14 Water Productivity and Potato Cultivation

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Abstract

This chapter provides a review of work done at the International Potato Center (CIP) on improving water productivity in potato. Generally, potato is shallow-rooted and sensitive to even mild water deficits. Most of CIP's work related to water productivity was done in the 1980s as part of a research programme to develop improved germplasm and agronomic practices for potato production in warm tropical environments. Heat-tolerant as well as drought-tolerant materials were selected and tested under a range of warm climates, with studies conducted to quantify evapotranspiration, stomatal conductance, leaf water potential, soil water dynamics and root growth. These same parameters were also determined in agronomic field experiments designed to quantify the effects of mulching, intercropping and close plant spacing on yield and water-use efficiency. Although needed, similar detailed studies on water-productivity components have yet to be done for potato grown more commonly in cooler environments at high altitudes in the tropics.

Introduction

In terms of global production, potato (*Solanum tuberosum* L.) is the fourth most important food crop after maize, rice and wheat (Table 14.1). The current production of 306 million t represents a modest increase worldwide of 15.5% since the early 1960s. Such global statistics, however, mask the much greater expansion of potato production that has taken place in developing countries versus developed countries during the past 40 years. Hence, a more revealing story is told through the statistics shown in Fig. 14.1. While global production has increased from 265 to 306 million t, the proportion of that production coming from developed countries has decreased from 89% to 58%, which translates into an actual decrease in production in developed countries. Meanwhile, the proportion of global production coming from developing countries has increased from 11% to 42%, representing a remarkable increase in production of 100 million t, i.e. from 29 to 129 million t (340.9% increase from 1961–1963 to 1998–2000).

Much of the increase in potato production in developing countries has occurred in Asia, most notably in China and India. Although yields have improved in both countries, the increase in production can be attributed mainly to a continuous expansion of area planted to potato (Fig. 14.2). From 1985–1987 to 1995–1997, the average annual rate of

Table 14.1. Global area, yield and production for the four most important food crops averaged over the years 1998–2000 (FAOSTAT, October 2001).

Crop	Area (million ha)	Yield (t ha^{-1})	Production (million t)
Maize	139	4.4	604
Rice	154	3.9	595
Wheat	215	2.7	588
Potato	19	15.9	306

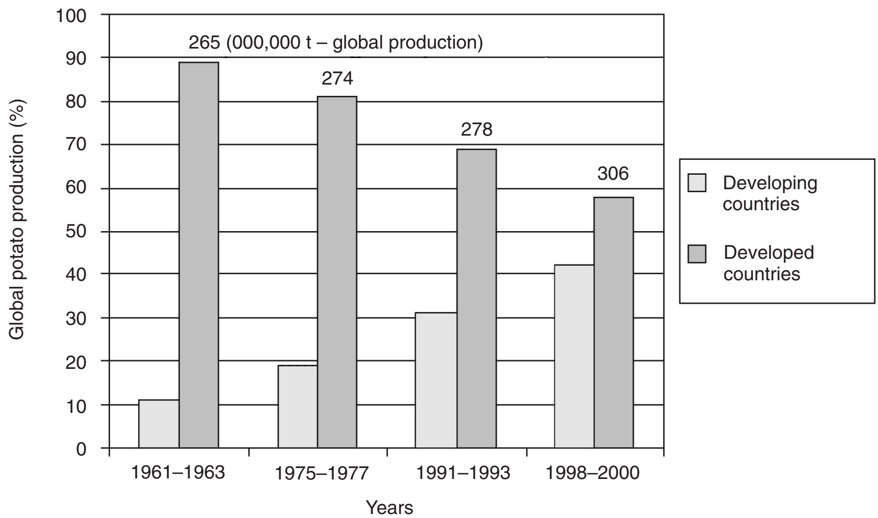

Fig. 14.1. Percentage of global potato production coming from developed and developing countries from 1961–1963 to 1998–2000 (FAOSTAT, October 2001).

