temperature sum in day-degrees, d °C) is required to complete a growing season. The required temperature sum may vary strongly among varieties. Based on earlier work (van Keulen & Stol, 1995; Haverkort, 1990) the minimum threshold for the temperature sum, both in the *global study* and in the *regional study*, was set at 1250 and the maximum at 2000, with a base temperature of 2°C.

2.2.2 Temperature-dependent LUE

In the previous study (Stol *et al.*, 1991), Light Use Efficiency (LUE) was not dependent on temperature. Now we accounted for this based on present ecophysiological knowledge[2] (Kooman & Haverkort, 1995). The base value of LUE is multiplied by a reduction factor TF, the value of which depends on the daily mean temperature as shown in Figure 3.

2.2.3 Start of simulations under water-limited conditions

In the previous study (Stol *et al.*, 1991), soil water balances were calculated from eighty days before planting onward. In the present study we started running on the day of planting with a soil water content of 80% of field capacity. This is based on the assumption that farmers after winter or after a dry period plant as soon as the field is neither too dry nor too wet. Obviously the model will make mistakes for areas where it never rains such as in deserts where 80% of field capacity will not be reached.

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[2] Kooman (1995) also quantified a relationship between solar radiation and LUE but within the time frame available we could not include this in the present study. However, in a follow-up for potato this relationship can be quantified as follows (after Marcel van Oijen):
LUE = LUE7 * EXP(-KST*PAR – 7)
Where LUE7 = LUE ($g\ MJ^{-1}$) at average radiation levels in temperate climates (about 7 $MJ\ m^{-2}\ d^{-1}$)
PARAM LUE7 = 3
KST = extinction coefficient
PARAM KST = 0.056

2.2.4 Texture class and moisture availability

In the present study we only used texture classes to calculate the water holding capacity of the soil. As the FAO soil map only distinguishes three major soil texture classes, we took the data from these three classes from Stol *et al.* 1991 (Table 1).

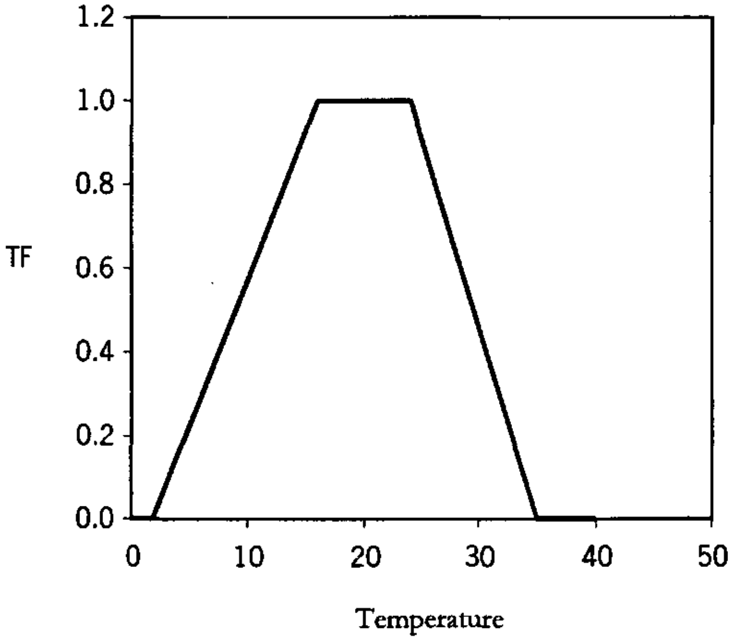

Figure 3. *Reduction factor TF (see text) versus daily mean temperature. This factor accounts for the effect of temperature on LUE (light use efficiency). (Kooman & Haverkort, 1995).*

Table 1. *Volumetric water content at field capacity and wilting point, and water holding capacity (cm m^{-1}).*

Water characteristic	Soil type Coarse	 Medium	 Fine
Field capacity	13	32	54
Permanent wilting point	4	10	44
Water holding capacity	9	22	10

2.3 Additional details for the *regional study*

For the *regional study* two regions are selected. The first region is South Asia, comprising the following countries: Bhutan, Bangladesh, India, Nepal and Pakistan; the second region is the Indonesian archipelago. Two approaches are followed. The first approach uses the global climatic data sets (as presented above) as basis for sensitivity analysis and ideotyping.

In the first approach of the *regional study*, the effect of upper temperature threshold on the growing season is explored. As already specified before, three upper temperature limits are used: 21, 24 and 27°C, the lower temperature threshold remains 5°C. The temperature requirement expressed in day-degrees (d °C) determines the growth cycle of the cultivar. The upper threshold value is increased with steps of 200 d °C to a maximum of 2400 d °C to explore the effect on the growth cycle and potential spatial distribution of the cultivar.

Based on the selection of temperature thresholds and temperature sums the following types are studied (Table 2).

Table 2. Selected cultivar types.

Maximum temperature threshold (°C)		Length of maximum growing season (d °C) Reference (2000)	Medium (2200)	Long (2400)
Reference	(21)	x	x	x
Warm tolerant	(24)	x	x	x
Heat tolerant	(27)	x	x	x

For all types the following minimum thresholds are used: an average temperature of 5 °C and a length of growing season of 1250 d °C.

The second approach of the *regional study* uses regional weather station data for a precised zonation of current potato cultivars. For this approach, data from regional weather stations were taken as a reference. In this regional data set, information on daily minimum temperatures and maximum temperatures was available; this allowed quantification of the relation between maximum temperatures and average temperature for each separate region. Next, this quantification was combined with the elevation data set and with data on quality in a calculation procedure.

2.4 Calculation procedure

2.4.1 Global data set

Using the threshold values defined above, the end of the growing season and the temperature sum for each type are calculated using the routines described in Appendix II.

Only when the temperatures requirements are met and the period is long enough to fit the minimum temperature sum (in all cases 1250 d °C) one or more growing season(s), to a maximum of three season(s), is/are defined. For the definition of each growing season the maximum temperature sum is the starting point of the calculation procedure; the minimum temperature sum is the lowest suited alternative. Note that the growing season is calculated for a 365 days cycle, so three harvests in 365 days does not automatically mean that there are three growing seasons within one calendar year.

For each season the end of the growing season and the total temperature sum are presented.

The results are presented on maps, each pixel representing an area of 0.5 x 0.5 arc degrees.

2.4.2 Regional data set

The regional data set is only used in the *regional study*. From the available stations in the regional data set the relation between the yearly average of maximum temperature, average temperature and minimum temperature, versus the altitude was established.

2.4.3 Quality

For the *regional study*, two simple relations between environment and potato quality were derived from Haverkort & Harris (1987). First: the dry matter content of tubers diminishes by 0.446% per °C temperature increase; second: the number of tubers per plant increases by 1.68 tuber per °C temperature increase. Base values were defined as 20% dry matter and 12 tubers, at 14 °C. These relations were linked to the relation between temperature and elevation derived from the regional data set.

2.4.4 Elevation

Three altitude levels were defined: low (< 650 m), medium (650-3000 m) and high (> 3000 m).

3. Results and discussion

3.1 *Global study:* Agroecological zoning

The calculations are shown here for the main potato season only. Where a second season is feasible, such as in the tropical highlands associated with the rainy seasons and in Mediterranean climates where a spring and an autumn crop can be grown, the results of the main season are depicted in the maps. Yields are represented as dry matter tons per hectare. Appendix I shows some statistics per region such as mean values, variance and skewness of distribution.

The following maps have been constructed:

South America:	potential yields and water-limited yields	(Fig. 4)
North America:	potential yields and water-limited yields	(Fig. 5)
North America:	Distribution of potato production in 1899, 1949 and 1990	(Fig. 6)
Meso America:	water-limited yields	(Fig. 7)
Europe:	potential yields and water-limited yields	(Fig. 8)
Africa:	potential yields and water-limited yields	(Fig. 9)
Asia:	potential yields and water-limited yields	(Fig. 10)
Indonesia:	water-limited yields	(Fig. 11)

3.1.1 Comments per region

South America

The Andean ecoregion, gene centre and origin of the potato, clearly has the highest potential yields of South America. In that area the highest yields are found well off the equator where the days are relatively long and cloudless assuring high levels of solar radiation. This area also coincides with very low yields when not irrigated because of the desert conditions prevailing here. The highest water-limited yields are encountered in the equatorial area of the Andies and the Mediterranean climate part of Argentina where winters are cool and rainy. In the potential production map the highest part of the Andean mountain range appears to be too cold to grow potatoes (Fig. 4).

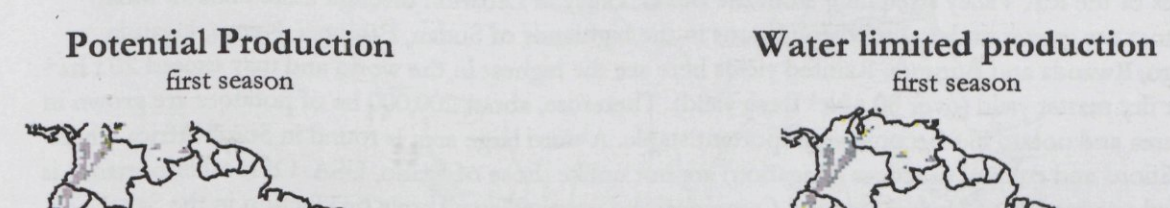

Figure 4. *Calculated potential (left) and water-limited (right) potato yield for South America.*

North America

The difference between potential production and water-limited production (Fig. 5) is striking. The water-limited production map shows relatively high yields in the Lake Area and in the East near the Canadian-US border. These areas traditionally had the highest production levels as is shown in the chart, (Fig. 6), where Long Island and Prince Edward Island had high densities a hundred years ago. When irrigation is available the highest yields are found in frost-free areas with high incidence of solar radiation in the western part of the continent. Idaho and Washington State, where most of the potatoes of the united States are grown under centre pivot irrigation, therefore show up in the chart with potatoes in the nineteen nineties. In California, where also high potential yields can be reached, potato production is low because of water scarcity and where water is available, farmers tend to grow higher value crops.

Meso America

Relatively high yielding areas are found in the Tolluca Valley (Fig. 7). Strangely, Cuba does not show any potato production area although it is known that (beside mainly irrigated production) some potato cultivation takes place under rainfed conditions.

Europe

Most potatoes in Europe are grown without irrigation. The water-limited production map shows predominantly yields between 10 and 15 t ha^{-1} dry matter equalling about 40 to 60 t ha^{-1}. Yields are lower at the northern fringes due to short season length as it is too cold and at the southern fringes as it is too dry (*c.f.* Fig. 8). This continent has some of the highest potato densities of the world with millions of hectares planted annually in countries as Poland, Russia and the Ukraine. Potato production in Turkey is also important with over 50% of the crop under irrigation.

Africa

The major potato growing areas in Africa are located near the Mediterranean Sea in Morocco, Algeria, Tunisia en Egypt where all crops are irrigated and only during part of the growing season receive some precipitation (Fig. 9). This is the case for the early part of the spring season and the late part of the autumn season crop. Another important potato growing area is that associated with the mountain ranges of the Rift Valley stretching from the Bekaa Valley in Lebanon through Lake Malawi. Most potatoes are grown under rainfed conditions in the highlands of Sudan, Ethiopia, Kenya, Uganda, Congo, Rwanda and Burundi. Rainfed yields here are the highest in the world and may exceed 20 t ha^{-1} tuber dry matter yield (over 80 t ha^{-1} fresh yield). Therefore, about 200,000 ha of potatoes are grown in this area and potato has become an important staple. A third large area is found in South Africa where conditions and cultural practices (irrigation) are not unlike those of Idaho, USA. Of local importance is rainfed production in Madagascar and Cameroon and irrigated small scale production in the Sahel region Mali, Senegal and Cabo Verde.

