Yield gaps and ecological footprints of potato production systems in Chile

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Abstract

In Chile potatoes are grown in a wide range of ecological zones and levels of technology resulting in wide ranges of crop management and yields. The aim of the present study was to assess yield gaps, resource use efficiencies and foot-printing in different potato cropping zones between 18 and 53 degrees South considering early and late crops, small and large holdings (>10 ha per year) and ware and seed potato crops. Two mathematical tools were used to generate data for comparisons: the LINTUL crop growth model to calculate potential yields and water need of each system and the Cool Farm Tool – Potato (CFT) to calculate the amount of CO_2 associated with the production of one ton of potato. Meteorological data for LINTUL came from official services and data needed to complete the CFT came from a survey carried out for the 10 sites yielding amounts of inputs and number of operations, potato yields and planting and harvest dates. The survey yielded 20 cropping systems with an average yield of 31 t ha^{-1}. Yields were related to daily growth rate and not with the length of the growing season. Considerable variation was found in resource use efficiency and CO_2 emission. It was concluded that large farms show a lower land foot print than small farms due to higher technological level but while applying more water and fertilizer they result in higher water and CO_2 footprints. Late crops may fetch higher off season prices but have higher land, water and CO_2 footprints. The most suitable potato production systems are the rainfed summer crops in the South with the lowest foot prints. The highest footprints have the irrigated winter crops in the Centre of Chile. The subsistence high altitude Andean crop in the utmost North has the highest land footprint but the lowest CO_2 emission. The description, analysis and benchmarking of the potato production systems in Chile allows strategies for improving footprints and profitability and yields information about future investments in research, development and production of the crop.

Key words: Chile, potato, Cool Farm Tool, carbon dioxide emissions, GHG, resource use efficiency, foot print, irrigation

Introduction

In 1974 the total area cropped with potato in Chile was 93,270 ha and total production was 1.0 million tons (yield 10.8 t/ha) (FAO 2013). According to Montaldo (1974), six production environments can be distinguished in the country as shown in Table 1. The northernmost area being Belen at 300 m altitude 18 degrees South and the southernmost Punta Arenas close to sea level at 53 degrees South (Table 1). Obviously photoperiod increases when going further South, so does precipitation (up to 41 degrees South). Yields were low from 2.34 t/ha to almost 10 t/ha in La Serena. Today, the average potato yield in Chile are higher, however, to date there are no studies regarding actual yields aimed to characterising and comparing current potato production systems from North to Southern Chile.

Currently, potato is the third staple food in Chile after wheat and maize. There are 67,000 potato producers, the majority plants less than one hectare per year. Average potato consumption is about 50 kg per capita of 16 million inhabitants of which 90% is fresh consumption, 10% as processed products: chips (crisps), French fries and mashed potatoes. Large sized, red skinned, yellow fleshed potatoes are preferred in the fresh market. Consumption is substantially higher in the „real" potato regions. Region of Los Lagos (around Osorno) consumes around 100 kg per capita. Per capita consumption at Chiloe island can be as high as 200 kg. During the last 50 years total potato production area decreased on average 45% (from 92147 to 49834 ha) (Fig. 1 a). However, total production has increased more than 50% (from 0.8 to 1.2 million tons) (Fig. 1 b). This followed the yield increase from about 8.8 to 24 t/ha over the past 50 years (Fig. 1 c). This increase is mainly due to improved crop management (better seed quality, use of fertilizers, fungicides and increased irrigation) in interaction with new potato varieties. However, despite of the yield increments during the last three decades, still yield gaps are expected between potential yield and actual yields due to deficiencies in crop management and also because following the law of decreasing returns the economic optimum is below the yield potential. Crop simulation models offer the opportunity to estimate potential yield. These simulation models are mathematical representations of our current understanding of crop development and growth in response to environmental factors. LINTUL-Potato crop growth models have been used previously in other environments to calculate potential yields (Caldiz and Struik 1999; Franke et al. 2011; Haverkort et al. 2013). So far no studies exist aimed at yield gaps through the application of crop simulation model in different potato growing areas of Chile.

