Estimating the potential impact of frost resistant potato cultivars in the Altiplano (Peru and Bolivia)

R. J. Hijmans1, B. Condori2, R. Carrillo2, and M. J. Kropff 3

Abstract

Frost damage causes significant losses in potato production in the Altiplano (Peru and Bolivia). We quantified the extent to which frost resistant cultivars could alleviate this problem, using a quantitative and constraint-specific agroecological zonation approach. The LINTUL potato growth simulation model was adapted to incorporate the effect of frost damage on yield, and calibrated using experimental data. High-resolution grids of monthly climate data were created for a number of variables, including absolute minimum temperature and its standard deviation, and used as input for the simulation model. The model was run for each grid cell, using a standard potato cultivar in which frost resistance parameters were changed in increments of 1°C. A geo-referenced database of potato distribution was used to process the output of the simulation model to calculate potato-area weighted results. The results indicate that when frost resistance increases from –1°C (current level) to –2°C or –3°C, average potato yield would increase 26 and 40%, respectively. After that, the effect flattens off and a further increase in resistance leads to only a small increase in simulated potato yield.

INTRODUCTION

The Altiplano is a high plateau in the Andes of Peru and Bolivia. In this study we focus on the part of the Altiplano called the TDPS system, named after the catchment of Lake Titicaca, the Desaguadero River, Lake Poopó, and the Salt Lake of Coipasa (OEA, 1996) (Figure 1). That excludes the southernmost part of the Altiplano, which is rather arid, sparsely populated, and less important for agriculture. Seventy-five percent of the TDPS system, hereinafter called the Altiplano, is between 3,600 and 4,300 m above sea level; the other 25% is higher. It comprises 149,000 km². Lake Titicaca, covering 8,400 km², is a conspicuous part of the topography that greatly influences local precipitation and temperature.

In 1993, the Altiplano had about 2.2 million inhabitants (OEA, 1996). The Altiplano is one of the poorest areas of the Americas, and poorer than most other parts of Bolivia and Peru. About 65% of the economically active population is engaged in agriculture (OEA, 1996). Most of the cropland is located below 4000 m; above that elevation land is used for grazing. Potato is by far the economically most important crop, accounting for 63% of the gross value of crop production (OEA, 1996). The area planted to potato is about 63,000 ha (G-DRU, 1996; INEI, 1996). Reported potato yields are low, at 5.2 t/ha in the Peruvian and northern Bolivian sections of the Altiplano, and 3.6 t/ha in the southern part of the Bolivian section (OEA, 1996; G-DRU, 1996). However, an extensive survey in four Departments of Bolivia (outside of the Altiplano) indicates that government statistics have underreported yields by as much as 50% (Terrazas et al., 1998).

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The growing season in the Altiplano extends between October and March, when maximum annual temperature coincides with the rainy season. In the agricultural zones, maximum temperature is around 18°C and minimum temperature around 4°C during the growing season (INTECSA, 1993; Frère et al., 1975). Precipitation is highest in the northeast and in peripheral areas of Lake Titicaca, around 800 mm/year, and lowest, about 200 mm, in the southwest. Production risk for potato is high due to a variety of factors, particularly drought, hail, and frost. Although there is an average frost-free period of about 140 d for the northern Altiplano and 110 d for the southern Altiplano (Le Tacon, 1989), night frosts caused by radiative cooling on clear nights may occur at any time during the growing season. The mid-season frost problem is common throughout the tropical highlands: see, e.g., Knapp (1988), for a description of frost incidence and potato production in Ecuador. However this is unlike potato production conditions in temperate regions, where frosts occur only at the beginning and end of the growing season. Booy (1961) describes a case of night frost damage on potatoes in the beginning of the growing season in the Netherlands.
Frost occurs when air temperature near the Earth’s surface drops below 0°C (Kalma et al., 1992). When frost damage is described in the literature, it is not always clear whether the reported temperatures refer to conditions at screen height (1.5 to 2 m) or at crop canopy height. In this study, temperature refers to screen height conditions. During a frost event, air temperature may be as much as 1°C lower at potato canopy height (De Bouet du Portal, 1993), and leaves might be colder still. The temperature at which frost damage occurs depends on the species and the cultivar. For S. tuberosum subsp. andigena, the most commonly grown potato in the Andes, frost damage is likely to occur when the temperature drops to -2°C or lower (Carrasco et al. 1997). Higher frost resistance exists in other cultivated and wild potato species. For example, cultivated potato species such as S. ajanhuiri and S. curtloobum incur damage at -3 to -5°C (Huanco, 1992; Tapia and Saravia, 1997), whereas S. jupezpuckii generally resists temperatures down to -5°C and lower (Huanco 1992, Canahua and Aguilar 1992, Tapia and Saravia 1997). With the exception of S. ajanhuiri, the tubers of the species with higher frost resistance tend to be bitter due to high levels of glycoalkaloids and therefore require processing before consumption. Henceforward, non-tuberosum cultivated potato species will be referred to as “bitter potatoes”.

