Agro-ecological characterization for potato production

A simulation study at the request of the International Potato Center (CIP), Lima, Peru

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December 1991

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Executive summary

To target research to production problems in those areas of Latin America, Africa and Asia where cultivation of potato is most promising, CIP and collaborating NARC's need to know what tuber yields can be expected under irrigated and rainfed conditions in different agro-ecological zones. Particularly for non-traditional zones, such information is hardly available. To increase the efficiency of the long and laborious process of experimentation, we explored agro-ecological characterization of many areas for potato production with a crop simulation model using local environmental data. The potential growth duration, potential yield and water-limited yield of potato crops were determined at as many locations as possible. Such maximum yields are directly related to environmental conditions, and are well predictable.

The results are aimed at supporting the setting of priorities in research on crop production and crop protection, and on sustainable use of resources and inputs. Socio-economic constraints, that often prevent farmers from achieving top yields, are excluded. This permits research planning to look beyond present limitations, and to identify areas where the crop can prosper after research has eliminated bottlenecks.

Most of our simulation results are presented in the form of maps:
- the worldwide distribution of the duration of potato growing seasons (map 3),
- the agro-biological potential yields of potato crops in irrigated conditions (main crop map 4, second crop map 5),
- the agro-biological potential yields of potato crops in rainfed conditions (map 6),
- the possible yield gain by irrigation of rainfed crops (map 7).

Weather conditions allows for two cropping periods per year in large subtropical areas. Expressed in dry matter, irrigated yield potentials range from 2 to 25 t ha^{-1}, while rainfed yields range from 0 to 20 t ha^{-1}. For fresh tuber yields, multiply by 4.3. Farmer attainable yields are around 50% lower. As a general trend, yields increase with radiation intercepted, and decrease with temperature, because of a decline in harvest index, and decline with drought. Elevation has a strong effect on production because of its relation to temperature.

These results are still of a preliminary nature, both in their degree of detail and in the number of interactions considered. Yet, tested against results of some field trials and exposed to expert knowledge, the results appeared to be acceptable and consistent. Calculations were made for a short-to-medium duration variety; cropping systems issues were not addressed. The spatial scales of weather and soil data blurred much of the local topography, so that results in hilly and mountainous areas should be interpreted carefully.

Keywords: agro-ecological characterization, zonation, simulation, potato growth, potential production, water-limited production, research planning

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1 Objectives and scope

For planning of research, CIP and collaborating NARC's need to know where in the world potato crops can be grown, and what their yield might be under irrigated and rainfed conditions. Yield trials at a large number of locations for many years have given a good insight in its yield potential, particularly for traditional potato growing areas. For non-traditional zones, this information is hardly available. Yet, the crop is rapidly expanding into new zones (van der Zaag and Horton, 1983, CIP, 1991). To target research to production problems in those areas of Latin America, Africa and Asia where potato production is most promising, knowledge is indispensable of the crops potential under irrigated and rainfed conditions in different agro-ecological zones. To increase the efficiency of the long, laborious and expensive process of experimentation, this study explored agro-ecological characterization of many areas for potato production with a crop model and with local data on the environment.

The objective of this study was: to establish the potential growth duration, potential yield and water-limited yield of potato crops as accurately as possible and at as many locations as possible, given limitations of time and data. Validation of model and data was part of the procedure. The duration of the growing season was defined as the continuous period in which the minimum temperature is above 5 and the maximum temperature is below 28 °C. For the crop to produce tubers, the season should exceed a minimum duration, equivalent to a temperature sum of 1250 °Cd, with a base temperature of 2 °C. In general, yields increase with the amount of radiation intercepted, and decrease with temperature because the harvest index declines. Yields are also strongly related to elevation. Potential production refers to the tuber yield of the potato crop (in t ha^{-1} dry weight; for fresh weight multiply by 4.3) that can be produced under conditions of optimum water supply (applying irrigation, if necessary), nutrient supply, and pest management. Water limited production refers to the tuber yield in the same situation, but without supplementary irrigation. The model and data used are documented elsewhere.

Results presented can be used as a basis for discussions on potentials of potato crops in different agro-ecological zones among breeders and physiologists, for yield gap analysis in these zones by agronomists and crop protectionists, for designing optimum testing programs for new varieties under different conditions for breeders, and indirectly for policy making.

The scope of the simulation study was restricted in several ways. First, we only addressed the agro-biological potential of potato crops, excluding the socio-economic constraints that often prevent farmers from achieving top yields. In this way, research planning can look beyond present limitations and identify areas where the crop could prosper in the future. Moreover, this restriction was imposed by the lack of well-developed methodologies to perform such socio-economic analyses. To avoid presenting an overly optimistic view, we have assumed, as a rule of thumb, the potato yield attainable in practice by farmers is 50% of the agrobiological potential at a location. The study has been restricted to exploring the possibilities for production of one or more crops of potato at each location per year. The choice of varieties was too large to address at this stage, so that we simulated only one variety of short-to-medium duration, insensitive to daylength. Cropping systems issues, such as alternative crop species or unsustainable narrow rotations, were not considered. Efficiency of water use for production is an implicit part of computation of water-limited yields. The possible yield gain due to irrigation is equal to the difference between the potential and water-limited yields. Nutrient requirements and inputs for weeds, pest and disease control were not yet quantified. Sweet potato was excluded from the study because a model for this crop is still insufficiently parameterized.

Despite the intensive three months effort that went into the study, its results are of a preliminary nature. The reasons are several: limited sets of reliable weather data (lengths of time series, and number of locations), a very restricted set of soil data could be acquired in time, and only few sets of crop data were available to parameterize and evaluate the model. These constraints led to important limitations in the degree of detail of the results and in the number of interactions considered. Yet, a worldwide overview of potentials for irrigated and rainfed potato production could be composed. When the outcome was tested against results of some field trials and exposed to expert knowledge, the results stood up and proved consistent. Lack of detail in soil data forced us to simulate conditions where soils are always moderately deep, without stones, well permeable and flat, and where water logging is absent. The spatial scales of the soil and weather data blurred much of the local topography, so that special care is to be taken with interpretation of the results in hilly and mountainous areas.

2 Background of crop modelling at CABO

Crop modelling has established its place as a tool in agricultural research over the last decades (Seligman, 1990), even though scepticism about its role and usefulness is being expressed (Monteith, 1981).

The advent of the use of computers as an aid in analysing the consequences of insights in crop physiology for crop growth and yield can be traced back to the early sixties, when C.T. de Wit, then working at IBS, one of the predecessors of CABO-DLO, worked on modelling of canopy assimilation. He published in 1965 the report *'Photosynthesis of leaf canopies'*, in which a procedure was described that 'allowed calculation of the daily photosynthesis of a canopy with known characteristics for any time and place on earth, from the relevant meteorological data'.

This procedure was subsequently incorporated in the Elementary Crop growth Simulator (ELCROS), a model that simulated dynamically dry matter accumulation of a maize crop (de Wit et al., 1970), and paid attention to the distribution of the material between aboveground and belowground plant parts (Brouwer and de Wit, 1969). Increased insights in processes governing canopy behaviour formed the basis for expansion of comprehensive models, aiming at explanation of quantitative aspects of crop growth in terms of the underlying processes, especially assimilation, respiration and transpiration (de Wit et al., 1978). These models mainly dealt with the biological limits of agricultural production, and thus with what has subsequently been defined as *potential production*. They served on the one hand as research tools, to test hypotheses and examine the consequences of alternative theories, but on the other hand their results were used as yardsticks for agricultural achievements, that soon appeared also technologically attainable (de Wit et al., 1979) and thus inspired confidence in the models. They also formed the basis for research on 'yield-limiting' and 'yield-reducing' factors to identify the causes of the gaps between the calculated potential production levels and actually achieved experimental yields (de Wit, 1975), which for wheat, for example, pointed to the crucial role of the so-called 'ripening diseases' during the grain-filling phase. Subsequent developments were characterized by two major activities: (i) introduction of quantitative descriptions of the effects of yield-limiting factors, notably water, which required incorporation of the soil water balance in simulation models (van Keulen, 1975) and nitrogen, requiring description of the soil nitrogen balance (Seligman and van Keulen, 1981) and (ii) the derivation of so-called 'summary models' (Penning de Vries, 1982) that presented simplified descriptions of many of the relevant processes on the basis of the quantitative insights gained from the comprehensive models (van Keulen et al., 1982). Summary models are applicable on a wide scale, as their data requirements were lower.

Extensive research on the applicability of these models has shown that the models describing *water-limited* yields form an accurate basis for predicting the effects of temporary water shortage on crop performance, and may be used therefore with confidence for yield predictions of different crops under arid and semi-arid conditions or where rainfall patterns may induce periods of water deficiency (Alagos, 1991, Wan Suleiman and Rushidah, 1991, van Keulen, 1987).

The models including the nitrogen balance of the soil and the effects of temporary nitrogen deficiency on crop performance, are still largely in the preliminary stage (Penning de Vries, 1982), as knowledge of the processes underlying the transformations of nitrogen is fragmentary (van Keulen and Stol, 1991). Hence, calculation of *nutrient-limited* yields using these models is in many cases speculative. Nevertheless, application of these models for exploratory studies increases insight in the relative importance of different growth-limiting factors, and if properly 'calibrated' they may be used for management recommendations (van Keulen and Seligman, 1987).

The developments of these models and their present state-of-the-art, have resulted therefore in their application for agro-ecological characterization, particularly at the level of *potential yield* and *water-limited yield* (van Keulen and van Diepen, 1990). This essentially comprises an assessment of the suitability of various environments for different types of land use. Such results are very similar to physical land evaluation, originally conceived by soil scientists. Crop and soil modelling forms an essential component of quantified land evaluation (van Diepen et al., 1991) and has wide applicability in land use planning procedures.

In recent years, results of crop growth simulation models have also been used to generate technical coefficients for agricultural production techniques as a basis for optimization techniques, such as Multiple Goal Linear Programming (van Keulen, 1990). These techniques hold the promise of identifying and quantifying the options for agricultural development under multiple objectives, and under given sets of regional constraints.