growth in potato production was 6.2% in China, with a growth rate in area planted of 3.3% $year^{-1}$ (CIP, 1998). Most of the growth in potato production in Asia has occurred in the interior highlands of China and on the Indo-Gangetic plains of India. Potato has emerged as an important food crop on the Indo-Gangetic plains following an expansion in irrigation infrastructure and the construction of large cold-storage facilities for storing potato before sale and as a seed crop during summer (Bardhan Roy *et al.*, 1999). Whereas potato is grown as a cool, dry-season (winter) irrigated crop on the Indo-Gangetic plains, in China it is grown mostly under rain-fed conditions during summer.

Potato production is expected to continue to increase in developing countries, providing an important source of food, nutrition and income. Recent projections for developing countries show an expected annual growth rate in potato production of 2.7% during the period 1993–2020 (Scott *et al.*, 2000). For global potato production, Scott *et al.* (2000) estimate that 80% of the projected increase will come from developing countries, with 64% coming from Asia alone. They also go on to project that, in Asia, most of the increase in production will have to come from improvements in yield, since area expansion is expected to decrease substantially.

The growing demand for potato – as both a fresh and processed food – and a decreasing availability of land for area expansion mean that yields will have to be improved through some combination of germplasm enhancement, better crop protection and more efficient and productive management

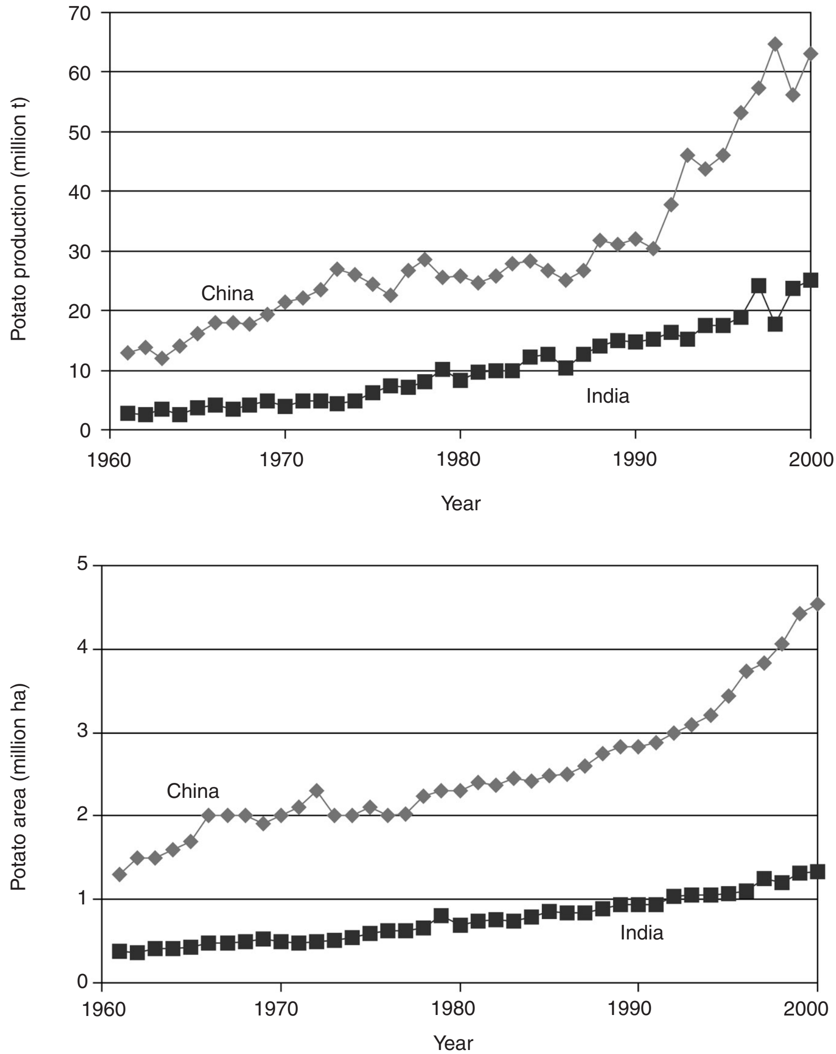

Fig. 14.2. Potato production and area harvested in China and India from 1961 to 2000 (FAOSTAT, October 2001).