Hijmans (1999) estimated that 25% of total area planted to potato in the Altiplano has an extremely high (> 33 %) frost risk of a -2°C event occurring once every 3 yr. He concluded that this high-risk area is most likely planted with bitter potatoes. This was supported by Canahua and Aguilar (1992) and Huanco (1992), who estimate that about one-third of total potato area of the Peruvian Altiplano is planted with bitter potatoes, of which 60% are S. jupezpuckii, and 33% are S. curtloobum (Canahua and Aguilar 1992). It was also supported by Rea’s (1992) estimate that bitter potatoes comprise 15% of total potato area in Bolivia, where more bitter potatoes are found in the Altiplano than in most other zones.

Frost can cause partial or complete loss of leaf area of a potato crop, leading to a reduction in photosynthesis and hence yield. In turn, crop failure caused by frost damage may lead to a decrease in the total area planted to potato in the subsequent season due to seed shortage (Morlon 1989). The high production risks presented by frost and other factors may also lead to less investment in agriculture, resulting in decreased production, despite of the weather conditions in a given year.

Farmers can prevent or reduce frost damage by planting potatoes on warm soil (with a high thermal conductivity, (cf. Booy 1961)) and on slopes, where frost incidence is lower than on the valley floor (De Bouet du Portal 1993); applying frost-related management practices such as the use of smoke, rustic greenhouses (Aguirre et al. 1999), and raised beds (Sánchez de Lozada et al. 1998); and planting frost resistant potato cultivars. Since the latter method is the most practical, a breeding program has been established that aims to produce frost resistant potato cultivars similar to S. tuberosum (Carrasco et al. 1997). Previously, successful breeding for frost resistance had been reported in the USA (Dearborn 1969). This paper assesses the potential impact of potato cultivars with increased frost resistance in Bolivia. This assessment is carried using a framework for quantitative and constraint-specific agro-ecological zonation.

Agroecological zones (AEZs) stratify an area into environmentally homogeneous domains usually derived from climate and soil data (e.g., FAO 1978-81, Kassam et al. 1991). AEZs are useful for selecting test sites, interpreting experimental data, targeting technology, setting research priorities, and ex-ante impact assessment (Wood and Pardey 1998). For example, Gryseels et al. (1992) used AEZs to set priorities for the Consultative Group on International Agricultural Research (CGIAR). AEZs can be classified as generic or specific, and as quantitative or qualitative. Qualitative AEZs can be ordinal or not. The International Potato Center (1991) uses a generic, qualitative zonation for global potato production. This zonation divides global potato production into 6 zones ranging from “temperate” to “subtropical lowland”. Generic zonation was also used in a FAO (1978-81) study in which production areas were divided into four ordinal zones and designated “very suitable” to “not suitable” for rainfed potato. Stol et al. (1991) and Van Keulen and Stol (1995) developed a generic and quantitative zonation, using a simulation model and a climate and soil database within a Geographic Information System to calculate potential and water-limited yield for global potato production.