3 Data

3.1 Weather

The weather data used in this study were obtained from the Müller database, a global set of long-term monthly average values of weather variables of 978 meteorological stations (Müller, 1982, 1987). The following variables were used in this study:

- temperature (°C),
- maximum temperature (°C),
- minimum temperature (°C),
- precipitation (mm),
- number of days with more than 0.1 mm precipitation (-),
- sunshine duration (hours),
- amount of global radiation (Ly d^{-1}).

For a number of stations not all of these data were available. For each station the name, country, longitude, latitude, elevation and climatic classification according to Köppen and Troll and Paffen are given. The series of observations cover mostly the period 1931-1960. If the time-span is shorter than 30 year, data were mostly collected during the sixties and seventies. The database from 1982 was expanded with data of 12 weather-stations in Mexico from the 1987 publication to have a better coverage in that area. Additional stations from the United States of America were not included, because the purpose of this study was to focus on Latin America, Africa and Asia.

For the calculations of potential production, the amount of radiation or sunshine duration, and the minimum and maximum temperatures or average temperature are needed. For the quantification of water-limitation, mean monthly precipitation and the number of days with precipitation are also required.

For the identification of potential growing seasons and the calculations of both potential and water-limited production, daily values of weather variables are required. Mean monthly values of weather variables from the Müller database have been transformed therefore into daily values. Monthly values have been assigned to day numbers at the middle of the months, daily values in between have been derived by means of linear interpolation. The amount of daily rainfall however, is determined by a random distribution of the long-term average monthly rainfall over the long-term average monthly number of raindays.

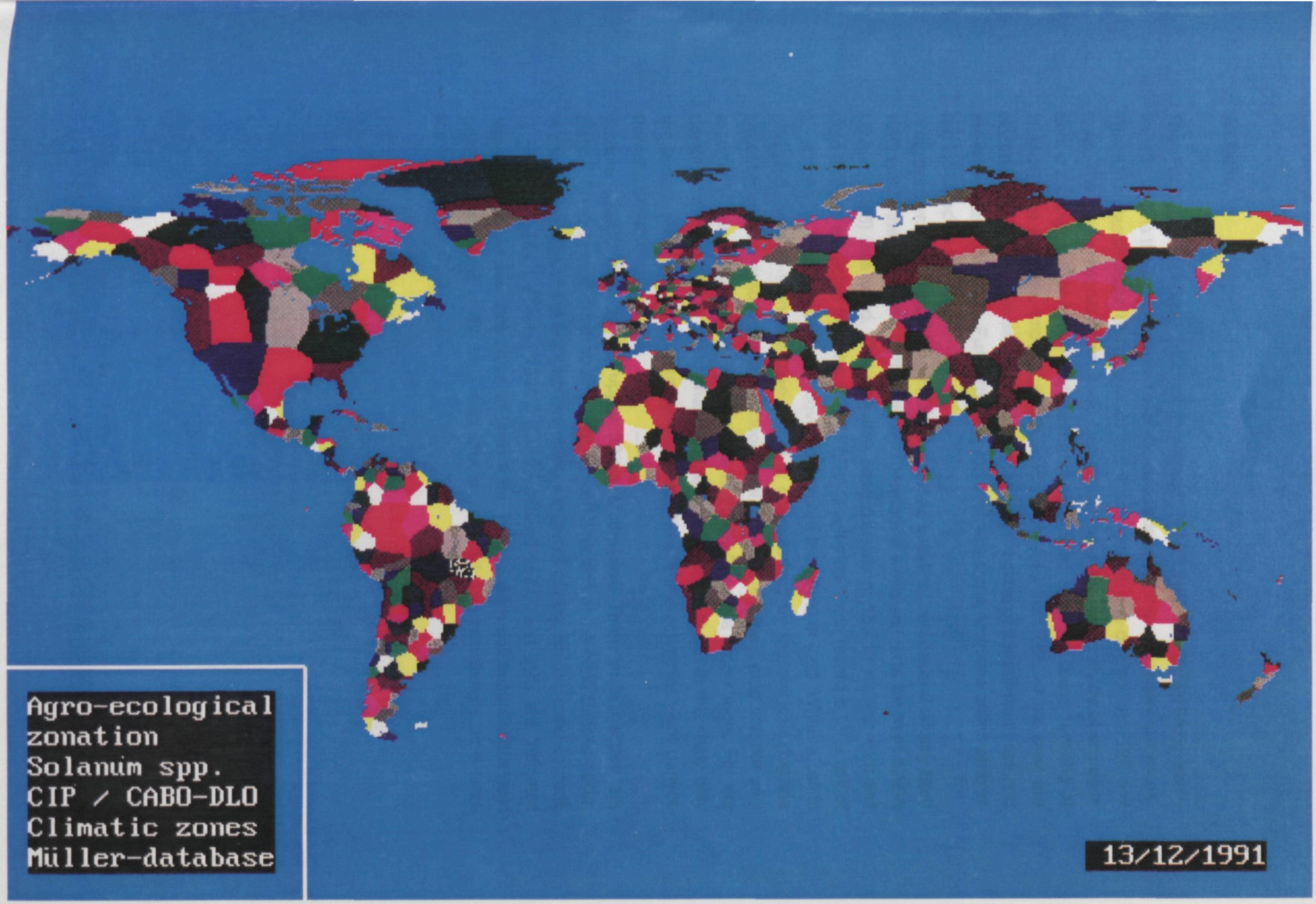
Data were first analysed for quality control. A short program was made which alert when (monthly) values of:

- location parameters; longitude, latitude and elevation are impossible or extreme,
- global radiation, sunshine duration or rainfall are negative,
- both global radiation and sunshine duration are absent,
- daily sunshine duration exceeds actual daylength,
- daily atmospheric transmission coefficients are less than 0.1 or more than 0.85 (Spitters et al., 1986),
- minimum temperature exceeds maximum temperature,
- minimum or maximum temperature exceed preset extreme values.

All records of the Müller database were also checked with a statistical procedure which alerts on skew distributions of weather variables. All alerted records, including rainfall, were checked and corrected on the basis of the most recent publication of the database (Müller, 1987).

To estimate daily total global radiation when only sunshine duration was available, the Ångstrøm formula was used. In this formula two regression parameters r_a and r_b are required. The values of these parameters were estimated using Köppen's climatic classification (Bartholomew et al., 1988) in combination with values given by FAO (Frère and Popov, 1979).

To make the Müller data available for simulation in a flexible way, the data were transformed into the format of the CABO-DLO/TPE weather system (van Kraalingen et al., 1991).


Agro-ecological
zonation
Solanum spp.
CIP / CABO-DLO
Climatic zones
Müller-database
13/12/1991

3.2 Soils

The FAO/UNESCO soil map of the world (FAO/UNESCO, 1974-1981), scale 1:5,000,000, is the basic document for the classification of the world's soil resources. The FAO classification comprises 26 major soil groups sub-divided into 106 soil units. The map presents about 5000 map units. These are associations of soil units and are composed of a dominant soil and associated soils, the latter covering at least 20% of the area. Important soils which cover less than 20% of the area are added as inclusions. For each association the textural class of the dominant soil and the slope class are given. Furthermore, properties like stony, lithic and saline phases are indicated on the map.

A digitized version of the FAO/UNESCO soil map could not be obtained directly from FAO within the timeframe of this study. Therefore a world soil data file from NASA (Zobler, 1986) was used. This soil data base consists of 15,413 records with soil data that are extracted from the FAO/UNESCO soil map. Each record is for a cell of 1° latitude by 1° longitude that is covered by more than 50% of land. When a cell is occupied by more than one map unit, it is characterized by the unit covering the largest area. The associated and included soil units of the largest map unit are only recorded by a numeric code, which refers to the FAO source map sheets. For the dominant soil unit, slope class, phase and texture class are given. In this study only the texture class was used to represent a cell. No soil characteristics were derived from the soil names.

Texture classes refer to the upper 30 cm of the soil. Three main classes are distinguished: coarse, medium and fine; five combinations of the main classes occur. A characterization of the eight texture classes in terms of clay, silt and sand content, is given in table 1 (Zobler, 1986). Beside mineral soils, peat soils are indicated separately in the soil data base. In table 1 the area of each soil texture class (and peat) as percentage of the total map area is indicated. The remaining area is land-ice or unknown.

Table 1. Characterization and percentage map area of texture classes (Zobler, 1986).

	coarse	coarse-medium	medium	medium-fine	fine	coarse-medium-fine	coarse-fine	peat
% clay	9	20	30	48	67	35	38	-
% silt	8	20	33	25	17	19	12	-
% sand	83	60	37	27	17	46	50	-
% map area	24	7	42	6	12	< 1	< 1	1

For use in the crop growth model, the water holding capacity of the soils was derived from the texture classes. This was done on the basis of an earlier estimate of the water holding capacity of soils in the European Communities (Reinds et al., 1991). These European soils were also classified according to the FAO/UNESCO system. Table 2 shows the volumetric water contents at field capacity and wilting point that were used. The difference between the two is the water holding capacity.

Table 2. Volumetric water content (cm/m) at field capacity and wilting point, and water holding capacity (cm/m).