An interesting scenario would be to overlay the potential yield map with a water-availability map (through irrigation; Fig. 9) and thus predict what will happen following the case in the USA.

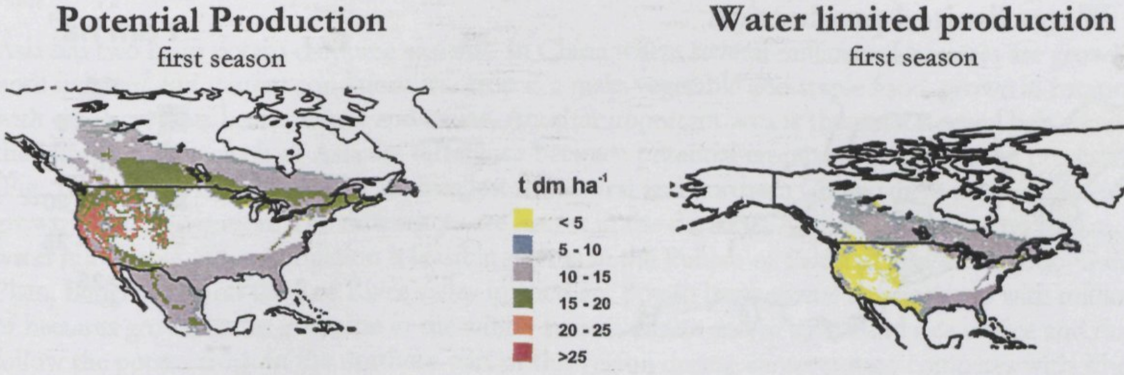

Figure 5. Calculated potential (left) and water-limited (right) potato yield for North America.

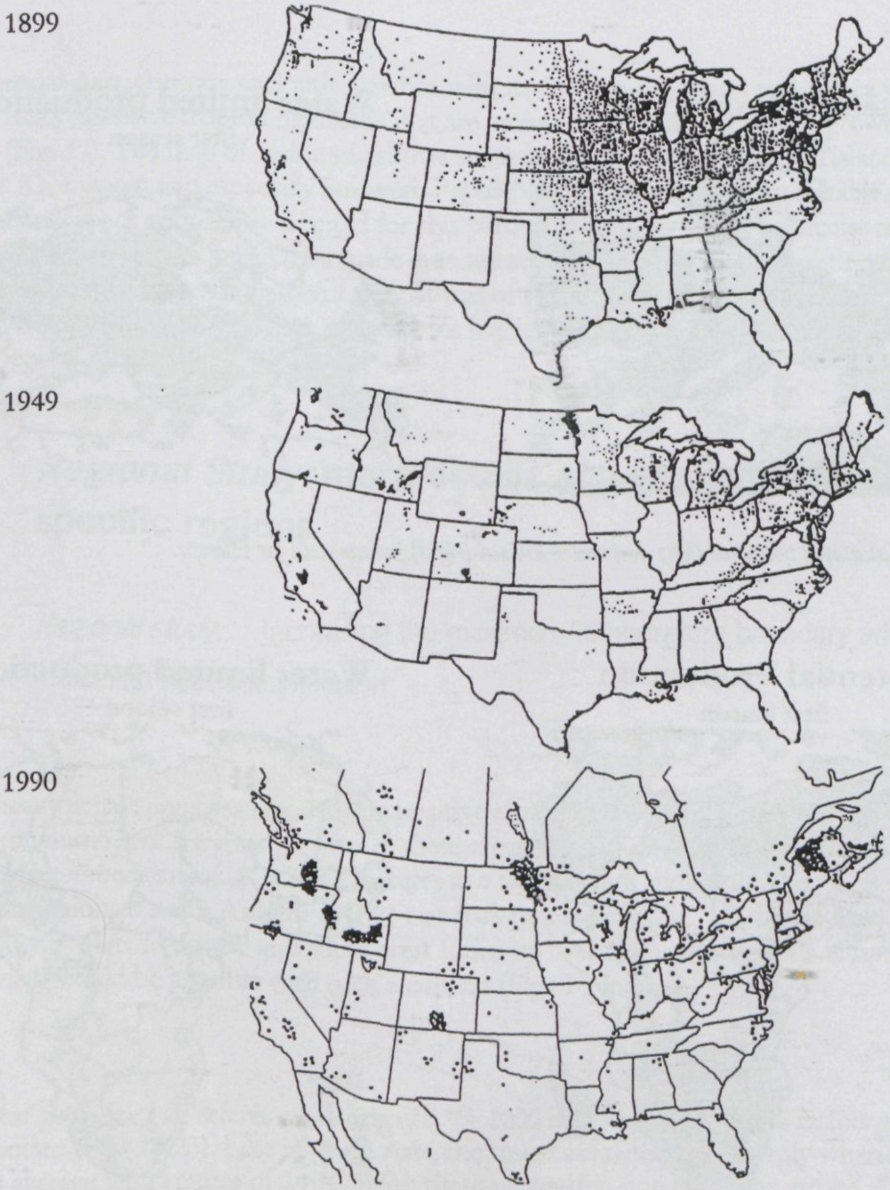

Figure 6. Distribution of potato production in 1899, 1949 and 1990.

Source: Hawkins, A. 1957. Highlights of a half-century in potato production. American Potato Journal, 343(1):25-29
Rowe, R.C. (ed). 1993. Potato Health Management. APS Press. Minnesota, USA

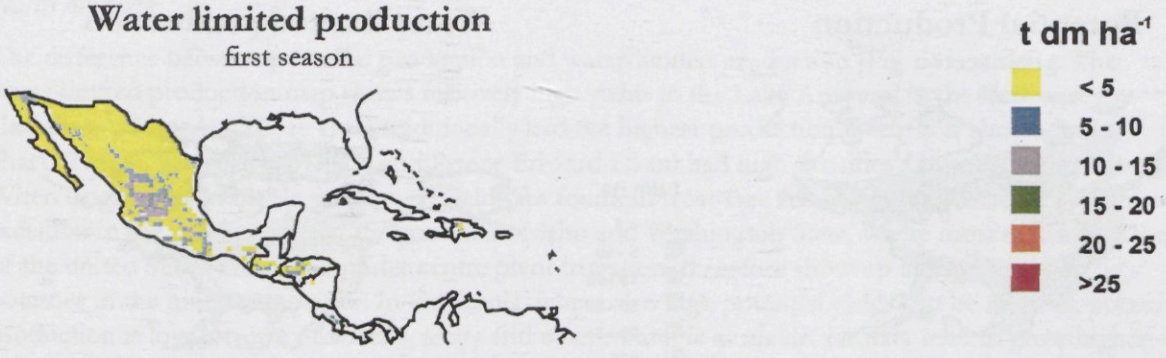

Figure 7. Calculated water-limited potato yield for Meso America (for calculated potential yield see Fig. 5 (left)).

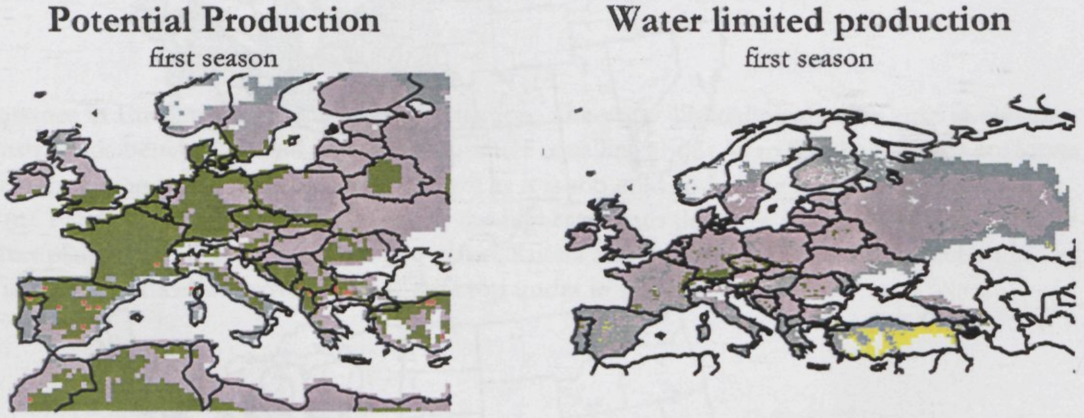

Figure 8. Calculated potential (left) and water-limited (right) potato yield for Europe.

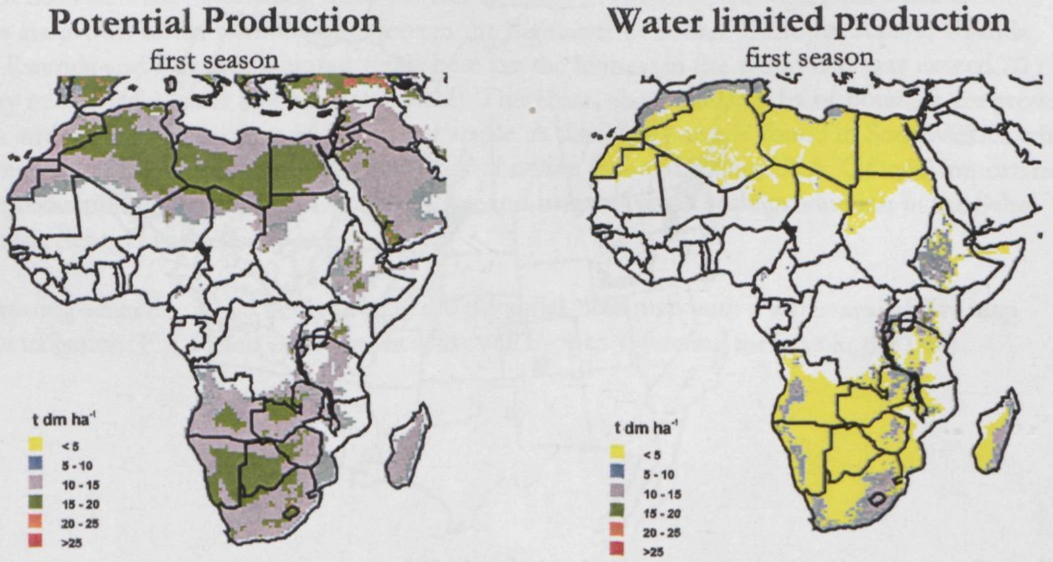

Figure 9. Calculated potential (left) and water-limited (right) potato yield for Africa.

Asia

Asia has two main potato cropping systems. In China where several millions of hectares are grown in both irrigated and rainfed conditions the crop is a main vegetable and staple food, grown in rotation with other crops as beans, wheat and maize. Another important area is the potato-cereal belt south of the Himalaya. For much of Asia the difference between potential crops and irrigated crop production (Fig. 10) is large. The differences are smallest for central and northern China where most potatoes are grown without irrigation. The differences are largest in the desert of Afghanistan where no irrigation water is available. Where irrigation is feasible such as in the Punjab of Pakistan and India, Indo-Gangetic Plain, Bangladesh and the Red River valley in Vietnam potato has become a major crop with millions of hectares grown under irrigation in the winter season. Maize and rice, jute and rice or rice and rice follow the potato crop. In the northern part of this region during winter potato competes with wheat for water. Where until recently only one monsoon potato crop was grown, now irrigation makes it possible to grow three crops a year. Actual hazards are salinisation in the Punjab and mining of micro- and meso-minerals in many parts of the rest of the region.