The generic character of the AEZs described above makes them useful as a general reference that can be understood intuitively. However, they are difficult to use when addressing specific research questions. Facilitated by the progress in information technology and the development of geo-referenced databases, more flexible and specific approaches to agroecological zonation are emerging (Wood and Pardey 1998, Corbett 1998). Hijmans (1999)
produced a specific zonation for frost-risk in potato on the Altiplano in which interpolated, monthly, extreme minimum-temperature data were used to calculate the probability of absolute minimum temperature events throughout the year. Hijmans (1999) concluded that the introduction of potato cultivars with increased frost resistance could strongly reduce frost damage. If frost resistance in potato increases from -1 to -2°C, and damage only occurs at -3°C and lower, the percentage of the current potato area with a frost event less than once every 10 yr nearly doubles, increasing from 18 to 32%. However, this study did not quantify the potential effect on yield of a potato cultivar with increased frost resistance.

To estimate the potential impact of a new agricultural technology such as a frost resistant potato cultivar, Wood and Pardey (1998) advocate the use of specific agroecological zonation for the problem at hand and then to estimate changes in yield or production costs for each zone. Estimating yield loss due to frost damage is difficult because it depends on the probability as well as the timing of an absolute minimum temperature event. For example, a frost event of a specific magnitude in the middle of the growing season will have a sharply different effect on yield than one that occurs at the end of the growing season as most potatoes will have been formed by then. Eliciting estimates on frost-induced changes in yield from experts or farmers is one alternative (Valdivia et al. 1997), but may result in highly subjective data. Producing a good estimate for a large heterogeneous area can prove to be very difficult.

This study demonstrates how crop growth simulation models provide a useful alternative to eliciting techniques or classification criteria in determining yield change from frost damage. Crop growth simulation models are mathematical description of a crop’s response to the environment. They encapsulate our knowledge of eco-physiological processes, and they can be used to process environmental data as to produce easy-to-interpret output such as yield. By comparing the output of different model runs e.g., representing current and new technology, the effect of technology adoption can be estimated. Instead of estimating differences for predefined agroecological zones, the model is run for small grid cells and the results can be aggregated by, e.g., administrative unit, or by production zone. Agroecological zones can be formed after the calculations, using the model output.

MATERIAL AND METHODS

General framework

The general framework for constraint-specific and quantitative agroecological zonation is illustrated in Figure 2. As opposed to generic zonation approaches, the study is driven by a specific question. The framework is flexible in the sense that the different types of data used, and how they are combined, depends on the specific problem at hand as well as data availability. Model choice depends on what is available and on the type and scale of corresponding input data that is needed. In most cases, this includes data on weather and soil. Once models are selected, different model runs can be compared using ancillary data to interpret and aggregate output. Ancillary data will typically include crop distribution and administrative boundaries.

Simulation model

A slightly modified version of the LINTUL potato growth simulation model (Spitters, 1987; Stol et al., 1991) was used. The LINTUL model is based on a thermal-time dependent description of ground cover. Ground cover is used to calculate intercepted radiation, and a constant radiation-use efficiency (RUE) parameter is used to calculate dry matter production. Allocation of dry matter to the various organs is thermal-time dependent. The effect of frost was modeled using a simple damage function in which loss of ground cover is described as a linear function of minimum temperature between two temperatures: the “critical temperature” ($T_{cr}$) and the “leaves-dead” temperature $T_{ld}$ (Figure 3). Above $T_{cr}$ there is no frost damage. If temperature drops below $T_{ld}$, all leaves are lost. This type of relation was described by Sukumaran and Weiser (1972) for excised leaflets of different potato cultivars and species. Subsequent ground cover expansion is also reduced by frost, depending on a linear function between $T_{ld}$ and the regrowth temperature, $T_{rg}$. Even at $T_{ld}$ when the crop loses all its leaves, the crop may continue to grow. However, when the temperatures drop below $T_{rg}$ growth ceases. We assume that frost does not have an effect on the radiation-use efficiency of the remaining foliage.

The simulation model was calibrated for the native potato cultivar ‘Gendarme’ using data collected during field trials in Patacamaya (La Paz Department, Peru).
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Bolivia) in the 1998/99 season. In this experiment the potato crop did not suffer any significant stress, although the growing season ended somewhat prematurely due to a number of frosts. Ground cover expansion parameters were derived by fitting the curves with biweekly observations. Radiation-use efficiency was calculated using observed ground cover and biomass from four sequential harvests. The parameters for dry matter distribution between foliage and tubers were also estimated from the sequential harvest data. The model was validated with data from Poni (Department of La Paz, Bolivia) in 1996/97. In Poni there was a mid-season, -2°C frost on February 1, 1997 that led to considerable damage of crop foliage. Planting distance (0.7 x 0.3 m) and all other crop management practices, such as fertilization, were similar in both trials.