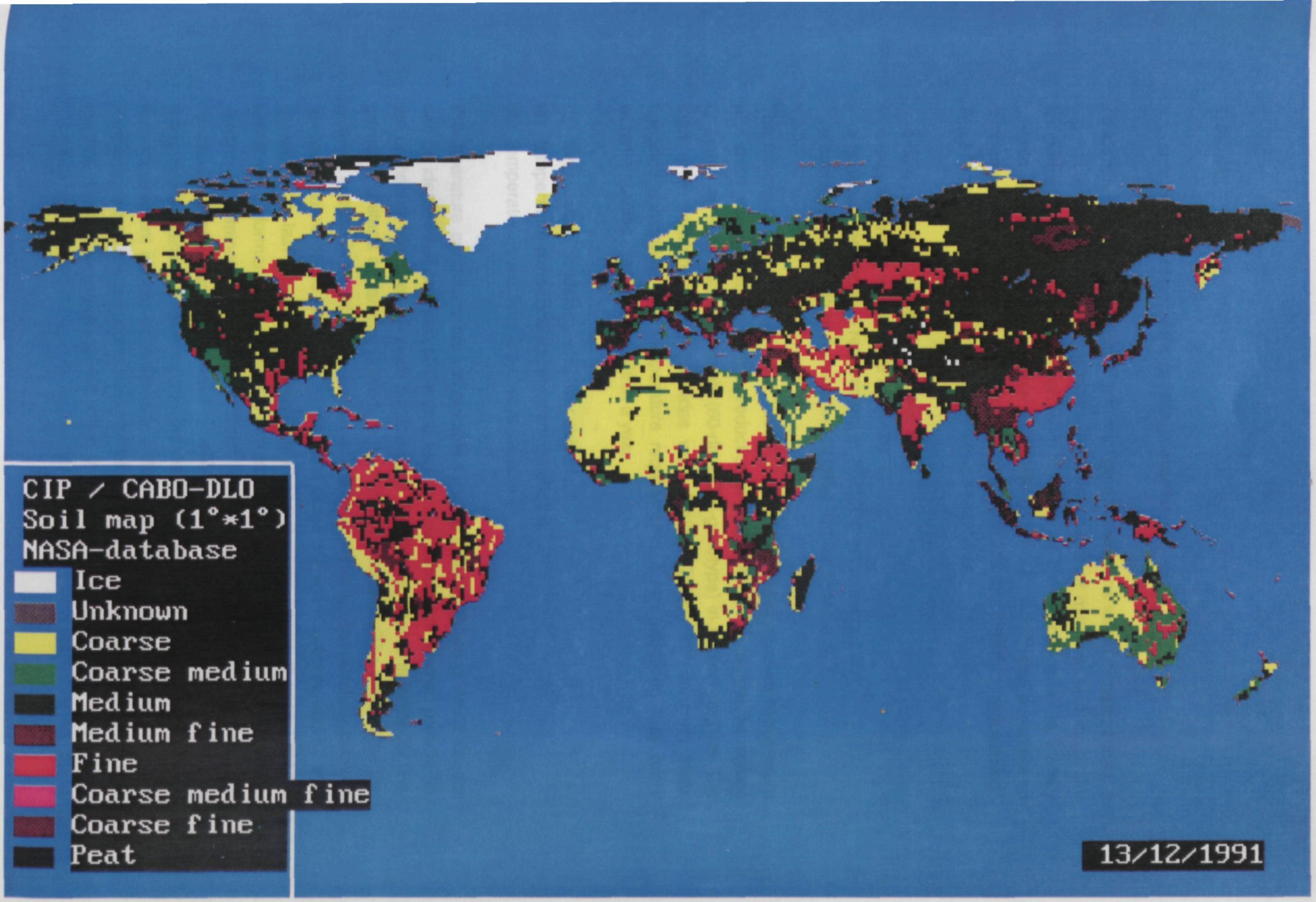
	coarse	coarse-medium	medium	medium-fine	fine	coarse-medium-fine	coarse-fine	peat
field capacity	13	24	32	46	54	24	24	52
wilting point	4	10	10	30	44	10	10	13
water holding capacity	9	14	22	16	10	14	14	39

3.3 Geographical distribution of weather and soils

The basis for the geographic component of the study was a terrestrial grid with a resolution of 0.5° longitude and latitude as obtained from IIASA (Leemans and Cramer, 1990). For 978 weather stations, monthly temperature data were available. With a standard algorithm, each grid cell was allocated to the nearest weather station, thus creating a map of climatic zones (Map 1). Within a zone the climatic characteristics are supposed to be represented by the centrally located weather station. For each climatic zone, the number and length of growing seasons were calculated from the temperature data (Section 4.1, Map 3).

For the calculation of potential and water-limited yields with the crop growth model, a more complete set of monthly climatic data is needed: in addition to temperature also sunshine duration or global radiation, precipitation and number of rain days. This combination of data was available for 688 weather stations. On the basis of these stations a new coverage of climatic zones was made, forming the basis for further model calculations and presentation of results.

For the calculation of water-limited yields, climatic data had to be combined with soil data. The soil data were available for a 1° longitude by latitude grid (Section 3.2). Map 2 shows the geographical distribution of the soil textures. By means of an overlay, each terrestrial 0.5° x 0.5° grid cell within each climatic zone was allocated to the corresponding soil grid cell. In this way, the relative area of each soil type within a climatic zone could be determined. For each soil type occurring in a climatic zone, the water-limited yield was calculated separately, and subsequently the area-weighted average yield within a zone was determined and indicated on the map.


CIP / CABO-DLO
Soil map (1°*1°)
NASA-database
Ice
Unknown
Coarse
Coarse medium
Medium
Medium fine
Fine
Coarse medium fine
Coarse fine
Peat
13/12/1991

Map 2

4. Model

4.1 Identification of potential growing seasons

To identify number and length of potential growing seasons within climatic zones, a procedure was developed that scans the daily course of minimum and maximum temperatures throughout the year. The objective of the procedure is to identify periods with temperatures suitable for potato growth, for which the accumulated temperature sum, above a base temperature, exceeds the minimum requirement. The temperature constraints for crop growing seasons are:

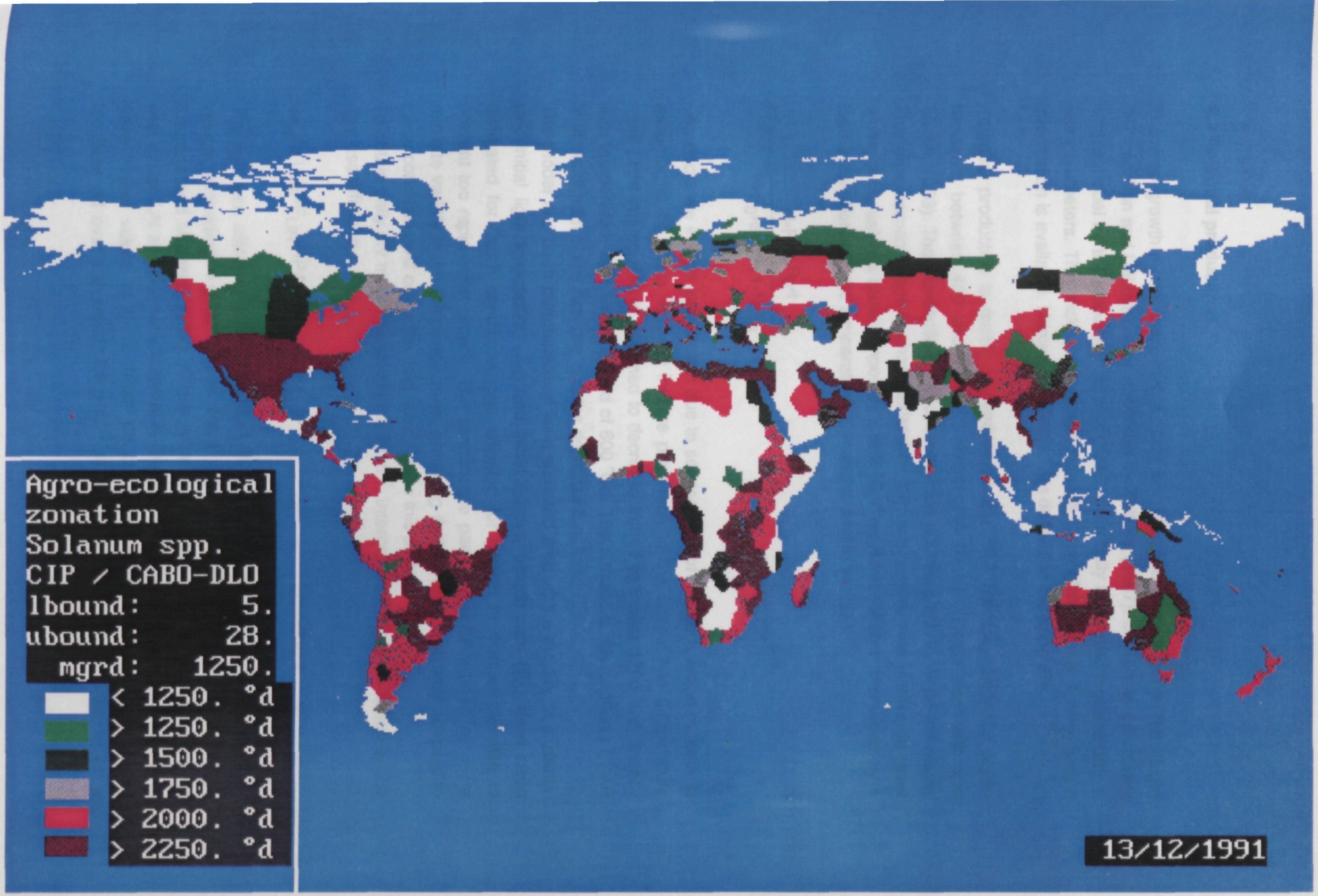
- a daily minimum temperature above 5 °C,
- a daily maximum temperature below 28 °C,
- a minimum temperature requirement of 1250 °Cd (base temp. 2 °C),
- a maximum temperature requirement of 2000 °Cd (base temp. 2 °C).

The minimum crop requirement of 1250 °Cd matches the temperature requirement of a short growing season for the production of seed-potatoes in temperate regions or that of an early maturing variety (60-days CIP-genotype) in tropical regions. The start of a growing season coincides with planting. Taking into account these specified constraints and temperature requirements, three situations may occur within a specific climatic zone within a year:

(i) temperature conditions are never suitable,
(ii) temperature conditions are sometimes suitable,
(iii) temperature conditions are always suitable.

If temperature conditions are not suitable for crop growth, (i), no growing season can be identified. If only part of the year has suitable conditions for crop growth, (ii), the procedure identifies for each climatic zone the first day that is suitable for crop growth and starts a planning procedure for 365 days onwards. The start of the first growing season is set at the first day that the daily minimum temperature exceeds the lower bound or the maximum temperature drops below the upper bound for crop growth. In the last situation, planting is assumed two weeks earlier, to accelerate the breaking of dormancy of physiologically young potatoes. The proposed growing season is terminated if the accumulated temperature sum exceeds at least the minimum temperature requirement, while the minimum or maximum day temperature reaches a value outside the defined limits, or if the maximum temperature requirement is reached while temperatures are still suitable for crop growth. If temperature has exceeded the defined limits, a next season can be identified from the first day that temperatures are within the bounds. If the maximum temperature requirement was met while the temperatures where still suitable for crop growth, the evaluation procedure was re-initialized and a second growing season may be identified, directly following the first growing season.