Indonesia

Tropical equatorial Asia, contrary to South America with its Andean ecoregion and Africa with its Rift Valley region lacks extensive tropical highlands that are eminently suitable for potato growth and development (Fig. 11). The map of Indonesia shows some incidental highlands at the island of Sumatra, Java, Kalimantan and especially Sulawesi. Papua New Guinea also shows suitable environments but that area is not sufficiently adapted for this particular industry at this particular moment. The huge demand for potatoes in this area made it an attractive case study to work with more detailed digital maps than the ones used in the *global study*. It was of special interest to make scenarios of what would happen if potato was adapted to 3 or 6 degrees higher temperatures. This was done as part of the following *regional study*.

3.2 *Regional Study:* more details and quality aspects for specific regions

3.2.1 *Regional study:* Increasing the maximum temperature boundary and maximum heat accumulation

South Asia

Breeding for heat tolerant potatoes has a strong positive effect on the area suited for potato (Fig. 12) and increases the number of harvests per year in these areas (Figs 13 and 14). A cultivar which can survive at an average temperature of 27 °C and matures at a temperature sum of 2400 d °C, is suited for nearly the whole region of south Asia for at least one harvest per year (Fig. 15). In the Indo Gangetic plain and the higher parts of central and south-west India, up to three harvests with a temperature sum of 2400 d °C each would be possible with such a cultivar (Figs 16 and 17).

Indonesia

With the cultivar properties at 'reference' setting (21 °C, 2000 d °C) hardly any area in Indonesia would be suited for potato (Figs 18-23). Like in south Asia, the suited area increases sharply when the cultivar can survive an average temperature of 24 °C. With these properties, potato can be grown in all higher regions of Indonesia with three harvests (compare Figs 18-23 with Fig. 1) and a cultivar which can survive an average temperature of 27 °C is suited for almost the whole area of Indonesia.

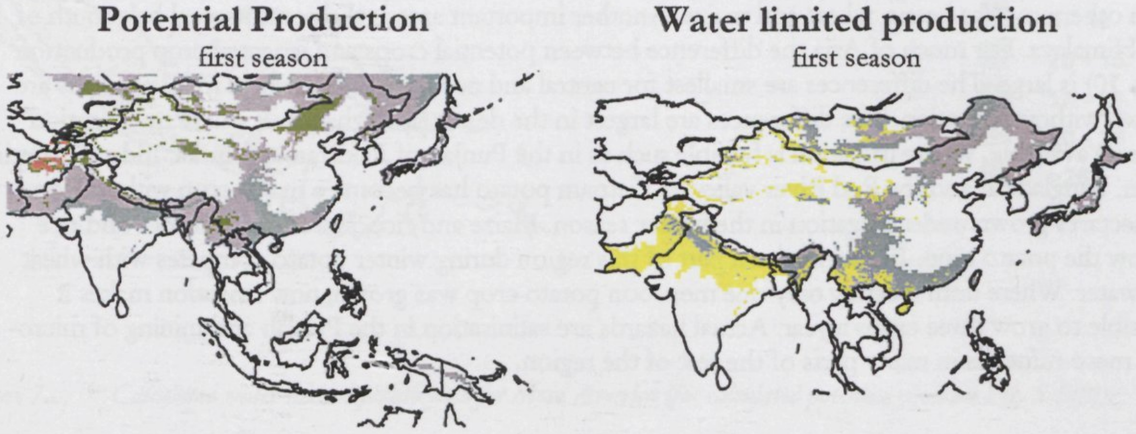

Figure 10. Calculated potential (left) and water-limited (right) potato yield for Asia.

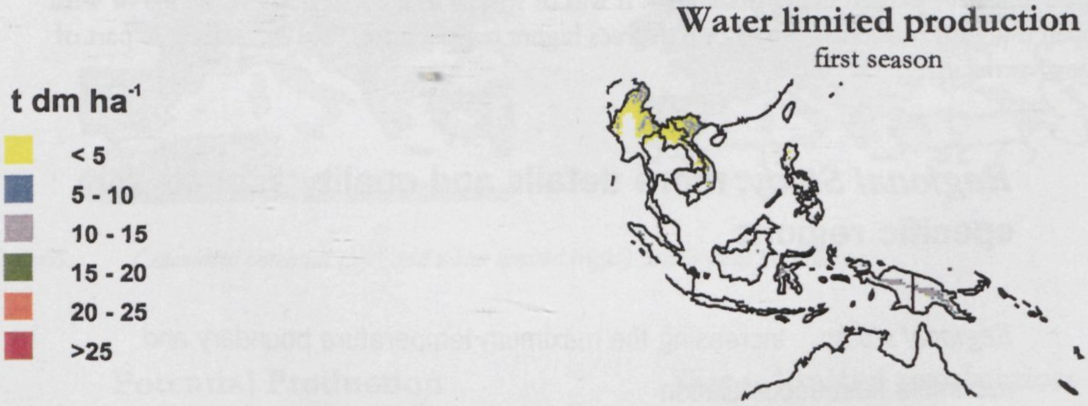

Figure 11. Calculated water-limited potato yield for Indonesia (for calculated potential yield see Fig. 10 (left)).

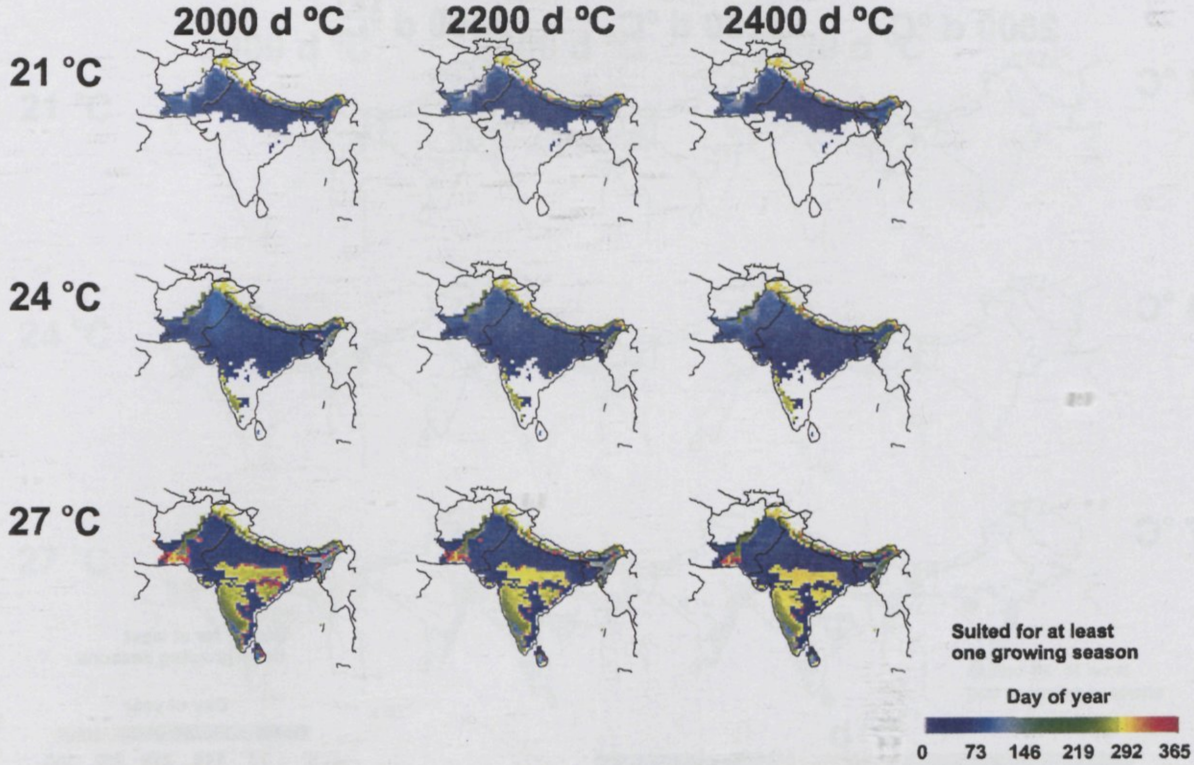

Figure 12. *Area suited for at least one growing season, south Asia. The end of the first growing season is shown.*

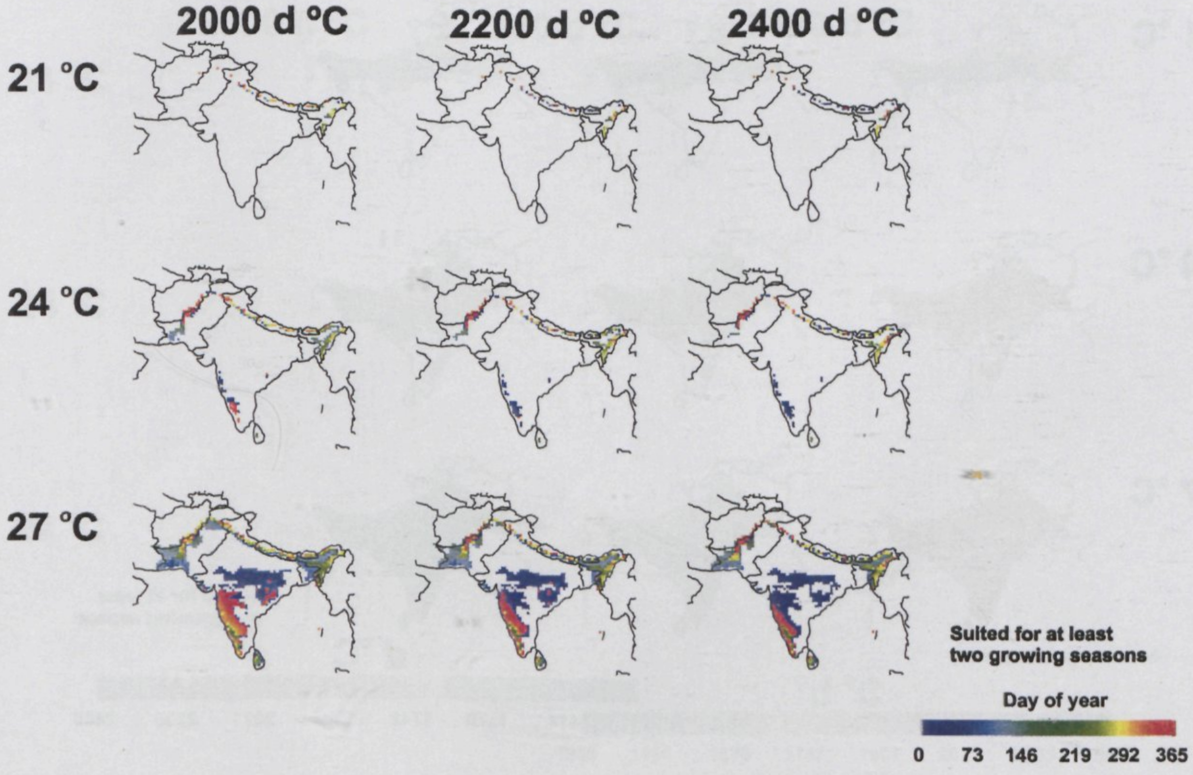

Figure 13. *Area suited for at least two growing seasons, south Asia. The end of the second growing season is shown.*