Weather data

A weather database described by INTECSA (1993) was used. The database consists of data from 139 weather stations (Figure 1). For most weather stations there are at least 30 years of monthly records of total precipitation and average minimum and maximum temperature data. There is also a considerable amount of data on monthly extreme minimum temperature (44 stations), and other climate variables.

Monthly climate surfaces were generated for minimum and maximum temperature, absolute minimum temperature and its standard deviation, and solar radiation. The ANUPLIN program developed by Hutchinson (1995, 1997) was used to interpolate climate data from weather stations and produce high-resolution climate surfaces (grids). ANUPLIN fits Laplacian smoothing spline functions of two or more independent variables (longitude, latitude, and usually elevation) through the climate observations. This method relies on the strong dependence of climate (especially temperature) on elevation, but allows the size of this dependence to vary over time and space (Corbett, 1998). Elevation data was taken from the U.S. Geological Survey’s GTOPO30 database, and used as an independent co-variable. The GTOPO30 and climate surface data have a resolution of 30-arc seconds (approximately 1 km²).

Figure 2. Flow diagram for quantitative and constraint-specific agroecological zonation using a simulation model and georeferenced databases.
Figure 3. Description of frost damage (relative fraction of ground cover loss) as a function of minimum temperature for a standard S. tuberosum ssp. andigena potato cultivar from the Altiplano (T_cr = -1, T_ld = -3). Estimated from Carrasco et al. (1997) and the Pomani experiment.

As the simulation model needs daily weather data, these were generated from the monthly climate data. For each grid cell 100 years of synthetic weather were generated to run the simulation model. Daily minimum and maximum temperatures were calculated by linear interpolation of the monthly averages. On one random day of each month, minimum temperature was simulated, using a random value drawn from a normal distribution described by the monthly average extreme minimum temperature and its standard deviation.

Potato distribution

A geo-referenced potato distribution database was created for the Altiplano. District level census data (INEI, 1993) was used for Peru, and departmental level census data (G-DRU, 1996) and maps of crop distribution (ZONISIG, 1998) were used for Bolivia.

Estimating the effect of resistance

The potential yield of ‘Gendarme’ was compared with the potential yield of constructed genotypes that differed from ‘Gendarme’ in their level of frost resistance only. Frost resistance was described with functions like the one in Figure 3. The parameters used are presented in Table 1.

In the Altiplano, most potatoes are planted in October or November and harvested in April or May. For this study, we fixed emergence arbitrarily at November 25. Because of the stochasticity of the weather generator, the model was run 100 times per grid cell, once for each generated “year”. The model outputs were averaged by grid cell and treatment. Then, the relative yield difference between these averages was calculated by grid cell. These results were weighted by the potato area in each grid cell and tabulated.

Table 1. Different levels of frost resistance used in the simulations. No damage occurs above critical temperature T_cr [°C]. At T_ld, 100% of the foliage is damaged. When temperatures drop below T_rg, the crop stops growing. R-1 is the current level of resistance in Solanum tuberosum ssp. andigena.

<table>
<thead>
<tr>
<th>Resistance level</th>
<th>T_cr</th>
<th>T_ld</th>
<th>T_rg</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>0</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>R-1</td>
<td>-1</td>
<td>-3</td>
<td>-4</td>
</tr>
<tr>
<td>R-2</td>
<td>-2</td>
<td>-4</td>
<td>-5</td>
</tr>
<tr>
<td>R-3</td>
<td>-3</td>
<td>-5</td>
<td>-6</td>
</tr>
<tr>
<td>R-4</td>
<td>-4</td>
<td>-6</td>
<td>-7</td>
</tr>
<tr>
<td>R-5</td>
<td>-5</td>
<td>-7</td>
<td>-8</td>
</tr>
</tbody>
</table>

RESULTS

Model calibration

Based on the 1998 experiment, crop growth duration of ‘Gendarme’ (between emergence and senescence) was estimated at 1250°Cd (base temperature = 0°C), with tuberization starting at 500°Cd after emergence. Radiation-use efficiency was estimated at 2.5 g/MJ (PAR), a value comparable to those reported in the literature (cf. Stol et al., 1991).