Up to three potato growing seasons may be identified within one year. The selected cropping calendar is not synchronized with rainfall at all, because only temperatures are taken into account. The potential durations of the growing seasons as calculated with the procedure are shown on Map 3. Climatic zones that have more than one growing season are indicated with black dots.


Agro-ecological
zonation
Solanum spp.
CIP / CABO-DLO
lbound: 5.
ubound: 28.
mgrd: 1250.
< 1250. °d
> 1250. °d
> 1500. °d
> 1750. °d
> 2000. °d
> 2250. °d
13/12/1991

Map 3

4.2 Potential production

The crop growth model used in this study is a modified version of LINTUL (Light INTerception and UtiLization) as described by Spitters (1987). LINTUL is a relatively simple model for the calculation of crop growth on a daily basis and requires only a few parameters. This makes the model suitable for a global study if only limited information is available. Names of variables are defined in the appendix.

Potential production is mainly dependent on the PAR (photosynthetically active radiation, between 400 and 700 nm) intercepted by the foliage (Monteith and Elston, 1983). The interception is a function of the phenological development stage. This development stage is characterized by the temperature sum starting at plant emergence, using a base temperature of 2 °C. The interception is described by a logistic function with the temperature sum as the driving variable:

$$F_{LINT} = \frac{N*F_0*e^{R_0*t}}{N*F_0*e^{R_0*t}+1-N*F_0} \qquad \text{Equation 1}$$

The decrease in light interception due to senescence of foliage towards maturity is assumed to be linear in direct inverse proportion to the increase in temperature sum. Light interception is assumed to decrease from 1 to 0 after 1200 °Cd, linearly with temperature sum over a period of 600 °Cd. The simulated interception of PAR is the minimum of the increase and the decrease function.

The model has been parameterized for a standard crop with a density of 4 plants m^2. Initial light interception (F_0) and initial relative growth rate (R_0) have been estimated for Dutch conditions, and adjusted for growth in warmer climates to prevent too rapid initial growth. The senescence parameters have been set for a mid late variety in the temperate zone, assuming that a variety optimally adapted to these conditions will cover the field according to this pattern.

To obtain daily dry matter production in kg m^{-2}, intercepted PAR is multiplied by the light use efficiency:

$$W_{tot} = LUE*F_{LINT}*PAR \qquad \text{Equation 2}$$

The light use efficiency (LUE) has been set at a value of 2.9 g MJ^{-1}. In literature, values exceeding 4 g MJ^{-1} have been reported (Haverkort and Harris, 1987, Khurana and McLaren, 1982). These values have been derived from experiments with a high LAI and in a rainy summer in England at low radiation levels, which both gave higher values of LUE. When we compared with experiments at different locations all over the world, 2.9 g MJ^{-1} suited well. The LUE is taken to be a

constant because little variation was expected within the temperature boundaries in this study.
Finally total tuber production is calculated by multiplying total dry matter production by a harvest index:

$W_{TU} = W_{TOT}*HI$ Equation 3

The harvest index is related to the average temperature during tuber growth (t_{av}). The potato crop partitions more dry matter to the foliage when the temperature is higher (Bodlaender, 1960, Haverkort, 1990, Figure 1). Up to 15 °C, the harvest index remains constant at 0.8, and decreases at higher temperatures to reach 0 at 28 °C.

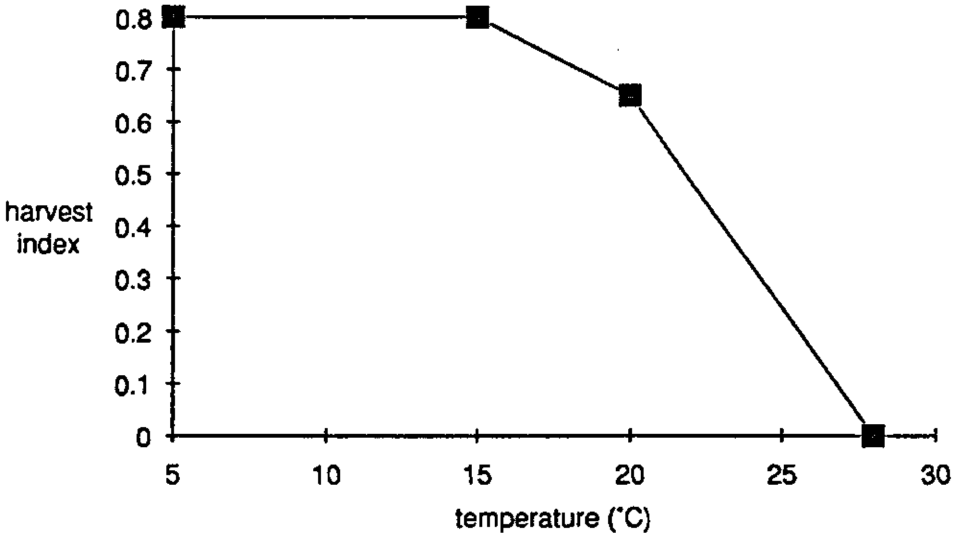


Figure 1. Effect of average temperature during tuber growth on harvest index

4.3 Water-limited production

A simple soil water balance model for a freely draining soil profile was used (Spitters and Schapendonk, 1990). The maximum rooting zone from which the crop can extract moisture for transpiration is a single homogeneous layer of 60 cm depth. The rate of change of soil moisture in this layer is calculated as:

$\delta S = I_n - P - E - T$ Equation 4

All precipitation in excess of field capacity percolates from the rooting zone. Soil surface evaporation rate is calculated according to equation 5.

$E = E_r * (1-e^{-0.7k*LAI})*F_{sm2}$ Equation 5

The E_r is the reference evapotranspiration calculated according to the Makkink equation from radiation and temperature. The factor F_{sm2} accounts for the drying of the top 2 cm, according to van Keulen and Seligman (1987). To determine the value of F_{sm2}, the soil moisture content of this layer is calculated separately. Potential crop transpiration rate is dependent on LAI, using LAI equal to 4 for the reference transpiration:

$$T_P = E_r * F_{cr} * \frac{(1-e^{-0.7k*LAI})}{(1-e^{-0.7k*4})} \qquad \text{Equation 6}$$

Actual transpiration becomes reduced, when the availability of soil moisture becomes limiting. The ratio between actual and potential transpiration is supposed to decrease linearly with soil moisture content from unity at the critical soil moisture content (Driessen, 1986) to zero at wilting point:

$$\frac{T_A}{T_P} = \frac{SM-SM_{wp}}{SM_{cr}-SM_{wp}} \text{ with } 0 \leq \frac{T_A}{T_P} \leq 1 \qquad \text{Equation 7}$$

The value of the critical soil moisture content increases with increasing reference evapotranspiration.

Two major crop growth processes were supposed to be affected by water stress: growth and leaf senescence. The level of drought stress, calculated each day, is expressed as:

$$S_d = (1 - \frac{T_A}{T_P}) - 0.2 \qquad \text{with } S_d \geq 0 \qquad \text{Equation 8}$$

The reduction by 0.2 accounts for the tolerance of the leaves to low degrees of stress. The reduction of the growth rate due to drought stress is simulated according to the relation shown in Figure 2. The effect on leaf senescence is accounted for through the cumulative value of drought stress. It is supposed that, due to accelerated leaf senescence, the crop canopy does not expand any further once the cumulative drought stress exceeds 10. From then onwards, light interception decreases irreversibly (Figure 3). Effects of water-logging were not taken into account.