systems. The average yield of 15.9 t ha^{-1} currently estimated at the global level (Table 14.1) is much below the yields of 30–50 t ha^{-1} commonly obtained across a range of environments and management systems, so it would seem that there is considerable scope for improvement (Allen and Scott, 1992). Critical to achieving improved yields will be access to an adequate water supply, including more efficient use of all available water in both irrigated and rain-fed systems.

The purpose of this chapter is to review water-use issues in potato production, at least to the extent that the research programme at the International Potato Center (CIP) has been able to address them. More specifically, the review will focus on what has been done at CIP that could be useful for improving the efficiency or productivity of water in both rain-fed and irrigated potato systems in developing countries. Topics to be addressed include an analysis of the relationship between yield and water supply, genotypic differences in response to water supply, the impact of agronomic practices on water use and the potential role of simulation models as both research and application tools. Since research on these topics at CIP has been limited, the reader may wish to refer to recent reviews of more extensive work by the wider research community in Wright and Stark (1990), Gregory and Simmonds (1992), Vayda (1994) and Jefferies (1995).

Yield and Water Supply

Most of the work done at CIP on water use and potato production was conducted in the 1980s as part of a research programme to develop improved germplasm and agronomic practices for potato production in warm tropical environments (Midmore and Rhoades, 1987; Midmore *et al.*, 1991; Midmore, 1992). Warm tropical environments were generally defined as those having a day length of 10–14 h, minimum night-time temperatures of 18–20°C, mean maximum temperatures greater than 25°C and mean annual soil temperatures at 50 cm depth of 22°C or more. Since high temperature was considered to be a primary cause of low yields in warm climates, the programme led to an active breeding effort to develop heat-tolerant clones.

The clones that were found to possess heat tolerance were those that were strongly induced to initiate tubers under high temperatures, were more efficient in the conversion of intercepted radiation to dry matter under high temperatures and matured earlier than non-tolerant clones. Later, field studies showed that selection for heat tolerance had also improved water-use efficiency, as calculated from the per unit increase in fresh tuber yield per unit of applied water, but only in warm climates (Trebejo and Midmore, 1990). In this section, we shall examine more closely the water-use efficiencies defined by the Trebejo and Midmore (1990) studies. Further reference to water-use efficiency will stress instead the term water productivity, which will be taken here to mean the ratio of fresh tuber yield to applied water expressed as kg ha^{-1} mm^{-1}.

Using a single line-source-sprinkler irrigation system, Trebejo and Midmore (1990) studied the growth and yield response of three potato clones to variable rates of water supply in contrasting hot and cool seasons in the coastal desert environment of Lima, Peru (12°05′S at 240 m above sea level). Like most of coastal Peru, there is no effective rainfall in Lima and plants only grow with irrigation. The hot (summer) and cool (winter) seasons in this environment are unique not only because of differences in temperature regimes, but also because the winter season has much less solar radiation and higher humidity due to the impact of the cold Humbolt current on local weather. Basically, the winter remains somewhat cloudy, with frequent periods of fog. During El Niño years, when warmer waters displace the current, the winter season is distinctly cooler, with greater solar radiation and less humidity. The Trebejo and Midmore (1990) study was conducted in 1985, which was not an El Niño year, so the winter and summer seasons were typical of most years.