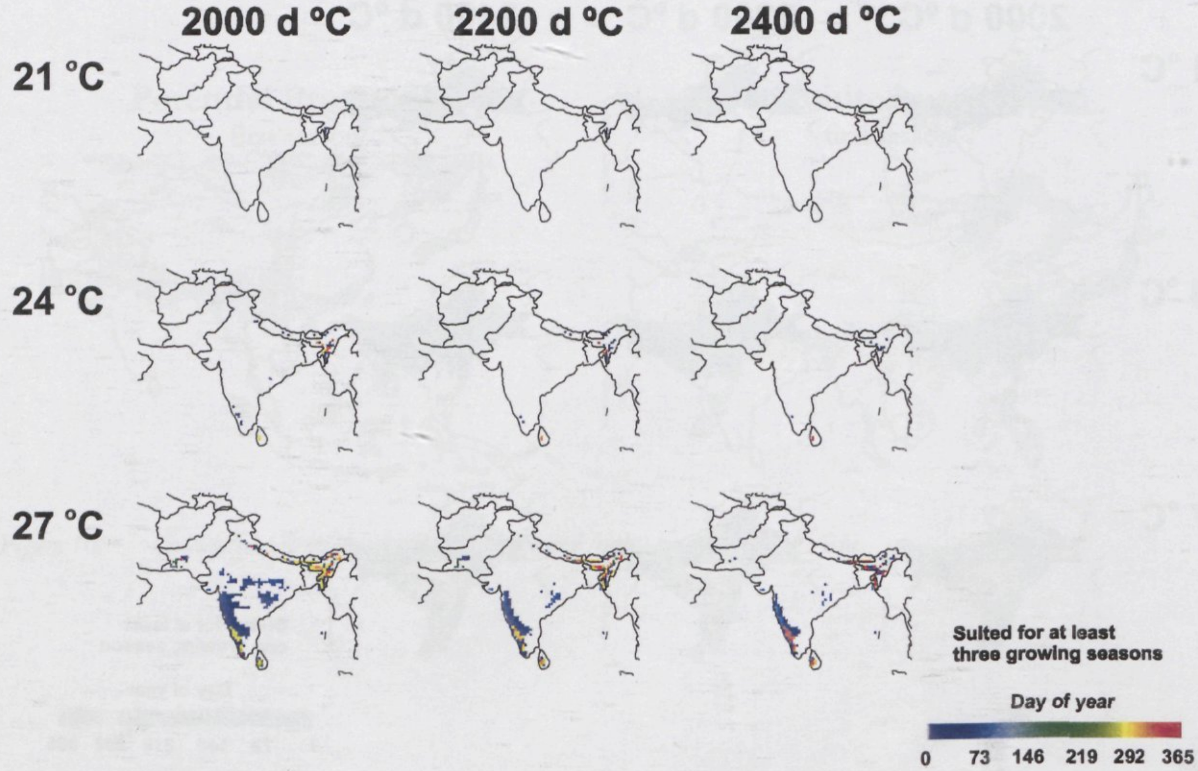

Figure 14. *Area suited for three growing seasons, south Asia. The end of the third growing season is shown.*

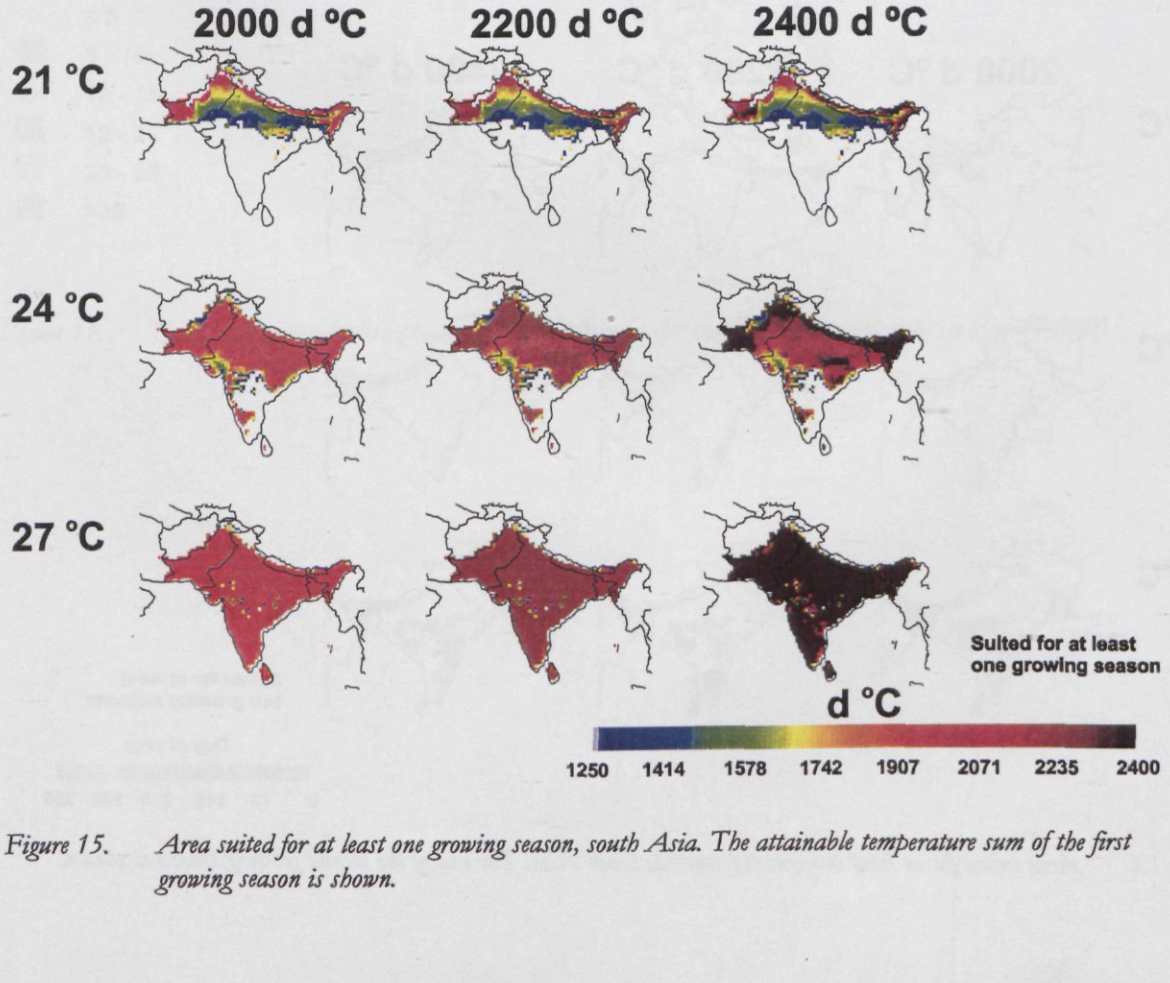

Figure 15. *Area suited for at least one growing season, south Asia. The attainable temperature sum of the first growing season is shown.*

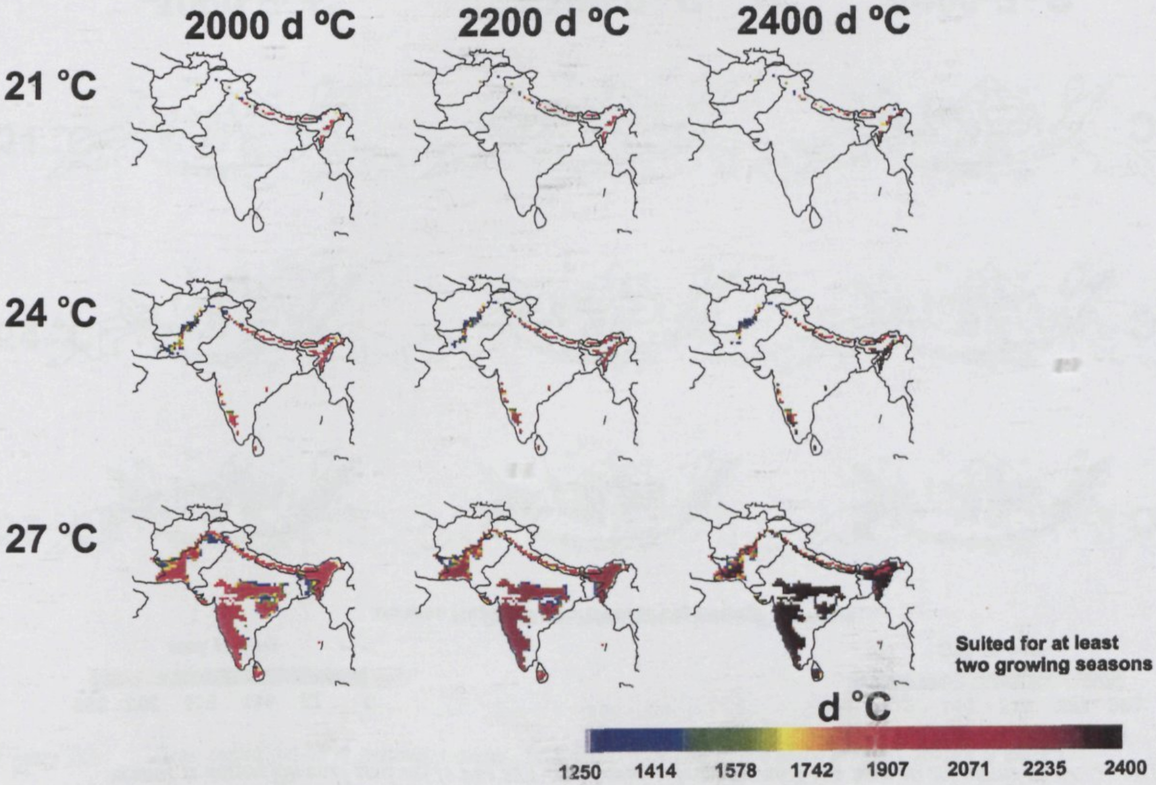

Figure 16. *Area suited for at least two growing seasons, south Asia. The attainable temperature sum of the second growing season is shown.*

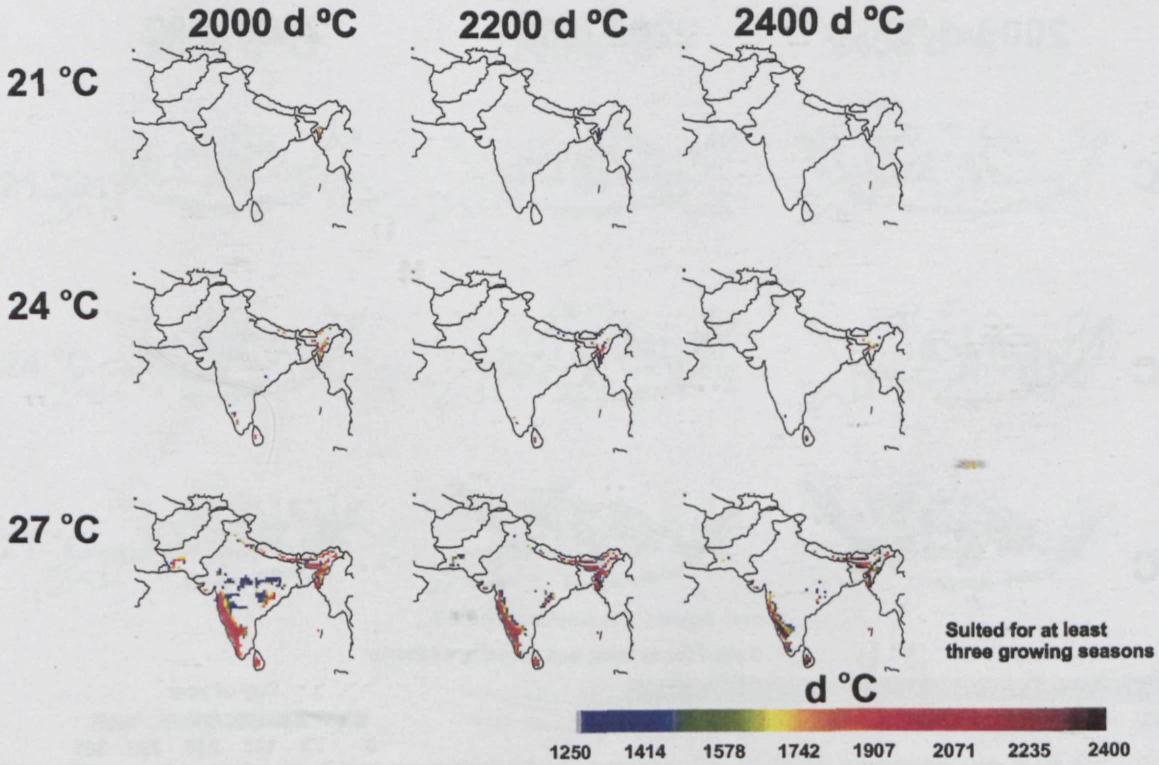

Figure 17. *Area suited for at least three growing seasons, south Asia. The attainable temperature sum of the third growing season is shown.*