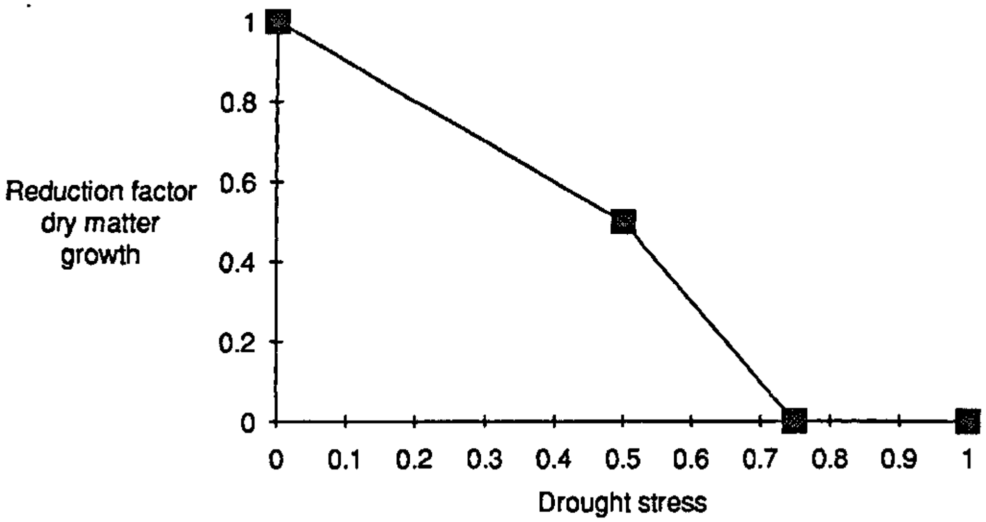


Figure 2. Effect of daily drought stress on dry matter growth

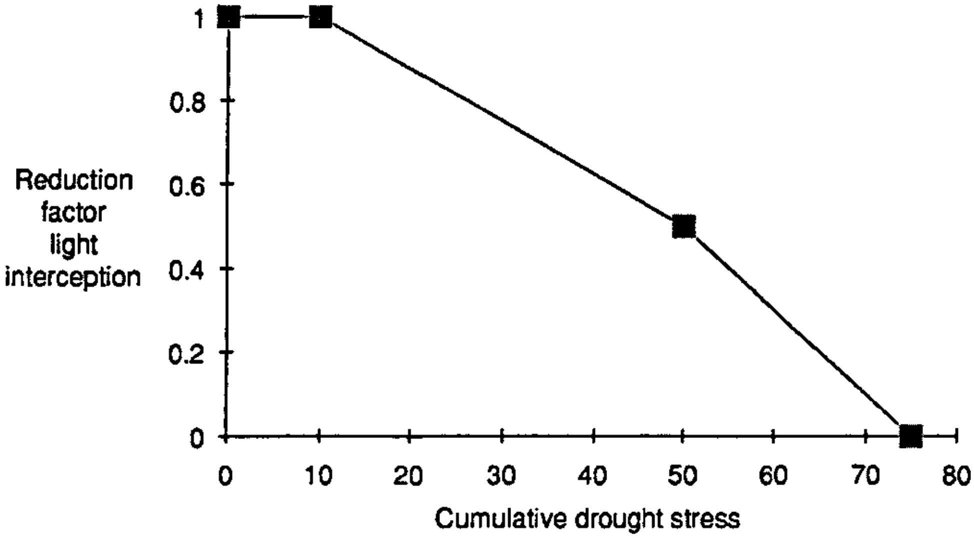


Figure 3. Effect of cumulative drought stress on light interception

4.4 Initialization

Section 4.1 explains the identification of the date(s) of planting for potential production. For simulation of water-limited production, the soil water balance has been initialized 80 days before planting, with the soil moisture content set at field capacity. During the 80 days, the soil may dry out or remain wet, depending on the local climate. After planting, for both potential and water-limited production, a temperature sum of 200 °Cd (with a base temperature of 2°C) is needed to complete emergence and start crop growth. The minimum period needed for emergence, is set at two weeks.

For potential production, one simulation run with long-term average weather was executed for each climatic zone. Water-limited yield was also calculated with long-term average weather, but for each soil type in a climatic zone a separate run was made. Yield variability due to annual fluctuations of weather is probably significant but was not evaluated in this study.

5 Simulation results

5.1 Potential production

Potential yield of the potato crop is the maximum tuber dry matter production that can be achieved given planting and harvest dates (Haverkort, 1986a). To a specific variety, potential yields are only dependent on solar radiation and temperature. All other conditions such as water and nutrient supply and pest and disease control are assumed to be optimal at this production level. Assuming temperature limits of 5 and 28 °C and a light use efficiency of 2.9 g MJ^{-1}, potential yields for the various agro-ecological zones as shown on Map 4 may be achieved in the highest yielding season. For climatic zones with more than one cropping season annually, potential yields of the second yielding season are shown on Map 5.

The frequency distribution of the yields in the highest yielding season is shown in Figure 4. They range from 2.2 to about 25 t ha^{-1} with an average close to 13 t ha^{-1}. Assuming a dry matter content in the tubers of 23%, the global mean potential fresh tuber yield is then estimated at about 56 t ha^{-1} per season. The frequency distribution of the yields in the secondary season is shown in Figure 5. The highest potential yields (Map 4) are found in the temperate zones at latitudes between 40° and 50° in the northern as well as the southern hemisphere. At higher latitudes, yields are lower because to low temperatures in spring and autumn reduce the length of the growing season. Closer to the equator, high summer temperatures reduce the length of the growing season and lead to low harvest indices. Areas with high potential yields are the tropical Highlands with suitable temperatures year-round. On an annual basis potential yields in Mediterranean climate are higher than those in the temperate zones because at least two (spring and autumn) crops can be grown.

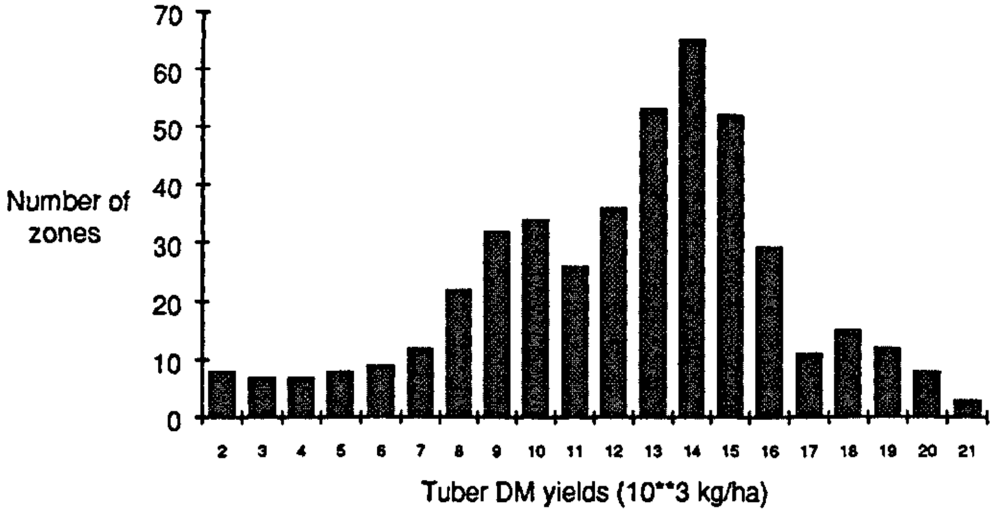


Figure 4. Frequency distribution of potential yields (dry weight) in the highest yielding season

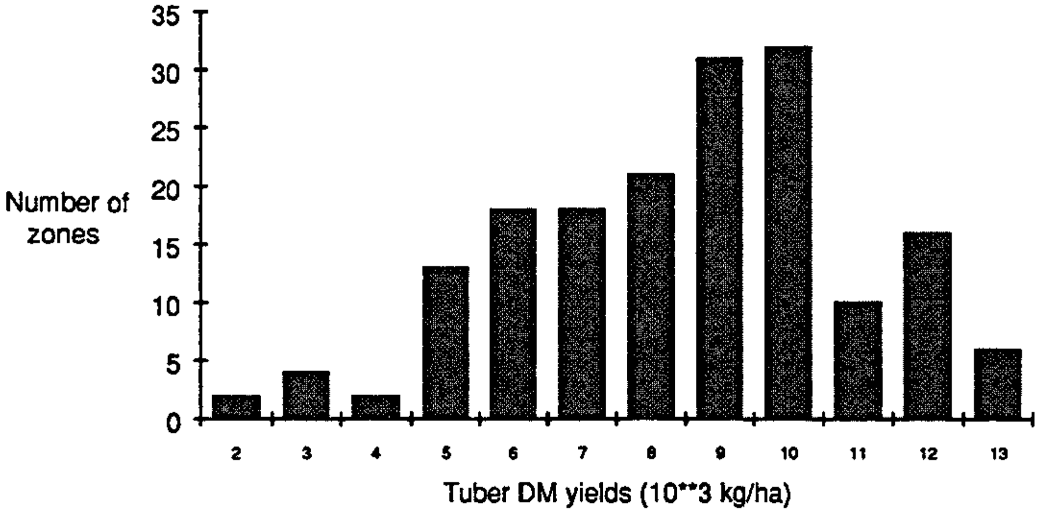


Figure 5. Frequency distribution of potential yields (dry weight) in the second highest yielding season

5.2 Water-limited production

Water-limited yields are, in addition to temperature and radiation, dependent on precipitation and soil type. Within a given climatic zone, more than one soil type may occur. The area-weighted average water-limited yields for each climatic zone are shown on Map 6. In climatic zones suitable for double cropping, only the highest yielding crop is indicated on the map. Depending on rainfall distribution over the year, the highest yielding season for potential production may not coincide with the best season for water-limited production (Figure 6). The frequency distribution of water-limited yields in the highest yielding season is shown in Figure 7. They range from 0 to about 20 t ha^{-1} with an average close to 8 t ha^{-1} (about 35 t ha^{-1} fresh weight). The highest water-limited yields (Map 6) are found in climatic zones in Canada (East), Uruguay, Ecuador, Chile, Ireland, India (South), Sri-Lanka and New-Zealand. In Latin America, yields are strongly reduced due to low precipitation in Colombia, Peru, Bolivia, Chile (South) and Argentine (Midd and South). In Africa yields are reduced north of the tropic of Cancer, and in South Africa between 20° and 30° latitude, southern latitude. In Asia strong yield reductions due to low precipitation are calculated for China (NW), Kazachstan (W) and Mongolia, in Australia in Western-Australia and part of New-South Wales. In climatic zones with large areas of soils with a low water holding capacity (textures coarse and fine), yields are more strongly reduced.

Potential minus water-limited yields are indicated on Map 7. On the basis of this map, the yield increase as a result of irrigation may be evaluated.