The three potato clones chosen by Trebejo and Midmore (1990) included two heat-tolerant clones (DTO33 and LT1) and one Peruvian cultivar (Revolución) well adapted to normal coastal winter conditions. All three were planted in rows parallel to the single-line source and managed equally, except for the amount of water during the summer and winter seasons of 1985. The single-line source was set up to apply water in a decreasing gradient away from the line, with growth and yield analyses conducted on plants in rows 2, 4 and 6 extending out from the line. In both seasons, irrigation water was applied so that row 2 received an amount needed to replace water evaporated from a class A evaporation tank. The other rows therefore received progressively less water, and there was no effective rainfall during either season. No runoff from the surface or drainage below the rooting zone was assumed to occur, so all applied water was available for plant uptake.

The response of fresh tuber yield to applied water, averaged across the three clones, is shown in Fig. 14.3. Clearly, water productivity was much greater during the

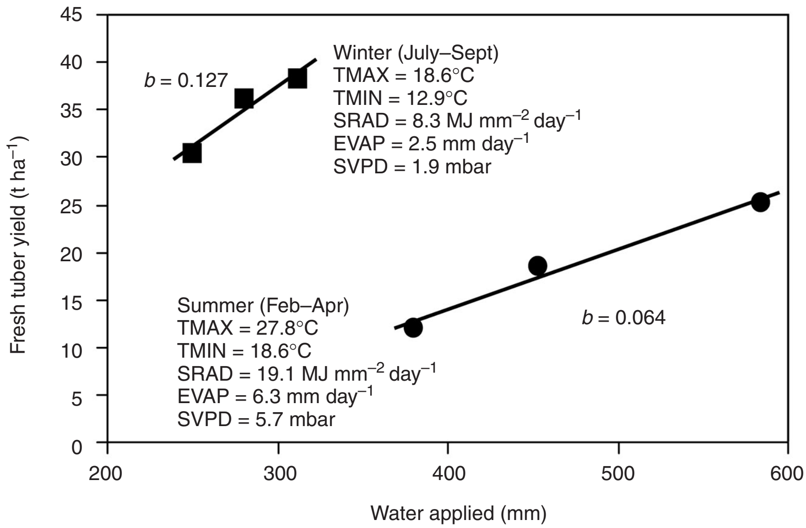

Fig. 14.3. Relationship between fresh tuber yields averaged across three potato clones and total water applied during the 1985 summer and winter seasons in Lima, Peru. The abbreviations represent weather-related variables averaged daily over respective growing seasons: TMAX is maximum temperature, TMIN is minimum temperature, SRAD is global solar radiation, EVAP is evaporation and SVPD is saturation vapour-pressure deficit of the air (data from Trebejo and Midmore, 1990).

winter season compared with the summer season. The relationship between fresh tuber yield and water applied was linear for both seasons, which is generally expected if soil evaporative losses and vapour-pressure deficits are equal across treatments within the same season (Sinclair *et al.*, 1984). The slopes of the linear relationships indicated that water productivity during the winter was 127 kg ha^{-1} mm^{-1}, but only 64 kg ha^{-1} mm^{-1} during the summer. These values are close to those of 54–120 kg ha^{-1} mm^{-1} reported by Wright and Stark (1990) for several studies with potato.

The amount of water applied to the potato crop grown during the more humid winter ranged from 250 mm to 312 mm, with the latter representing what was needed to replace class A pan-evaporation. A reduction of only 62 mm in water applied resulted in a decrease in fresh tuber yield from 38.2 t ha^{-1} to 30.3 t ha^{-1}. For the summer crop, applied water ranged from 380 mm to 584 mm and the associated yields ranged from 12.1 t ha^{-1} to 25.4 t ha^{-1}. Therefore, about half as much water was used during the winter to produce 150% more yield than that obtained in the summer. The same studies referred to earlier by Wright and Stark (1990) showed that seasonal water use averaged 607 mm (range 450–800 mm) and yield levels averaged 56 t ha^{-1} (range 33–72 t ha^{-1}).