The simulation model somewhat overestimates ground cover and biomass production in the 1996 experiment (Figures 4 and 5). This can partly be ascribed to growth reduction due to excess water in the experimental field. More data would be needed to further calibrate the model, but we considered it sufficiently accurate for use in this explorative study.

Effect of increased resistance

Changing frost resistance in ‘Gendarme’ leads to significant changes in simulated potential yield. The change in simulated potential potato yield when frost resistance (T_cr) in ‘Gendarme’ is increased from -1 to -2°C is shown in Figure 6. Only the area with the highest 75% yield at current resistance levels is taken into account. The other 25% is considered to be
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predominantly planted with bitter potatoes. The likelihood of adoption of frost resistant cultivars would be highest in areas with a high estimated yield increase. These areas would also be a good location for field trials with new genotypes.

Yield response is especially strong when frost resistance changes from 0 to -3 °C; after that the effect levels off (Table 2; Figures 7 and 8), especially when the area with a predominance of bitter potatoes is eliminated. Increasing frost resistance from -1 to -2°C over the whole potato area (excluding sections with a predominance of bitter potatoes) increases simulated yield by 26%. For the Altiplano, this would amount to a yield increase from 6 to about 7.6 t/ha. The 1.6 tons/ha increase over 44,800 ha (eliminating 30% of the total area, which is planted with bitter potatoes) would lead to an average yearly increase in potato production of 18%.

DISCUSSION AND CONCLUSION

Frost is an important constraint to potato production in the Altiplano. We have demonstrated that the adoption of potato cultivars with increased frost resistance would lead to a strong decrease in yield loss. Hence, breeding for increased frost resistance seems to be a viable goal. Based on the data presented here, we would suggest that Altiplano breeding programs aim to develop cultivars with -2°C frost resistance (i.e., a resistance increase of 1°C). This would have a major impact on yield (an average increase of 26%), and the probability of success in developing such cultivars seems high, given the relatively low increase in resistance required and the high levels of resistance available in wild and cultivated potatoes. After increasing current levels of resistance by more then 2°C, the return in investment levels off, while the research cost will probably increase.

This study only considered the current potato area. However, the introduction of new frost resistant potatoes could lead to relative shifts (within the same area) and absolute shifts (to other areas) in the Altiplano potato area. With the exception of the shores of Lake Titicaca, however, the Altiplano is not densely populated and agriculture is not intensive, so land availability does not seem to be a limiting factor in potato production. Therefore, rather than shifting production to new, colder areas, farmers would probably choose to increase production in current production zones. This would result in more efficient and less risky potato production. On the other hand, potential production areas at higher altitudes might be associated with better (less eroded) soil and more precipitation. Hence, some expansion of potato into higher areas could be expected with the introduction of cultivars with increased frost resistance. However, more in-depth knowledge of farmer strategies in relation to potato production and frost risk on the Altiplano is needed to predict farmers’ response.
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**Figure 6.** The Altiplano (TDPS system) in the andes of Peru and Bolivia. Simulated yield increased for ‘Gendarme’ when frost resistance increased from –1 to –2°C.

**Table 2.** Simulated potential potato yield for ‘Gendarme’ with different levels of imposed frost resistance (R0 is resistant (Te) to 0°C, R-1 to -1°C, etc.). Averages calculated for the total Altiplano potato area and for the area excluding sections with a predominance of bitter potatoes (75% of the total potato area).