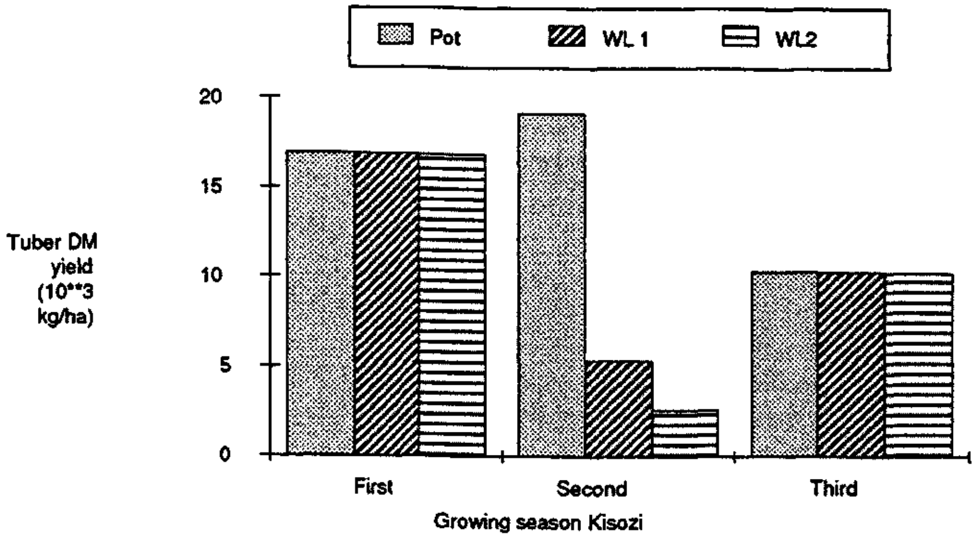


Figure 6. Potential (Pot.) and water-limited yield (WL1: soil-type with highest yield, WL2: soil-type with lowest yield), in a triple cropping in Kisozi (Burundi)

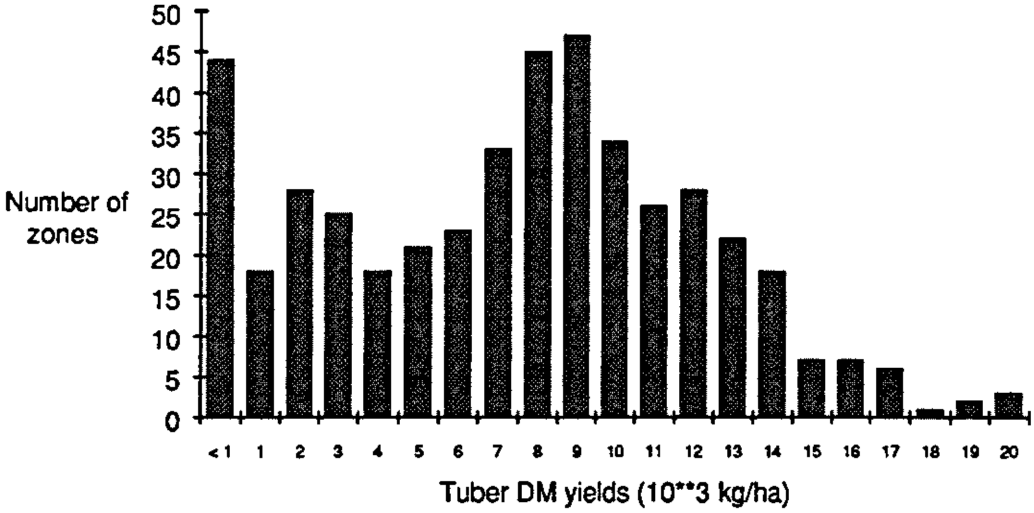


Figure 7. Frequency distribution of water-limited yield in the highest yielding season

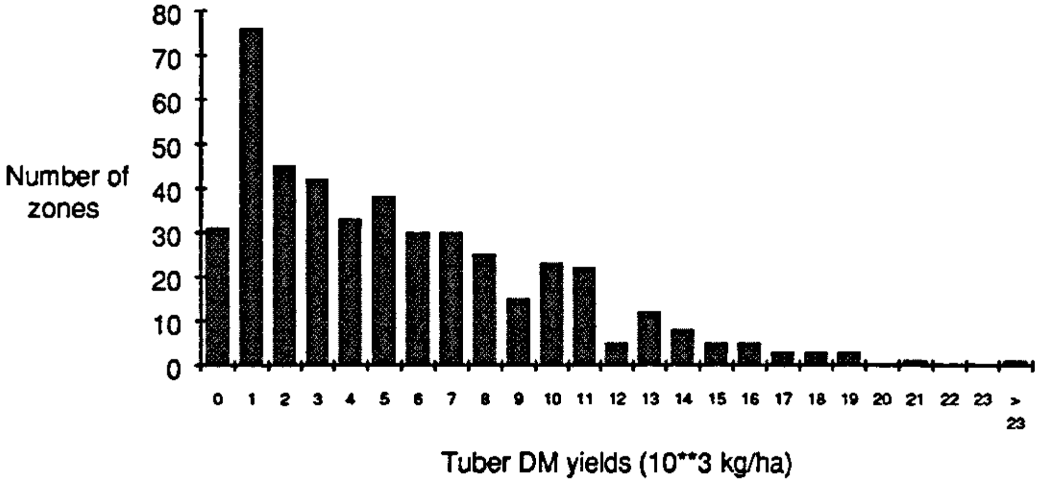
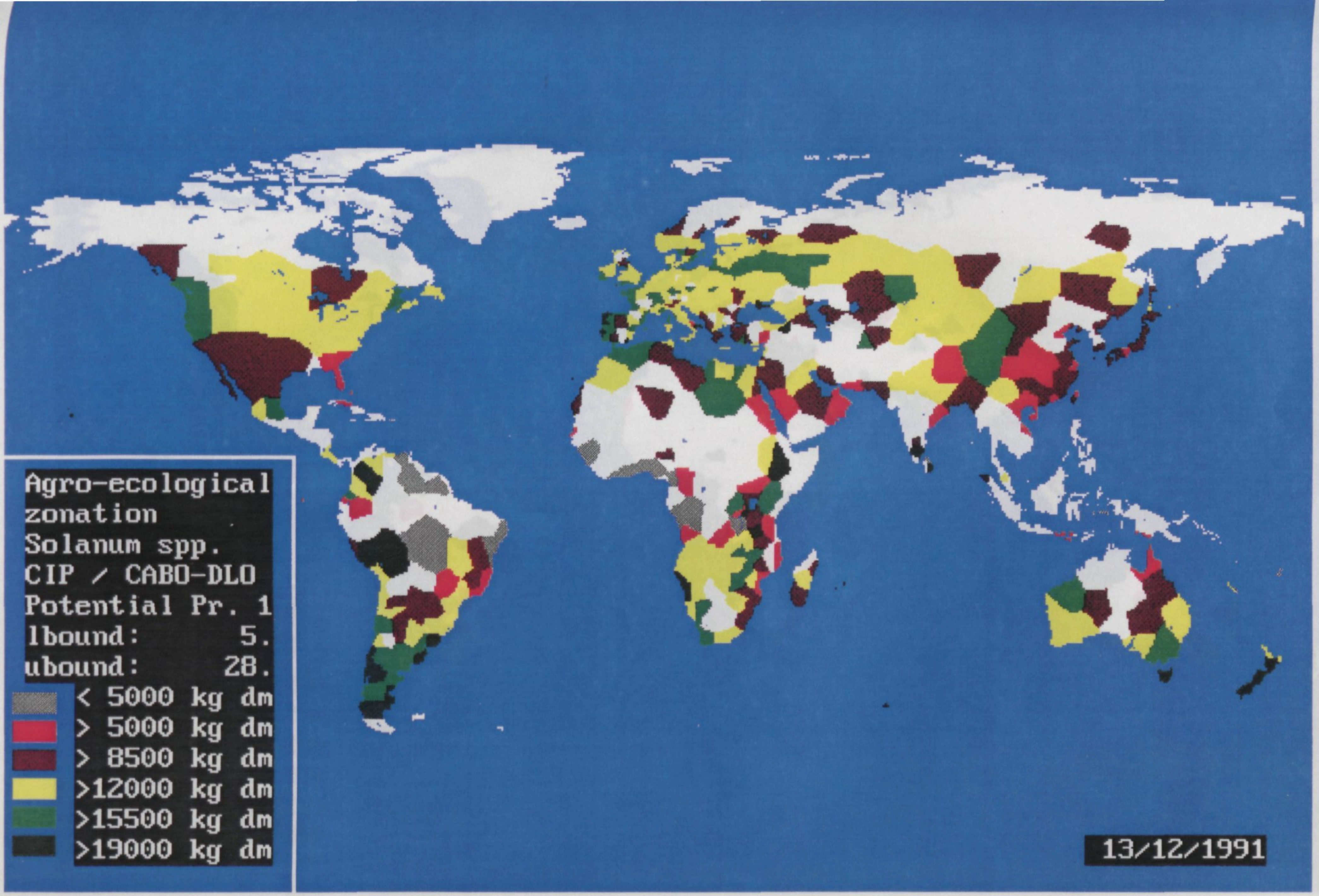
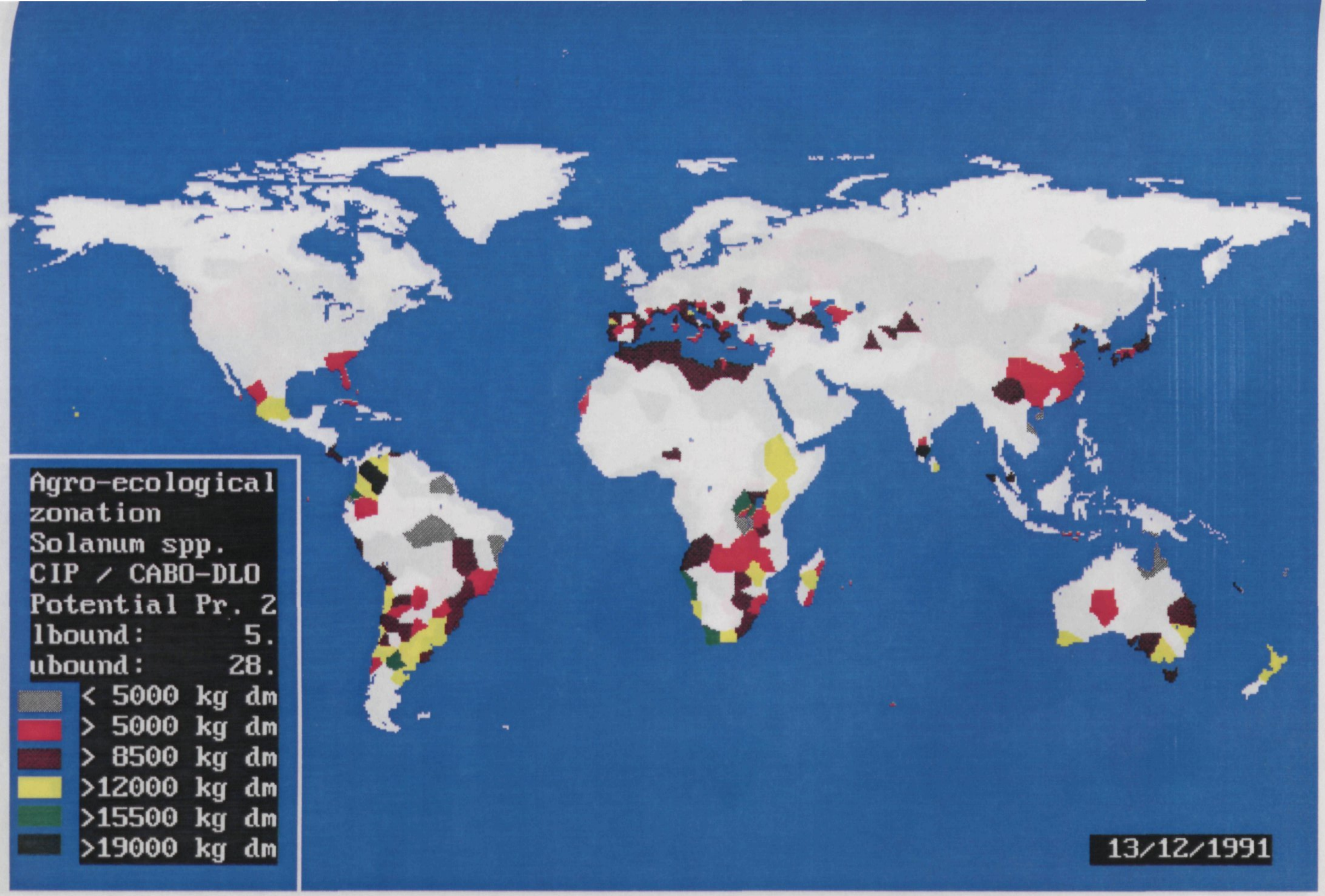