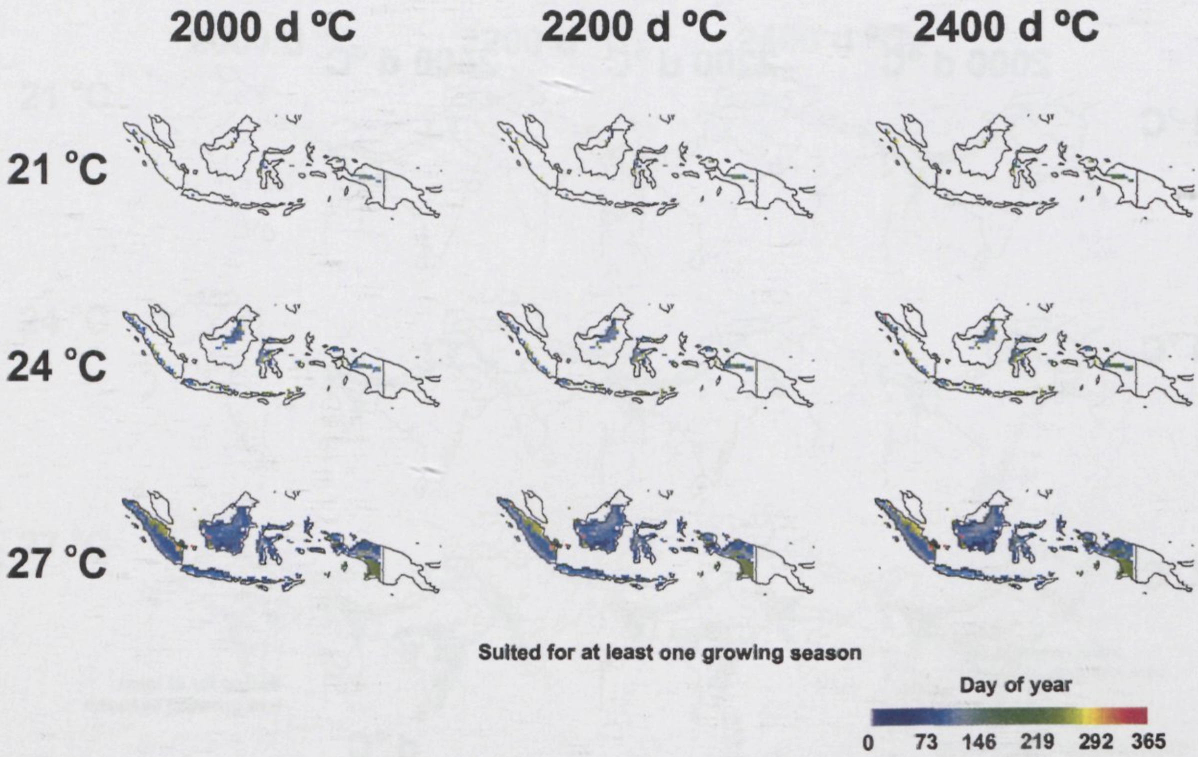

Figure 18. *Area suited for at least one growing season, Indonesia. The end of the first growing season is shown.*

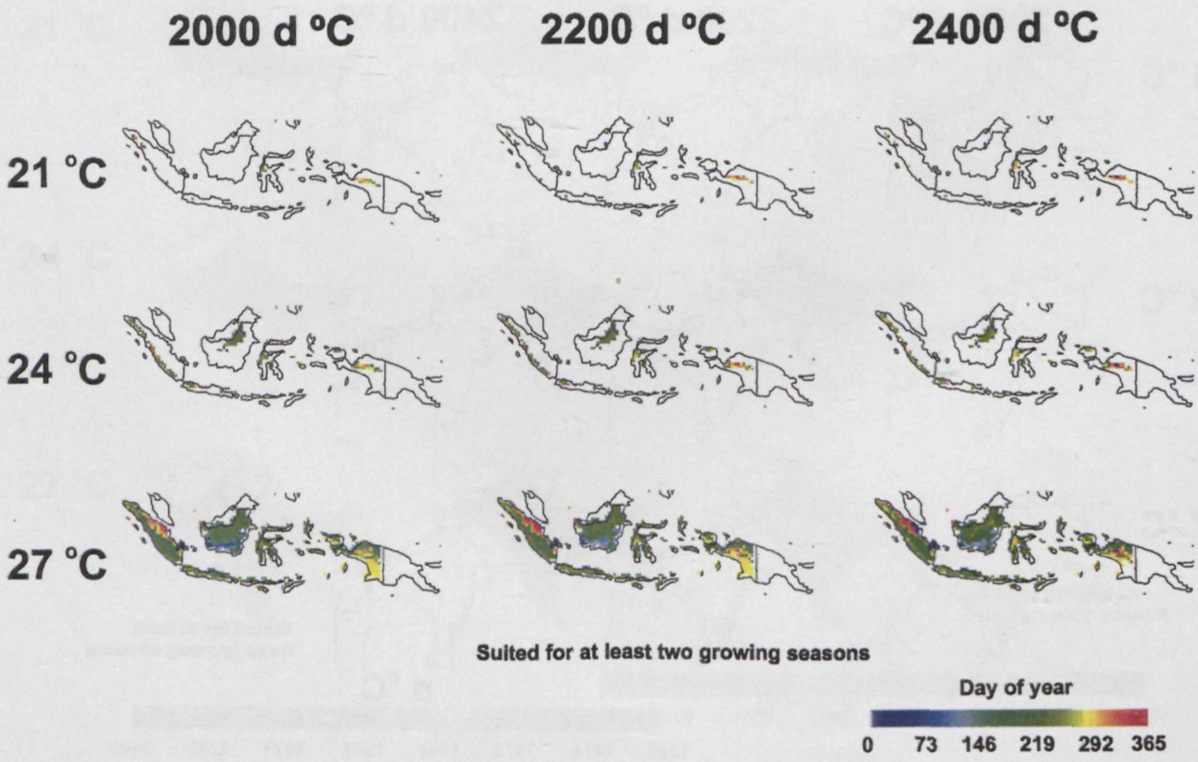

Figure 19. *Area suited for at least two growing seasons, Indonesia. The end of the second growing season is shown.*

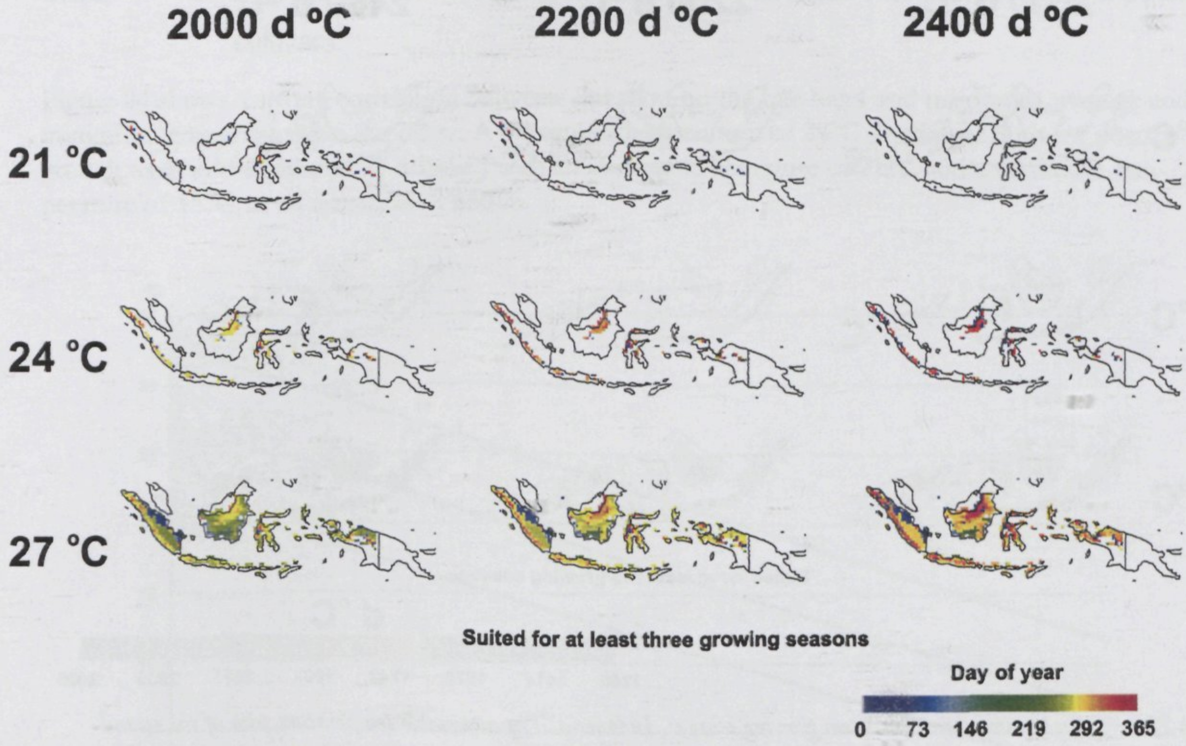

Figure 20. Area suited for three growing seasons, Indonesia. The end of the third growing season is shown.