<table>
<thead>
<tr>
<th>Resistance</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
<th>-4</th>
<th>-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>All potato area (100%)</td>
<td>16.0</td>
<td>24.3</td>
<td>31.7</td>
<td>37.5</td>
<td>41.6</td>
<td>44.3</td>
</tr>
<tr>
<td>Non-bitter potato area (75%)</td>
<td>20.6</td>
<td>30.6</td>
<td>38.6</td>
<td>43.7</td>
<td>46.6</td>
<td>48.0</td>
</tr>
</tbody>
</table>

This study focused on the potential impact of breeding potatoes with increased frost resistance but ignored frost resistant species such as S. juzepzuckii and S. ajanhuiri. With a few exceptions (Rea and Vacher, 1992; Tapia and Saravia, 1997), these species have not been the subject of scientific research. While they are often described as low yielding, Tapia and Saravia (1997) reported yields of 37 t/ha for S. juzepzuckii and 22 t/ha for S. ajanhuiri. These native species merit more basic and adaptive research, and need to be considered when designing strategies to diminish frost risk in potato production on the Altiplano.
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Figure 7. Cumulative distribution over total potato area in the Altiplano of simulated potential potato yields for ‘Gendarme’ with different imposed levels of frost resistance. R0 is resistant to 0°C, R-1 to –1°C, etc.

Figure 8. Simulated change in potential potato yield for ‘Gendarme’ with imposed different levels of frost resistance (Tcr= 0°C to –5°C), compared to that at the cultivar’s actual level resistance (Tcr= -1°C). Averages calculated for total potato area in the Altiplano (100%), and for the area excluding sections with predominance of bitter potatoes (75%).

Although the simulation-based method used in this study is more objective than other AEZ approaches, there are still numerous assumptions and potential sources of systematic error. Systematic error may have occurred because of the way the weather data was used but also because of other reasons. Outcomes are sensitive to changes in model parameters, notably in Tcr and Tld and in the parameters describing phenology.

Outcomes are highly dependent on the quality of the crop distribution data. This may very well be the greatest source of error in our estimates. Crop distribution data are important to obtain meaningful results from GIS-linked models. National-level crop distribution data are available through FAO, but data at a lower level of aggregation are hard to get. In order to obtain more precise results in future AEZ studies, efforts to assemble crop distribution databases should be intensified.

Our method is an improvement over other studies, which used site-specific weather station data; assuming simulation results were representative of each respective surrounding area (e.g., Stol et al., 1991, Penning de Vries et al., 1996 and Waddel et al., 1999). A major disadvantage of that approach is that the results become meaningless if weather stations are far apart and comprise different climatic conditions, which is often the case in mountain regions. If climate data is interpolated before use in a simulation model, more meaningful results can be obtained.

A disadvantage of spatial interpolation of weather data is that the gain in spatial resolution generally comes at the cost of temporal resolution. The choice between long-term, daily weather station data and interpolated monthly average climate data has important implications, since simulated yield from monthly climate data (as per average weather patterns) does not necessarily coincide with the average simulation calculated from daily data (De Wit and Van Keulen, 1987; Nonhebel, 1994). We interpolated monthly average extreme temperature and its standard deviation to generate daily weather data. A comparable but more elaborate approach, in which both average values and weather simulator parameters are interpolated, is described by Jones and Thornton (1999).

Although we used a very fine resolution grid, there can still be important differences in microclimate that we have ignored. For example, frost is often worse on valley bottoms than on slopes, because of nocturnal cold air drainage. In some areas, this is reflected by preferential use of hillsides, despite their shallower soils. In the future, remotely sensed temperature data might prove useful for improve the quality of the extreme minimum temperature surfaces (François et al., 2000).

Our method of creating daily minimum temperature through linear interpolation with one random extreme temperature per month is simple and could be improved. However, our study lacked time series of daily minimum temperature data, a prerequisite for testing more elaborate approaches. This is an important limitation because the results of this study are strongly influenced by even small variation in
minimum temperature data. One should realize, however, that ex-ante studies couldn't always be postponed long enough to allow for collection of all the data required for optimal analysis. In this type of study, researchers will have to strike a balance between ideal procedures and availability of data and models (Figure 2).

With the various potential sources of error it is hard to speculate whether we would have over or underestimated the potential for frost resistant potatoes on the Altiplano. But even if we overestimated the effect somewhat, our main conclusions would not fundamentally change. Given the broad genetic variability in frost resistance in wild and cultivated potato, and the strong simulated response in yield in the R0 to R-3 classes, breeding for frost resistance in potato for the Altiplano clearly has a high potential impact on potato yield.

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