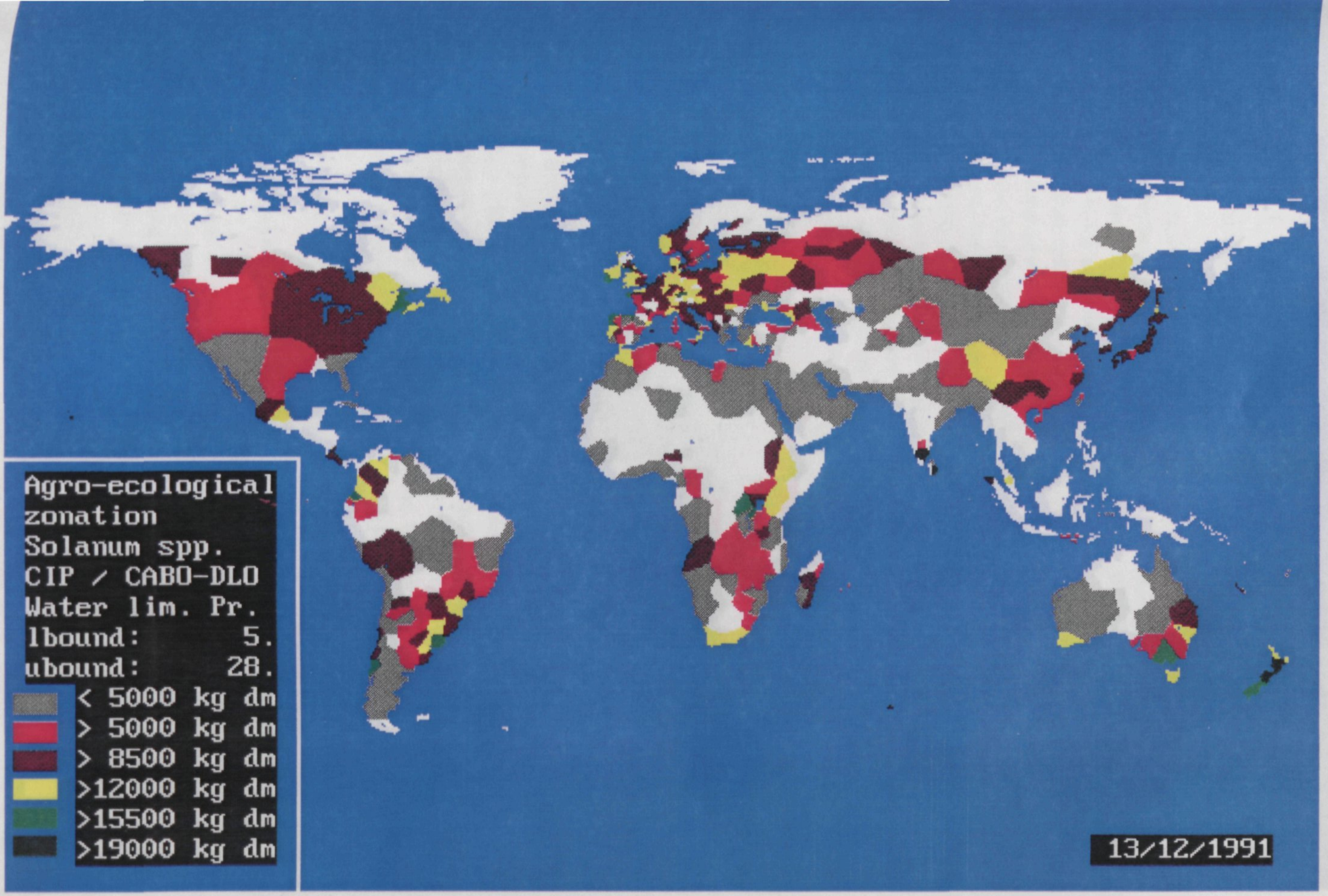
Figure 8. Frequency distribution of potential minus water-limited yields


Agro-ecological
zonation
Solanum spp.
CIP / CABO-DLO
Potential Pr. 1
lbound: 5.
ubound: 28.
< 5000 kg dm
> 5000 kg dm
> 8500 kg dm
>12000 kg dm
>15500 kg dm
>19000 kg dm
13/12/1991

Map 4


Agro-ecological
zonation
Solanum spp.
CIP / CABO-DLO
Potential Pr. 2
lbound: 5.
ubound: 28.
< 5000 kg dm
> 5000 kg dm
> 8500 kg dm
>12000 kg dm
>15500 kg dm
>19000 kg dm
13/12/1991

Map 5


Agro-ecological zonation
Solanum spp.
CIP / CABO-DLO
Water lim. Pr.
lbound: 5.
ubound: 28.
< 5000 kg dm
> 5000 kg dm
> 8500 kg dm
>12000 kg dm
>15500 kg dm
>19000 kg dm
13/12/1991

Map 6


13/12/1991
Agro-ecological
zonation
Solanum spp.
CIP / CABO-DLO
Pot minus Wat.L
lbound: 5.
ubound: 28.
▨ < 2500 kg dm
🟥 > 2500 kg dm
▨ > 5000 kg dm
🟨 > 7500 kg dm
🟩 >10000 kg dm
■ >12500 kg dm

Map 7

6 Comparison of simulated with measured yields

Potential yields depend on weather conditions and varietal properties, in this study, they are considered to be fixed, ceiling yields. However, higher potential yields could be reached with varieties with an extended period of foliar productivity. Lengthening the period of the presence of an active green foliage may be obtained through increased frost resistance and adaptation to low temperatures on one hand, or through increased adaptation to high temperatures on the other.

Furthermore, an increase in productivity may be achieved through genotypes that have a higher light use efficiency. Such cultivars may for instance keep the stomata open at periods during the day with a high evaporative demand of the atmosphere. Another means of increasing crop productivity is a more favourable pattern of dry matter distribution favouring tuber production over the production of foliage.

Water-limited yields can furthermore in some situations be improved by a better developed root system and improved drought resistance.

6.1 Experimental yields

'Experimental yields' are defined here as those obtained in experiments carried out by research institutes with genotypes that make best use of the available growing season (daylength adapted) and with an optimal supply of inputs such as irrigation, fertilizers and disease and pest control measures. Such yields are often not economically justified, as many input levels are well above those required for economically optimal dose responses. Experimental yields are closest to potential yields and the difference is often a matter of a few tonnes per hectare. Such differences are due to the unpredictability of the weather as the maximally required inputs are based on long-term weather expectations. The actual weather in a given experimental season may deviate from the long-term average, making certain levels of input (nitrogen supply for instance) sub-optimal. Experimental yields occasionally may be aimed at to validate model performance for potential production. The gap between experimental and potential yields may be more difficult to close in adverse climatic conditions for potato growth than in more suitable conditions, as many factors leading to reduced yields are not fully understood or unknown.

6.2 Attainable yields

'Attainable yields' are defined in this study as the yields that the best farmers can economically obtain when applying all available techniques. Attainable yields are often considerably lower than experimental yields, because the expected rates of return are so low that their application is too risky.

Figure 9 shows the relationship between the calculated potential yields for nine selected sites and their attainable yields. The latter were obtained in the global CIP-Canadian experiments carried out in the mid-eighties (Tai & Young). NARC's around the world received a set of genotypes and were invited to grow them under the best farmer's conditions. The proportion of the potential yield that was attained varied from 0.4 to 0.8, depending on the degree of adaptation of the best genotype to the environmental conditions and on unpredictable hazards, such as excessive rainfall causing an epidemic of late blight or an unexpected dry spell where the crop depended on rainfall only. Moreover, the calculation of potential yield was based on long-term average weather data and not on the actual weather data of the season in which the crops were grown. It is a general observation that attainable yields are about 50% of the potential yields. This ratio hardly differs in temperate or warmer climates. The best farmers in the Netherlands attain about 60 t ha^{-1}, whereas 120 t ha^{-1}, is calculated as the potential yield. Similarly, a Tunisian farmer obtains around 40 t ha^{-1} where 80 t ha^{-1} is the potential.