For both seasons, irrigation based on class A pan-evaporation did not appear to result in excessive water application, since maximum yields were obtained using this method. Nevertheless, seasonal evapotranspiration (ET) estimates that were obtained from gravimetric soil samples showed that cumulative water applied by irrigation was in excess of cumulative ET by about 90 mm (Trebejo and Midmore, 1990). Concerns about excessive irrigation or poor drainage are always valid in potato cultivation, since yield is as sensitive to reduced aeration as it is to drought stress, although yield loss due to the latter is more common (Wright and Stark, 1990). When less water was applied than that needed to replace class A pan-evaporation, water deficits obviously occurred and yield levels were depressed (Fig. 14.3).

Needless to say, potato farming in coastal Peru occurs during the winter, when the cool humid conditions are favourable for growth and more efficient use of irrigation water. The cooler temperatures result in delayed maturity, which provides more time for the interception of solar radiation and the conversion of intercepted radiation to dry matter. For the Trebejo and Midmore (1990) study, the mean harvest date of all three clones was 91 days after planting for the summer and 110 days after planting for the winter. During winter, less soil evaporation and the smaller vapour-pressure deficit of the air also combine to enhance water productivity when compared with the summer. Generally, more humid environments provide greater water productivity because of lower vapour-pressure deficit (Sinclair *et al.*, 1984).

Genotypic Differences in Response to Water Supply

Data from the Trebejo and Midmore (1990) study can also be used to illustrate genotypic differences in response to water supply. While the previous section compared water-productivity values averaged across all three clones, this section will discuss results for each clone averaged across all water-application levels.

Figure 14.4 shows the fresh tuber yield and the water productivity calculated for each clone during the winter and summer seasons. The two heat-tolerant clones, LT1 and DTO33, yielded more in the summer than Revolución, the cultivar better adapted to coastal winter conditions. Selection for heat tolerance has evidently improved adaptability to warmer climates, which is also reflected in greater water productivity when the heat-tolerant clones are compared with Revolución in the summer. None the less, better yields and water productivity were realized for all clones when grown during the winter compared with the summer. The highest yield and water productivity were obtained with Revolución grown during the winter.

In a comparison of the two heat-tolerant clones, LT1 probably performed better than DTO33 because of its later maturity. In the summer, LT1 was harvested 92 days after planting (DAP) versus 81 DAP for DTO33. In the winter, LT1 was harvested 112 DAP versus 103 DAP for DTO33.

Other evidence for genotypic differences in water productivity comes from a study of leaf resistances for 14 potato cultivars, conducted by Ekanayake and de Jong (1992). Greater water productivity could conceivably be obtained through manipulation of stomatal behaviour so that midday water stress triggers midday stomatal closure to prevent high transpiration rates and minimize damage to the crop (Sinclair *et al.*, 1984). Ekanayake and de Jong (1992) did find significant genotypic differences in leaf resistance or stomatal behaviour, indicating the possibility of improving water productivity and drought resistance through improved germplasm.

Another avenue for improving the water productivity of potato could be through deeper rooting to extract soil moisture from deeper in the profile. Recent investigation of a large number of clones in the desert conditions of Lima has shown genotypic differences in depth to rooting (N. Pallais, International Potato Center, Lima, Peru, 2000, personal communication).

Impact of Agronomic Practices on Water Use

Agronomic practices that reduce soil evaporation should tend to increase water productivity. In a study of the benefits of surface mulches on yield, Midmore *et al.* (1986b) showed that mulch increased tuber yield during the summer in Lima by 20%. Although it was not directly determined how much water productivity might have been affected, Midmore *et al.* (1986a) did conclude that mulch always increased soil-moisture retention. Thus enhanced yields obviously mean increased water productivity for the same amount of applied water, at least for the summer season in Lima. These same studies also showed that mulch resulted in earlier tuber initiation and greater tuber bulking rates.