The six distinct existing potato growing areas are described as follows:

I. The high Andean valleys in the North such as Putre in the region of Arica and Parinacota (Fig. 2) with mainly subsistence farming and low levels of technologies and use of fertilizers. Therefore, yields are low. Here local varieties are produced for family use and local markets. Average planting and harvest dates in this region are September 21th and February 9th, respectively.

Table 1 Site, latitude, agro-zone, month of planting, photoperiod at planting and maximum, annual rainfall and rainfall during the growing season and averaged yields of potato production systems Chile according to Montaldo (1974)

Site	**Latitude**	**Agro-zone**	**Planting**	**Photoperiod at planting/maximum (hours)**	**Annual/growth season rainfall (mm)**	**Average yield (t/ha)**
Belén	18°30’	North highlands	November	13.20/13.20	170/irrigated	2.34
La Serena	29°55	North	August	10.45/14.00	110/irrigated	9.95
Pichilemu	34°27’	Centre	August	10.45/14.30	756/100	3.24
Talca	35°26’	Centre South	September	11.20/14.30	742/irrigated	9.88
Chiloe	41°52’	Centre-South	October	12.30/15.00	2384/600	9.55
Punta Arenas	53°10’	Extreme South	November	14.30/16.15	436/100	8.97

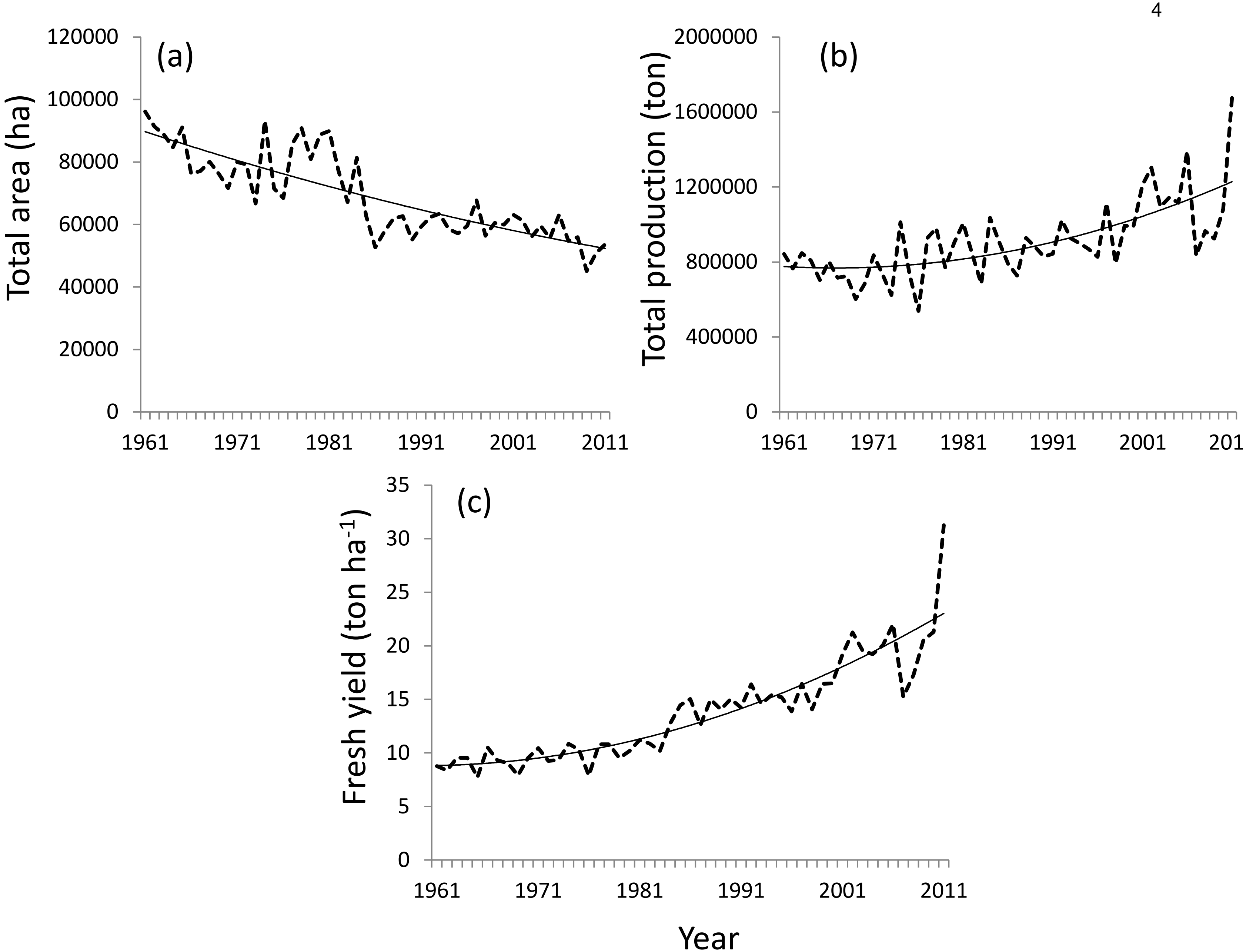

Fig. 1 Development of total area (a), total production (b) and fresh yield (c) of potato during the last 50 years in Chile. (FAO 2013)

II. The North comprises the regions of Antofagasta, Atacama and Coquimbo. This area is represented by La Serena (Fig. 2) where most of the north potato productions are located. About 5% of the total potato area is cultivated in this zone. In general, in this arid area about 60% of potatoes are grown between March and October (late planting or autumn-winter crops) while a 15% of potatoes are cultivated from July to December (early planting or spring crop) and another 12% is cultivated between December and May (late planting or summer crop). Summer and autumn crops are considered off-season crops. In this zone potato can only be grown in river valleys with irrigation.