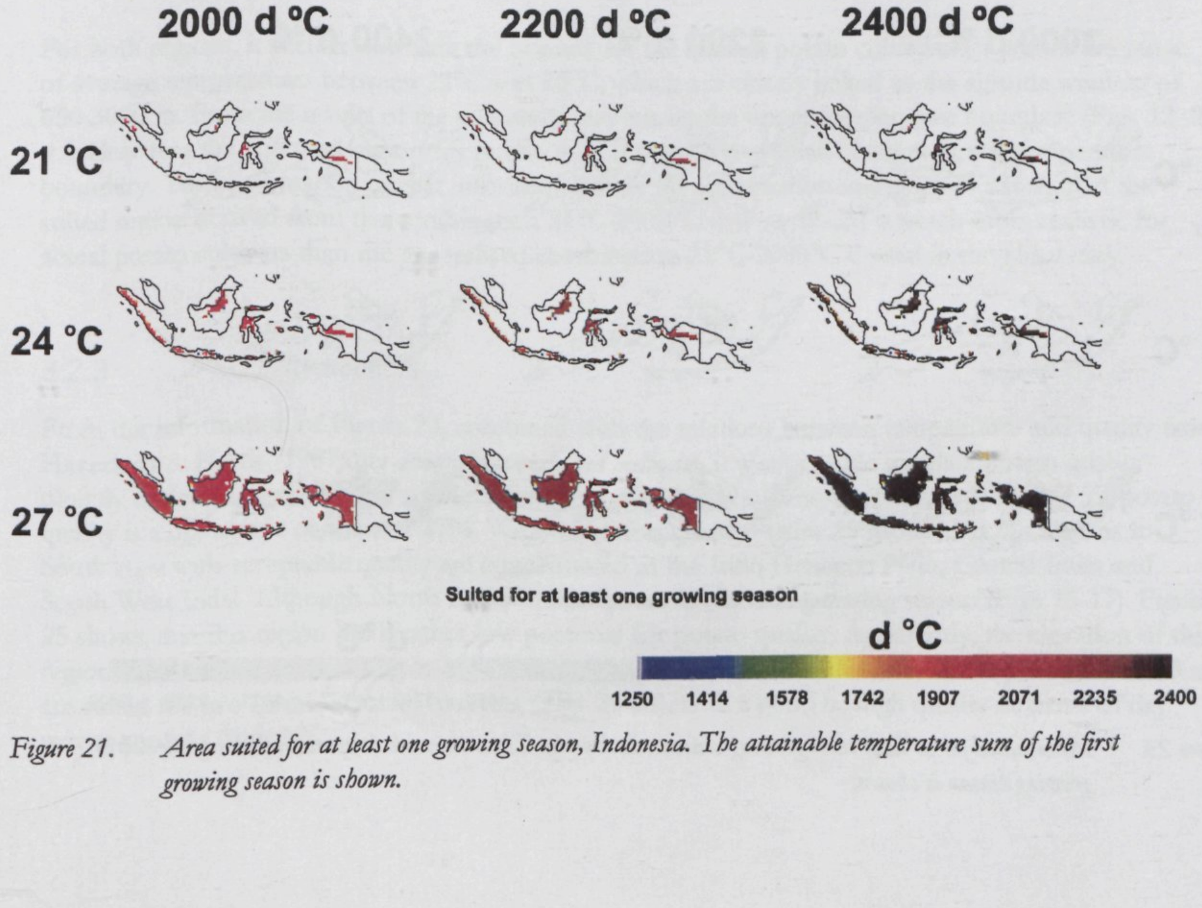

Figure 21. Area suited for at least one growing season, Indonesia. The attainable temperature sum of the first growing season is shown.

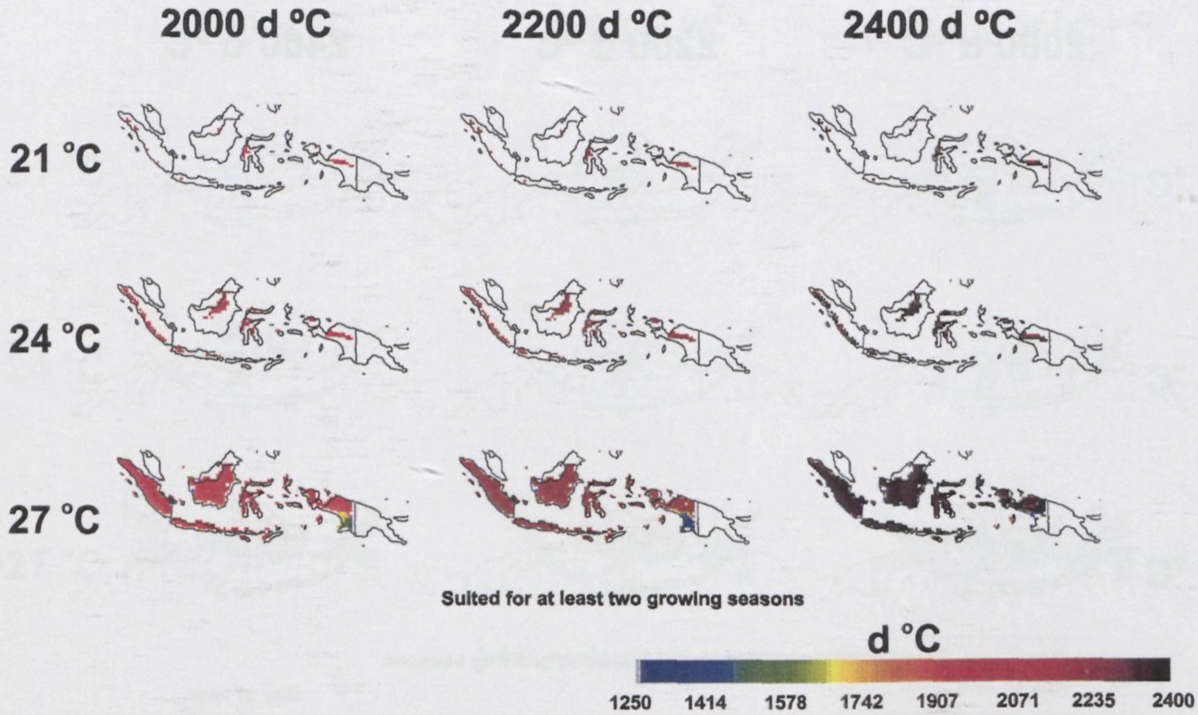

Figure 22. *Area suited for at least two growing seasons, Indonesia. The attainable temperature sum of the second growing season is shown.*

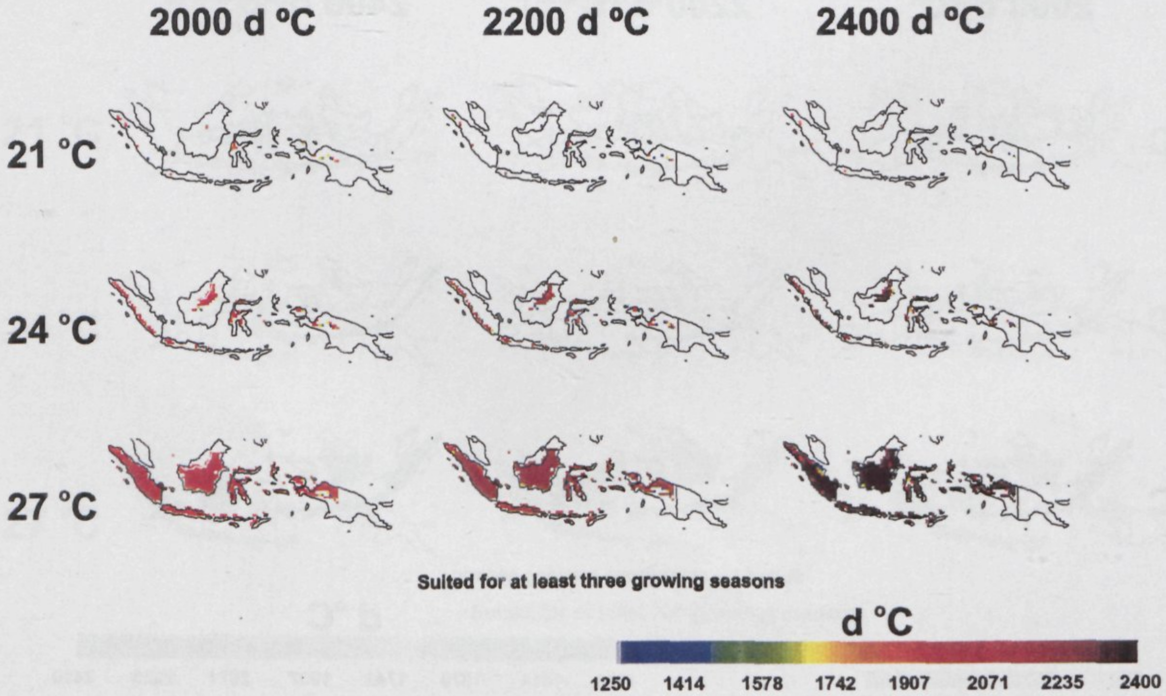

Figure 23. *Area suited for at least three growing seasons, Indonesia. The attainable temperature sum of the third growing season is shown.*

3.2.2 *Regional study*: Precising the regional temperature window for current potato cultivars

Figure 24 shows a strong correlation between elevation on the one hand and maximum, average and minimum temperatures on the other. A maximum temperature of 28°C (the upper limit for potato growth used in the *global study*) is linked with an average temperature of 23°C and a minimum temperature of 18°C, at an elevation of 650 m.

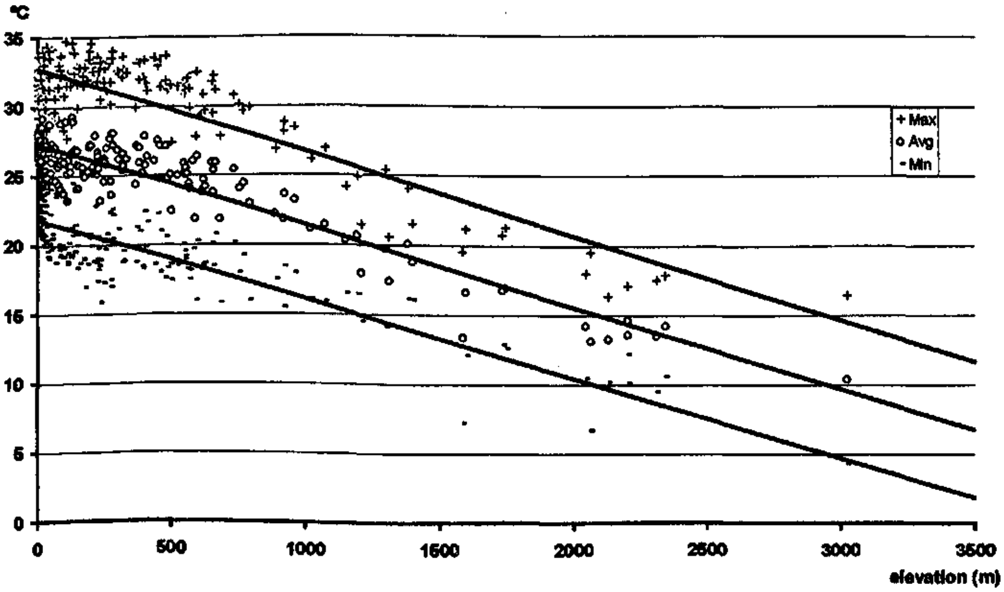

Figure 24. Minimum, average and maximum temperatures at different altitudes for India and South Asia.

For both regions, it is clear now that the boundaries for current potato cultivars are within the range of average temperatures between 23°C and 10°C, which are closely linked to the altitude window of 650-3000 m. From the results of the sensitivity analysis on the upper temperature boundary (Figs 12 -23) it is clear that the potential region for potato is very sensitive to small changes in this temperature boundary. The combination of that information with the information in Figure 24 shows that the suited region derived from the combination 24°C-2000°C d (Figs 12-23) is much more realistic for actual potato cultivars than the generalised combination 21°C-2000°C d used in the *global study*.

3.2.3 Quality aspects

From the information of Figure 24, combined with the relations between temperature and quality from Haverkort & Harris (1987) *(see section Materials and methods)*, it was possible to relate potato quality directly to detailed information on elevation from the elevation data set. The lower border for potato quality is a dry matter content of 17%. With this information, Figure 25 shows that the regions in South Asia with acceptable quality are concentrated in the Indo Gangetic Plain, Central India and South West India. Although North India has the potential for one growing season (Figs 15-17), Figure 25 shows that this region has a rather low potential for potato quality. Apparently, the elevation of this region is below 750 m, resulting in high average temperatures. For Indonesia, the regions above 650 m are suited for two or three potato harvests (Figs 21-23), with a good or high quality in terms of dry matter content (Fig. 26).

Figures 27 and 28 show the inverse relation between elevation and tuber number per plant. In fact, this information should be combined with a simulation of potato yield. In that case, information on the potential average tuber weight can be derived. However, this combination is outside the scope of the this study.