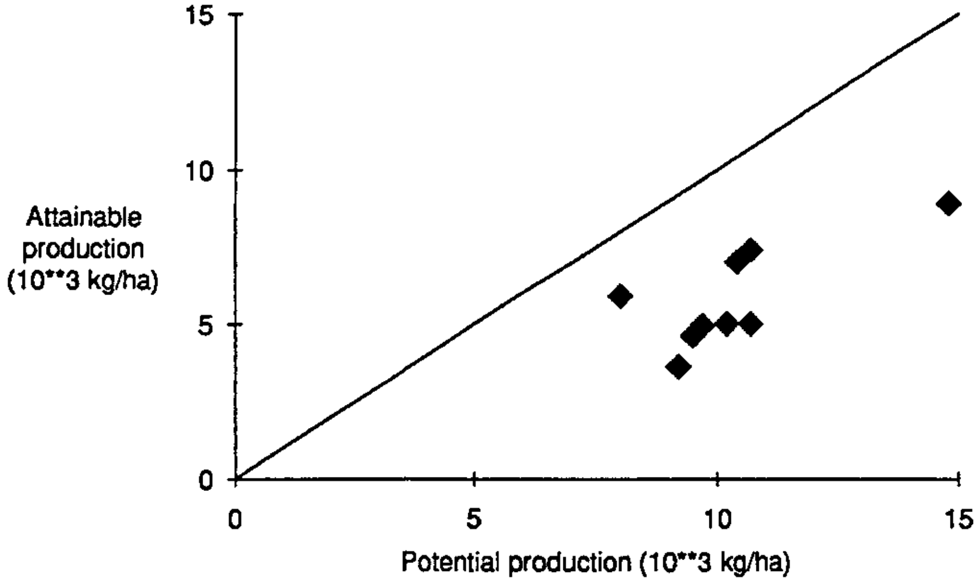


Figure 9. Attainable versus potential production

6.3 Actual yields

'Actual potato yields' are defined in this study as those obtained in a region under the prevailing meteorological conditions under the current level of inputs with the cultivars used. In temperate climates, actual yields are often closer to attainable yields than in tropical conditions, where less inputs and sometimes less adapted cultivars are used. Actual yields in Africa presently are about 8 t ha^{-1} and in Europe about 35 t ha^{-1} (Horton, 1988).

The calculation of potential yields allows comparison with the other yield levels: experimental, attainable and actual yields. The ratio's between these various yield levels and the potential yield level provide indications for the amount of inputs needed to increase yields. The lower the ratio, the more effective cultural practices, disease and pest control measures, the use of healthy seed and the introduction of more adapted genetic material are likely to be.

7 Sensitivity of potato production for elevation

One of the inaccuracies in this study, originates from the difference in elevation between a specific weather station and the area allocated to that station. Since temperature decreases with elevation, the altitude of the weather station is crucial and should be representative for the area it is allocated to. This factor may be important because 201 of the 978 stations in the Müller database have an elevation of more than 500 meter above sea level. When considering the implication of elevation effects on agro-ecological characterization, a distinction must be made between tropical and temperate regions. The production potential and the suitable area will be overestimated in tropical climatic zones when the weather station has an elevation higher than representative for the allocated zone. When the elevation of the station is lower than that of the allocated zone, both the production level and the suitable area will be underestimated. In temperate regions the effects will be opposite.

To test the sensitivity for elevation of both the identification procedure of growing seasons and the simulation model for potato production, the model was executed for a specific site in Burundi, the weather station Kisozi (elevation 2155 m above sea level). Number and length of the growing season(s) were determined by the identification program, potential production was subsequently calculated with the simulation model. A total of 12 reruns were made with the production model at 0, 1000, 2000 and 3000 meter above sea level (table 3). Using an adiabatic moist lapse rate of -0.6 °C per 100 meter, both minimum and maximum monthly temperatures were adapted with +12.9, +6.9, +0.9 and -5.1 °C respectively. The effect of a reduced pressure of CO_2 is small and was neglected.

The results are shown in table 3.

Table 3. Number, length and production of growing seasons in elevation sensitivity runs in Kisozi, Burundi, 3.5 °S, 2155 m elevation.

	0 m	1000 m	2000 m	3000 m
Season	unsuit	unsuit	1/1-7/5	18/9-8/3
Pot. Prod.	-	-	15500	26700
Season	-	-	8/5-21/9	-
Pot. Prod.	-	-	18000	-
Season	-	-	22/9-31/12	-
Pot. Prod.	-	-	12900	-

No potato growing season could be identified below 1000 meter because maximum temperatures exceed the specified upper bound for potato growth throughout the year. At 2000 meter above sea level, close to the elevation of the weather station, three seasons have been identified within one year. Two growing seasons, from January 1st till May 7th, and from May 8th till September 21st are characterized by the maximum temperature requirement of 2000 °Cd. From September 22nd a shorter growing season is possible which should be harvested before crop senescence. The potential production in these three growing seasons is 15500, 18000 and 12900 kg tuber dry weight per ha, respectively. At an elevation of 3000 meters above sea level, one long growing season has been identified with a production of 26700 kg per ha.

8 Discussion

The length of the growing season was best described by assuming that no crop growth is possible when the daily minimum temperatures are below 5 °C or the maximum temperatures are above 28 °C. Increasing the lower limit would exclude too many cool areas such as regions above 60 ° northern latitude or high mountainous areas. Lowering the maximum temperature would have resulted in exclusion of relatively warm sites and/or warm parts of the growing season, whereas the potato presently evidently is grown in such areas and parts of the year. Comparing the maps of agro-ecological characterization for potato crops of the present study with the survey map of areas where the crop is actually grown (FAO, 1978,1980,1981, Rhoades, 1987, CIP, 1991), it appears that the survey areas are much more limited in space than the suitable areas emanating from this study. This may be due to the assumptions underlying the calculations of potential production. In many areas potato could possibly be grown if precipitation or irrigation water would be available and or if the soils had sufficient water holding capacity to sustain a potato crop.

The outcome of this study was compared to an agro-ecological characterization study conducted recently in the EC (Van Lanen et al., in press). The results of the current study where consistent in trend and showed good agreement for potential production. In the Mediterranean area our results indicate higher water-limited yields, because of a preference for winter-crops, instead of crops planted in spring.

A number of options exist to refine the current study:

Availability of additional long-term weather data bases from agricultural research stations could increase the location specificity of the study.

Refining the weather data base on the basis of a geographical map with elevation would also lead to more detail.

The suitable area for potato production (Map 3) would be reduced by increased knowledge of the distribution of the precipitation, by knowledge of where irrigation possibilities exist and by more detailed soil maps than the one used in this study.

The current study may relatively easily be extended to include sweet potato but presently crucial crop characteristics were not available at CABO-DLO.

By including different crops in a rotation, optimal lengths of the growing seasons for each crop may be assessed and potential potato production for the proper length of the growing season may be calculated.

Production constraints such as lack of fertilizers or late blight pressure could be included in the study to gain insight in production levels below potential or water-limited yield.

Refinement of the characterization may increase further the relevance of the simulation results for strategic decisions for research planners and policy decision makers. Present production systems based on a combination of crops, such as potato and maize (Peru), potato and wheat (Turkey) or potato and rice (Madagascar) could be evaluated in terms of their potential to feed increasing populations. Aiming for longer or shorter growing seasons of one crop or the other will yield information on which system may produce the largest amount of food on an annual basis. Added information on the nutritional value of the various commodities may be an asset to arrive at a more balanced diet.

For breeding purposes a further refinement, especially with regard to the adaptation of the crop to higher and lower temperatures may be useful. Decreasing the lower limit of 5 °C will only be possible if increased frost resistance is incorporated in the cultivars grown in areas with a cold start and/or end of the growing season. Simulation can show what the global impact of frost resistance will be and which areas will benefit most from such a trait. A combination of adaptation to low and high temperatures will be beneficial in continental climates with frost in winter and rapidly increasing temperatures in spring.

Agro-ecological characterization may also be used to estimate the influence of global climatic changes. If temperatures rise by 2 °C, what will be the influence on the distribution of the potato crop ?. In the tropics the crop will move to higher elevation and in the temperate zones to higher latitudes. In the latter case, cultivars which are adapted to longer photoperiods will be needed.

9 Acknowledgements

The authors would like to thank Rik Leemans from the Dutch National Institute for Public Health and Environmental Protection (RIVM) for supplying both the IIASA and the Müller database with global weather data. The help of Lex Bouwman, from the same Institute, is acknowledged for his assistance in getting access to the global soil database by NASA.

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Appendix 1 List of variables

VARIABLE	MEANING	Value	UNITS
δS	daily rate of change in soil moisture		$(mm\ d^{-1})$
d	duration of leaf senescence	600	(°Cd)
E	soil evaporation		$(mm\ d^{-1})$
E_r	reference evapotranspiration for short grass		$(mm\ d^{-1})$
F_0	initial light interception capacity per plant	0.0012	$(MJ\ plant^{-1})$
F_{LINT}	light interception		$(MJ\ m^{-2})$
F_{cr}	cropfactor	1.1	(-)
F_{fsm2}	factor reducing soil evaporation because of drying out of top 2 cm.		(-)
HI	harvest index	$f(t_{av})$	(-)
I_n	infiltration from precipitation		$(mm\ d^{-1})$
k	extinction coefficient for PAR		(-)
LAI	leaf area index		$(m^2\ m^{-2})$
LUE	average light use efficiency	2.9	(gMJ^{-1})
N	plant density	4	(m^{-2})
P	percolation to layers below the root zone		$(mm\ d^{-1})$
PAR	incoming photosynthetically active radiation		$(MJ\ m^{-2}\ d^{-1})$
R_0	initial relative growth rate	0.0012	$(°C^{-1}d^{-1})$
SM	actual soil moisture content of the soil		$(cm^3\ cm^{-3})$
SM_a	soil moisture content at air dryness		$(cm^3\ cm^{-3})$
SM_{wp}	soil moisture content at wilting point		$(cm^3\ cm^{-3})$
SM_{fc}	soil moisture content at field capacity		$(cm^3\ cm^{-3})$
SM_{cr}	critical soil moisture content		$(cm^3\ cm^{-3})$
T	crop transpiration		$(mm\ d^{-1})$
T_r	transpiration reduction factor		(-)
t	temperature sum		(°Cd)
t_{av}	average temperature during tuber growth		(°C)
t_{50}	temperature sum when 50% of the leaves have died	1500	(°Cd)
W_{TOT}	total dry matter		$(g\ m^{-2})$
W_{TU}	tuber dry matter		$(g\ m^{-2})$

Acronyms

CABO-DLO - Centre for Agrobiological Research
CG - Consultative Group on International Agricultural Research
CIP - International Potato Center
LINTUL - Light INTerception and UtiLization model
NARC - National Agricultural Research Center