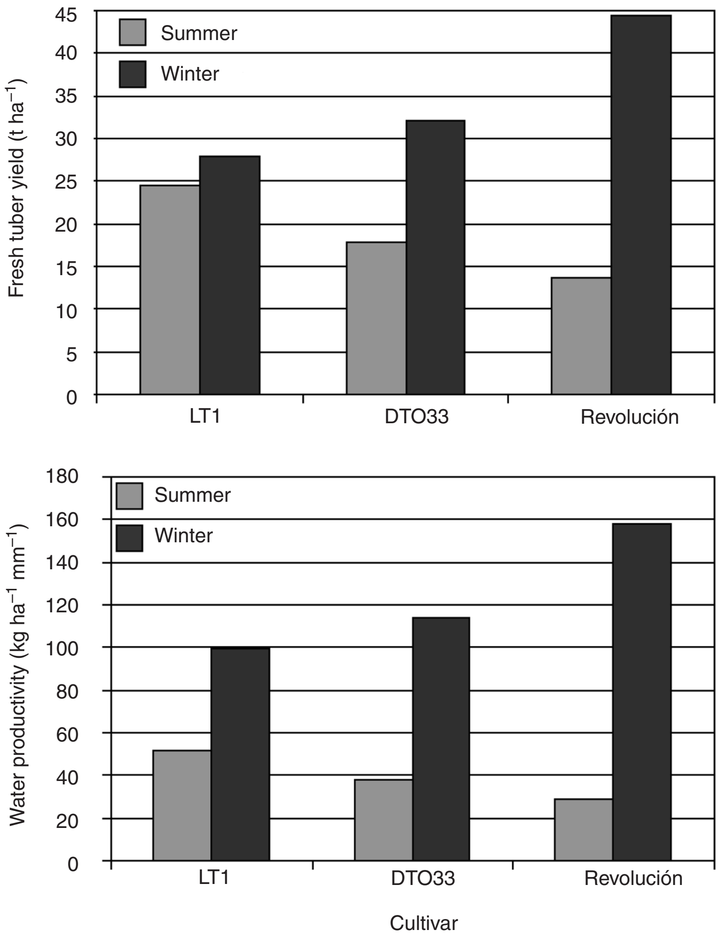

Fig. 14.4. Fresh tuber yields and estimated water productivity (expressed as kg fresh tubers ha^{-1} mm^{-1} of applied water) for three cultivars grown during the 1985 summer and winter seasons in Lima, Peru (data from Trebejo and Midmore, 1990).

Manrique and Meyer (1984) also studied the impact of mulches on potato yield during winter and summer seasons in Lima. They saw no effect on yields during the winter, but summer yields were increased by 58% with surface mulch, which improved soil-moisture retention.

Potential Role of Simulation Models

Owing to advances in computer technology and accessibility, models of soil and plant systems have become increasingly valuable instruments for assimilating knowledge gained from experimentation. Their use within a research programme has the potential to increase efficiency by emphasizing process-based research, rather than the study of merely site-specific net effects. Consequently, a modelling approach lends structure to a research programme, helping to focus on the quantitative description of soil and plant processes. This information can then be used to predict how the system might respond to different environmental and management factors. A modelling approach also provides a dynamic, quantitative framework for multidisciplinary input.

Although there are several potato models available, at CIP we have chosen to initially work with the SUBSTOR-Potato model (Ritchie *et al*., 1995). This model simulates, on a daily basis, the accumulation and partitioning of biomass and the phenological development of a potato crop as influenced by temperature, photoperiod, intercepted radiation and soil water and nitrogen (N) supply. To illustrate the comprehensive nature of the model, a listing of the processes that are simulated when accounting for N demand and supply are provided in Table 14.2. The environmental factors that the model uses to simulate each process are also shown. The model is thought to be especially valuable for studies of the interaction of water and N supply. SUBSTOR has been tested in various environments and has generally performed well when simulated data have been compared with measured data (Griffin *et al*., 1995; Mahdian and Gallichand, 1995; Ritchie *et al*., 1995; Travasso *et al*., 1997; Bowen *et al*., 1999).