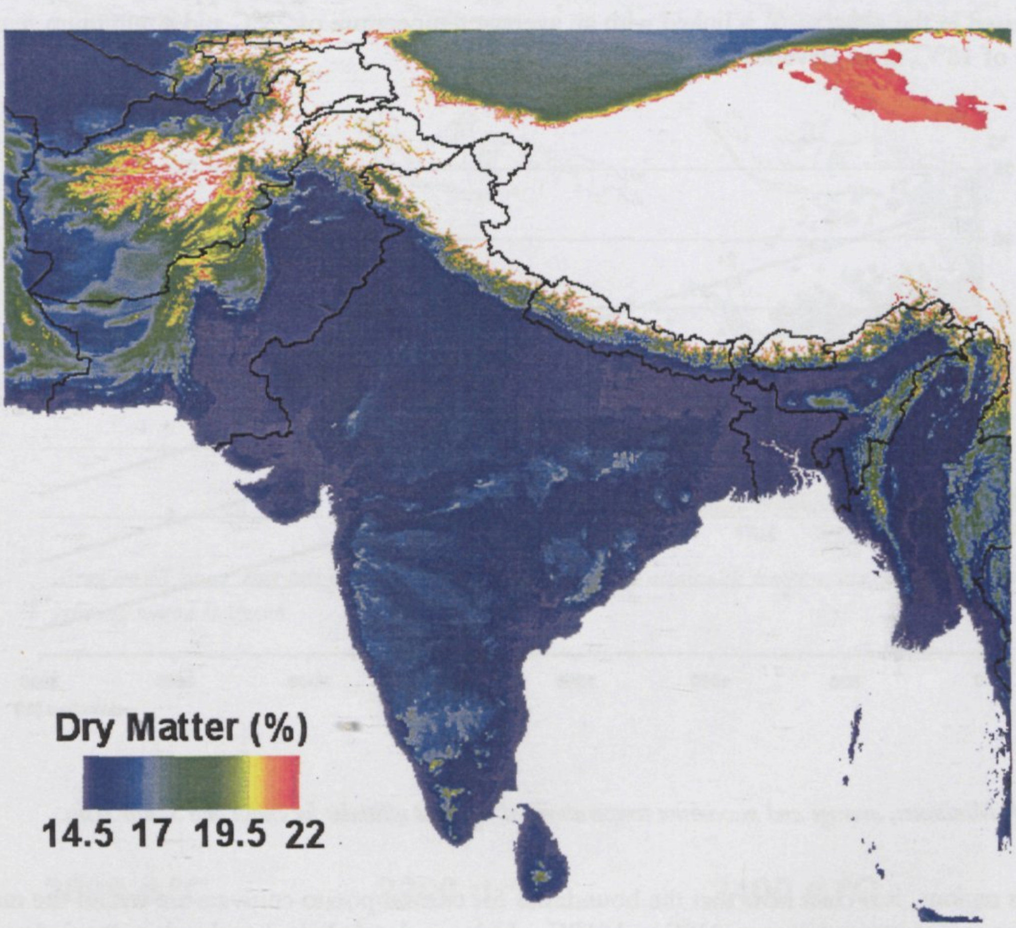

Figure 25. *Dry matter content (%) in South Asia.*

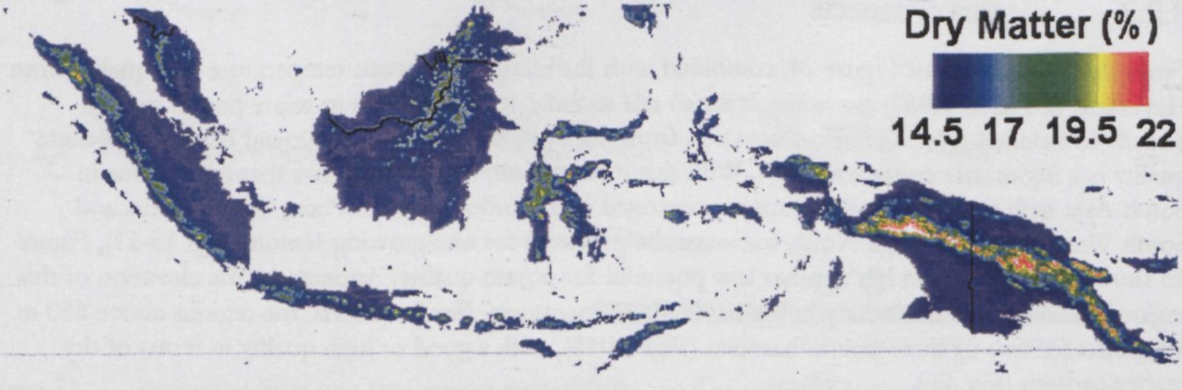

Figure 26. *Dry matter content (%) in Indonesia.*

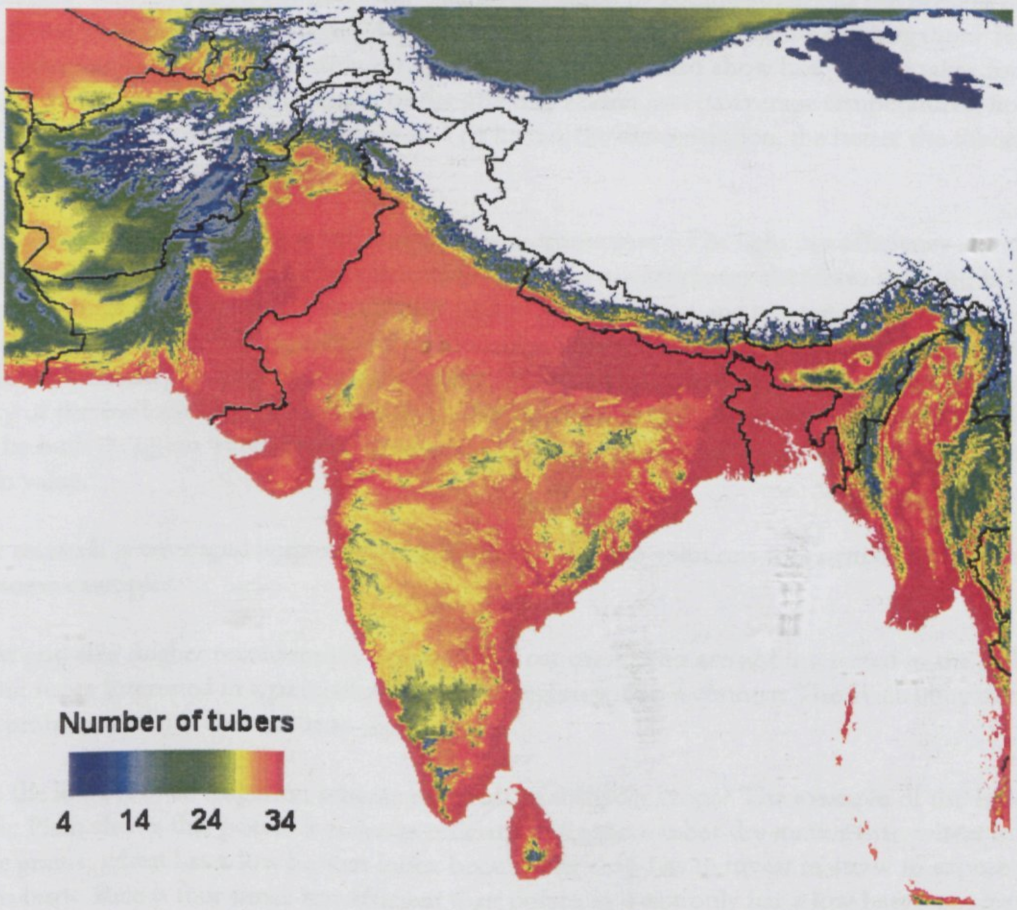

Figure 27. *Number of tubers in South Asia.*

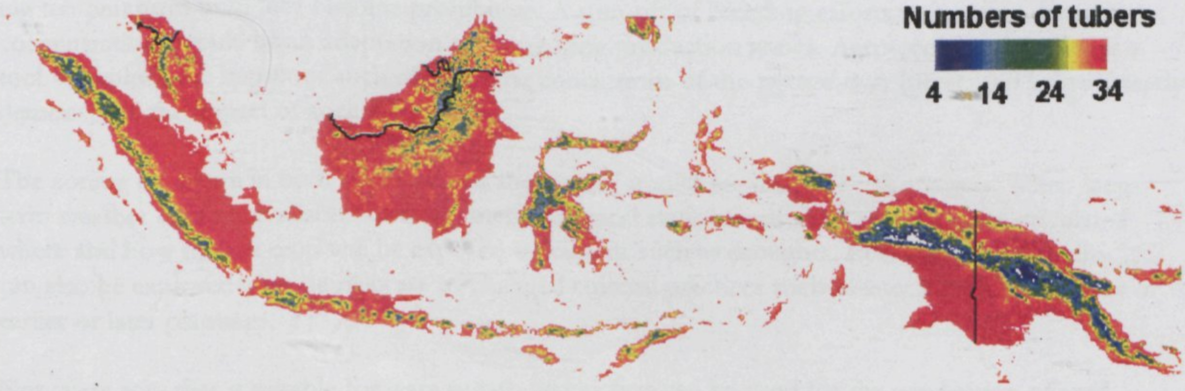

Figure 28. *Number of tubers in Indonesia.*

4. Conclusions

Users of agro-ecological zoning studies are interested in several aspects of the potato production chain. The question 'Where to grow my potatoes?' can be answered by zoning studies as the present one. The studies reveal comparative advantages of one area over the other, do farmers need irrigation? How far is the production area from population centres? The studies will also show how long it takes for a crop to mature, and, depending on the length of the growing season and its average temperatures, how high the dry matter concentration of the tubers is. The higher the concentration, the better the tubers are suited for storage and processing.

The methodology followed here is still amenable to improvement. The light use efficiency should be made dependent on the prevailing light intensity. Resource use efficiency decreases with the availability of the resource. *E.g.* ample water and nitrogen lead to low water use and nitrogen use efficiencies. Kooman & Haverkort (1995) found good relationships between mean daily incident solar radiation and the light use efficiency. Incorporating daily minimum and maximum temperatures would increase the accuracy of the explorations. For real desert-like areas where field capacity is never reached a threshold should be built in: *e.g.* no water-limited production possible when rainfall – evapotranspiration is below a certain value.

Further research is envisaged with partners interested in finding solutions for particular questions. Here follow some examples.

Reduced grid size (higher resolution) is needed for most users, who are not interested in the global scope but more interested in a particular country or region within a country. The availability of data is often a problem and it is also costly to digitise them.

What is the impact of an irrigation scheme on yields of different crops? The example of the Indo Gangetic Plain shows that potato is twice as efficient to produce tuber dry matter than wheat to produce grains; wheat has a low harvest index because the crop has to invest in straw to expose the grains to birds. Rice is four times less efficient than potato as it not only has a low harvest index but the paddy-grown crop also loses water through evaporation and then leaching is not even accounted for. Moreover, potato is grown in a cool season with a low evaporative demand, contrary to rice that is grown when temperatures are high.

Fresh yields based on temperature-related dry matter concentration often are of greater interest than the tuber dry matter yields shown here. For the fresh market a low dry matter concentration may be advantageous (selling water) but to store potatoes and especially for processing a high dry matter content is needed. Going downhill in tropical regions, the dry matter concentration decreases with increasing temperatures until they become prohibitive. A spin-off of breeding efforts to increase dry matter concentrations would be an adaptation to lower lying production zones. Agro-ecological zoning is a tool to explore the impact of such efforts. The conclusions of the *regional study* (presented below) clearly demonstrate the impact of such efforts.

The zoning as shown in both the *global* and the *regional* studies are used for risk analysis. When long-term weather data are available for many meteorological stations within an area it can be calculated where and how often a crop will be exposed to hazards such as droughts, frost or excessive rains. It can also be explored what he risks are of changed cultural practices such as later or earlier cultivars or earlier or later plantings.

Not every area that is suitable for ware potato production can be used for the production of seed potatoes. Seed potatoes need a long frost free period but with low temperatures to reduce the development of bacteria and of aphids as vectors of viruses. Adequate maps will show where the temperature sums increase relatively slowly indicative of a comparative advantage of such areas over others.

Breeding for heat tolerance

For both regions of the *regional study*, increasing the temperature threshold results logically in an increase of areas suitable for potato production. Increasing the temperature requirement results in a slight shift of the growing season; the crop needs more days to accumulate the required temperature sum. The selection of the upper temperature threshold has a distinct effect on the spatial distribution of the growing seasons, and shows a strong increase of the number of growing seasons for both South Asia and Indonesia. It is concluded that breeding for heat-tolerant potato cultivars increases the suited area for potato enormously.

The patterns in south Asia and Indonesia follow the elevation patterns. Three growing seasons are identified for the high temperature thresholds in both regions.

Growth of current potato cultivars

For growth of current potato cultivars, the combination of results of the regional data set (correct temperature limits and elevation), the elevation data set and the global data set, resulting in regional mapping of growth season and quality, shows that the regions in Indonesia above an altitude of 650 m are potentially suited for current potato growth with a growing season of at least 2000°C, with a good quality (a dry matter content of 18% or higher). Further, the study confirms that in South Asia, large areas are potentially suited for potato growth. Especially in the Indo Gangetic Plain, and the higher regions of central India and South-west India, the quality in terms of dry matter content is expected to be good. In north India, the quality of the potato yield is expected to be limited.

Future Perspectives

Improvement of the potato processing chain through quantitative approaches has much scope for further development. Together with partners in developing countries, the multinational food industry and funding agencies cases will have to be developed.

From the study several options for further research arise:

- Agro-ecological zoning for processing and seed potato in different regions, for instance Eastern Europe;
- Ecoregional study of potato in the Asian Potato-Cereal Belt (Pakistan, Nepal, India, Bangla Desh, China and Vietnam;
- Potato Processing in the Indo-Gangetic Plain in India. Here, near Calcutta, all potatoes are harvested in March and cause a glut on the market. It should be possible to use solar dehydration (it is hot and sunny in April and May) and process potatoes for the local market;
- Link water use and potato production on a regional scale;
- Determine the regional effects of climate change on potato production.

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Appendix I

Extended IDL Help

This page was created by the IDL library routine mk_html_help. For more information on this routine, refer to the IDL Online Help Navigator or type:

    ? mk_html_help

at the IDL command line prompt.

Last modified: Thu Jul 29 13:29:01 1999.

List of Routines

- CROP_SEASON
- CALCDEG
- CTSUM
- GROWING
- WFPD_TEMP

Routine Descriptions

CROP_SEASON

[List of Routines]

NAME:	crop_season	
PURPOSE:	Main program to calculate the growing season for a crop based on temperature ranges and day-degrees.	
FUNCTIONS:		
PROCEDURES:	crop_season	
CALLING SEQUENCE:	crop_season, TMBASE, TMMIN, TMMAX, MinSum, MaxSum	
KEYWORDS:		TempFile1 File containing temperature data. If keyword is not set then a file pick menu is activated.
INPUTS:	TMBASE	Base temperature (degrees Celsius)
	TMMIN	Minimum temperature (degrees Celsius)
	TMMAX	Maximum temperature (degrees Celsius)
	MinSum	Minimum temperature sum (day-degrees)
	MaxSum	Maximum temperature sum (day-degrees)
OUTPUTS:	1. grow	file containing results for 1st growing season
	2. grow	file containing results for 2nd growing season
	3. grow	file containing results for 3rd growing season
	File format:	

File formats: contains the following header:

```
Meteo_ID','TMAV1','TMAV2','TMAV3','TMAV4','TMAV5','TMAV6','TMAV7','TMAV8',
'TMAV9','TMAV10','TMAV11','TMAV12',
-32001,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00,-99.00
```

The data records follow this format, each line starts with a meteo_id.

_.grow contains the following information (no header, fixed format):

grid_id	grid number based on global grid of 0.5 x 0.5 deg.	position: 1 - 7
Meteo_ID	identifier of meteo station	position: 8 - 14
season_ id	1, 2 or 3	position: 15 - 21
start of season	day number	position: 22 - 28
end of season	day	position: 29 - 35
temperature sum	day-degrees	position: 36 - 42

The data records follow this format, each line starts with a meteo_id.

(See d:\usr\idl\season\crop_season.pro)

CALCDEG

[List of Routines]

NAME: CalcDeg

PURPOSE :

FUNCTIONS: CalcDeg

PROCEDURES: None

KEYWORDS: None

CALLING SEQUENCE: CalcDeg(data, TMBASE)

INPUTS:

data	array containing temperature data (degrees Celsius)
TMBASE	Base temperature (degrees Celsius)

OUTPUTS: Array containing temperature data (degrees Celsius) corrected with TMBASE

HISTORY

(See d:\usr\idl\season\calcdeg.pro)

CTSUM

[List of Routines]

NAME: CTSum

PURPOSE: Calculates the cumulative temperature sum
FUNCTIONS: CTsum

PROCEDURES:

KEYWORDS: None

CALLING SEQUENCE: CTSum(TempDays, StartS, EndS, TMBASE, TMMAX)

INPUTS:
TempDays Array containing temperature data
StartS Start of growing season (day number)
EndS End of growing season (day number)
TMBASE Base temperature (degrees Celsius)
TMMAX Maximum temperature (degrees Celsius)

OUTPUTS: Cumulative temperature sum (day-degrees)

(See d:\usr\idl\season\ctsum.pro)

GROWING

[List of Routines]

NAME: Growing

PURPOSE: Calculate begin and end of growing seasons, a maximum of 10 seasons is allowed.

FUNCTIONS: Growing

PROCEDURES: None

KEYWORDS: None

CALLING SEQUENCE: Growing(GrowSeason)

INPUTS: GrowSeason Array of possible grow days, 1 is a grow days, 0 no growth possible.
Growdays are defined by setting the minimum and maximum temperature thresholds.

OUTPUTS: Structure containing begin and end of up to 10 growing seasons.
STARTS INT Array[10]
ENDS INT Array[10]

(See d:\usr\idl\season\growing.pro)

WFPD_TEMP

[List of Routines]

NAME: wfpd_temp

PURPOSE:	down scaling of monthly temperature data to daily temperature data using linear interpolation.
FUNCTIONS:	wfpd_temp
PROCEDURES:	None
KEYWORDS:	None
CALLS:	interpol.pro
CALLING SEQUENCE:	wfpd_temp(afTemperature, aiDays, aiYear)
INPUTS:	afTemperatureArray of float with monthly temperature data
aiDays	Array of integer [1,15,46,74,105,135,166,196,227,258,288,319,349,365]
aiYear	array of integer containing daynumber 1. 365. (No leap year!)

OUTPUTS: Array of float with daily temperature data.

(See d:\usr\idl\model\wfpd_temp.pro)

Appendix II

Statistical information on potential production in the first season

(Biomass: total biomass produced (kg ha^{-1}); WSO: Weight Storage Organ (tuber; kg ha^{-1}))

```
Africa
Biomass
Mean:          18269.6
Variance:          8.23544e+006
Max            29396.4
Min             7561.49
Skewness:         -0.475645
Kurtosis:          0.0655468
WSO
Mean:          13421.1
Variance:          6.80296e+006
Max            23517.1
Min             4794.96
Skewness:         -0.421587
Kurtosis:         -0.196811
Australia
Biomass
Mean:          16553.4
Variance:          6.52956e+006
Max            24694.6
Min             9304.93
Skewness:         -0.283603
Kurtosis:          0.247089
WSO
Mean:          12703.7
Variance:          4.19544e+006
Max            19755.7
Min             5751.42
Skewness:         -0.249571
Kurtosis:          0.851163
Central America
Biomass
Mean:          17118.4
Variance:          9.00015e+006
Max            27579.7
Min             7899.07
Skewness:          0.638231
Kurtosis:          0.649417
WSO
Mean:          12663.0
Variance:          6.94437e+006
Max            22063.7
Min             5071.26
Skewness:          0.473826
Kurtosis:          0.499892
Central Asia
Biomass
Mean:          18854.2
Variance:          6.97254e+006
Max            29259.4
Min            12252.0
Skewness:          1.19432
Kurtosis:          2.04616
WSO
Mean:          14512.9
Variance:          4.07785e+006
Max            23407.6
Min             9801.56
Skewness:          1.29886
Kurtosis:          2.31367
Europe
Biomass
Mean:          18401.5
Variance:          1.63365e+007
Max            29402.8
Min             4758.85
Skewness:         -0.497273
Kurtosis:         -0.106234
WSO
Mean:          13992.2
Variance:          8.23509e+006
Max            23273.2
Min             3807.08
Skewness:         -0.433231
Kurtosis:         -0.0617995
Far East
Biomass
Mean:          16014.9
Variance:          9.85854e+006
Max            26695.2
Min             5327.28
Skewness:          0.209189
Kurtosis:         -0.735730
WSO
Mean:          12048.2
Variance:          6.95230e+006
Max            20911.8
Min             4261.82
Skewness:          0.224980
Kurtosis:         -0.684088
North America
Biomass
Mean:          19040.5
Variance:          2.63689e+007
Max            31985.2
Min             5060.53
Skewness:         -0.262478
Kurtosis:         -0.376243
WSO
Mean:          14712.6
Variance:          1.45538e+007
Max            25588.2
Min             4048.42
Skewness:         -0.196501
Kurtosis:         -0.0945399
New Zealand
Biomass
Mean:          13312.5
Variance:          5.46740e+006
Max            16533.3
Min             7272.67
Skewness:         -0.321052
Kurtosis:         -1.06282
WSO
Mean:          10488.8
Variance:          2.92155e+006
Max            13226.7
Min             5818.13
Skewness:         -0.436034
Kurtosis:         -0.876040
Near East
Biomass
Mean:          17743.9
Variance:          8.03993e+006
Max            30653.8
Min            10003.1
Skewness:          0.978696
Kurtosis:          3.60540
WSO
Mean:          13205.0
```

Variance: 6.14285e+006
Max 24523.0
Min 6592.13
Skewness: 0.507216
Kurtosis: 2.73652

South East Asia

Biomass

Mean: 15302.8
Variance: 6.14630e+006
Max 21264.9
Min 7868.55
Skewness: 0.0621110
Kurtosis: -0.167242

WSO

Mean: 10910.4
Variance: 4.96896e+006
Max 15587.1
Min 5143.79
Skewness: 0.239641
Kurtosis: -0.684699

Siberia

Biomass

Mean: 12424.9
Variance: 6.34634e+006
Max 19073.7
Min 5327.28
Skewness: 0.283052
Kurtosis: -0.847011

WSO

Mean: 9916.82
Variance: 3.93328e+006
Max 15258.9
Min 4261.82
Skewness: 0.253284
Kurtosis: -0.877628

South America

Biomass

Mean: 16152.5
Variance: 1.99864e+007
Max 32942.4
Min 7221.48
Skewness: 1.06275
Kurtosis: 0.829286

WSO

Mean: 12164.0
Variance: 1.47105e+007
Max 26353.9
Min 4587.38
Skewness: 1.07450
Kurtosis: 0.635771