We have begun to calibrate and test the SUBSTOR-Potato model across a wide range of environments and management systems in the Andes and more recently in the Indo-Gangetic plains of India. A comparison of simulated and observed tuber yields obtained from field studies in the Andes is shown in Fig. 14.5. This limited testing shows that the model realistically

Table 14.2. Major processes that are simulated and environmental factors that affect those processes in the N submodel of SUBSTOR-Potato (version 3).

Process simulated	Main factors influencing process
Crop N demand	
Growth	Solar radiation, temperature
Development	Photoperiod, temperature
Soil N supply	
Mineralization/immobilization	Soil temperature, soil water, C/N ratio
Nitrification	Soil temperature, soil water, soil pH, NH_4^+
Denitrification	Soil temperature, soil water, soil pH, soil C
NO_3^- leaching	Drainage
Urea hydrolysis	Soil temperature, soil water, soil pH, soil C
Uptake	Soil water, NO_3^-, NH_4^+, crop demand, root length density

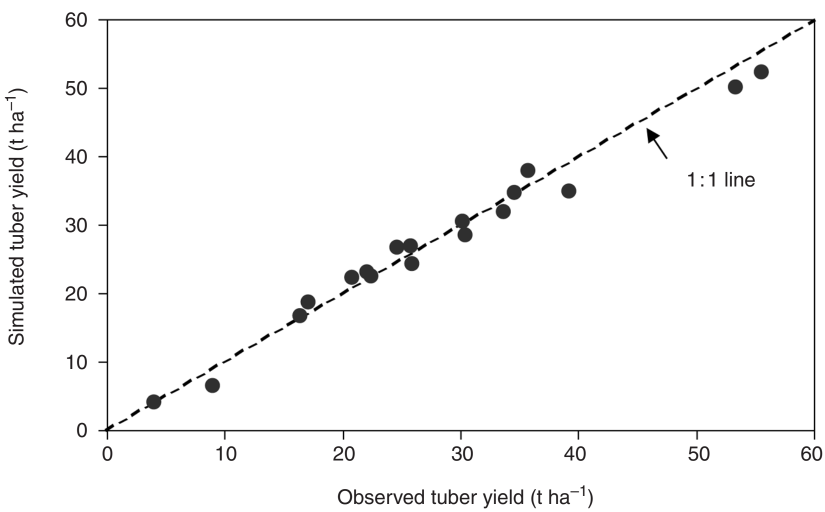

Fig. 14.5. Relationship between simulated and observed fresh weight of potato tubers for sites in Bolivia, Ecuador, Peru and Venezuela.

simulated fresh tuber yields that ranged from 4 t ha^{-1} to 56 t ha^{-1} due to differences in weather, soils, cultivars and management. Further testing is under way as we continue to critically evaluate the performance of SUBSTOR and search for ways to improve it and other models as research, education and management tools.

We hope that ongoing evaluation of the SUBSTOR-Potato model will provide us with a powerful tool for analysing the impact of weather variability on potato yields and water productivity under different management practices. The impact of weather variability on a given management option can be quantified by running the model with many different years of weather data. The weather data may be the daily values actually recorded at the site, or the model may statistically generate weather using historical data.

Conclusions

To date, the only major research done at CIP on addressing water-productivity issues has come about indirectly from its research programme in the 1980s to develop potato adapted to warm climates. Although this programme was successful in identifying heat-tolerant clones that can produce tubers under warm-temperature regimes and that may also have higher water productivity when grown in such environments, potato continues to be best adapted to cool-temperature regimes for both tuber-yield potential and greater water productivity. Water productivity will inevitably continue to be higher in humid conditions with low vapour-pressure deficit gradients. Nevertheless, it is clear that there exists a useful range of genetic variability that could be taken advantage of for more drought-tolerant and water-use-efficient genotypes, which should prove beneficial for both rainfed and irrigated potato systems. Other potentially fruitful lines of research for increasing water productivity at the field level include the investigation of more efficient irrigation systems, e.g. drip irrigation, and soil-management practices that emphasize less tillage and the maintenance of more residue on the soil surface.

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