III. The Centre stretches from the regions of Valparaiso to O´Higgins. A 14.6% of the total potato area is cultivated in this zone. This is the richest agricultural area of Chile because of its mild climate and proximity to markets. Early (July-December, spring crops) and late (January-Jun, summer crops) productions are found in this zone. This area supplies the Santiago market from September to November when potato prices are highest owing to low potato supply from the South. In Figure 2 this area is represented by La Ligua and Las Cabras.

IV. The Centre-South stretches from the regions of Maule to Biobío. A 23.3% of the total potato area is cultivated in this zone. In Figure 2 this area is represented by Chillán. Most potatoes are cultivated under rain-fed conditions from October to March. However, early (September) and late (November) planting dates are also found in this zone. Potato yields here are higher than in the centre owing to high levels of rainfall and fresh temperatures that permit longer crop cycles. However, yields are yet far from potential as most rain falls outside the cropping season (May-August).

V. The South stretches from the regions of La Araucanía to Los Lagos. A 57% of the total potato area is cultivated in this zone. Most of the production of seed potatoes takes place here. For the most part, potatoes are grown under rain-fed conditions and modern agricultural techniques are applied by big farmers (like in all country), but not often applied by most farmers. In Figure 2 this area is represented by Temuco, Llanquihue and Chiloé. Average planting and harvest dates in this region are October 10th and March 15th, respectively. Potato yields here are higher than in other zones owing to high levels of rainfall and fresh temperatures that permit longer crop cycles (Fig. 2). The island of Chiloe is situated on the southern tip of this region where some 30 hectares of native potatoes are grown producing about about 500 tons of *Papas Nativas* annually. Reputedly all *Solanum tuberosum* varieties are derived from this ancestry.

VI. The extreme South comprises the regions of Aysén and Magallanes, represented by Coyhaique (45° S) and Punta Arenas (53° S), respectively (Fig. 2). In both regions potatoes are produced for local consumption. Potatoes are grown under rain-fed conditions with low levels of technology and deficient knowledge about crop management. In addition, the crop cycle is shorter than the South region due to the late planting aimed at

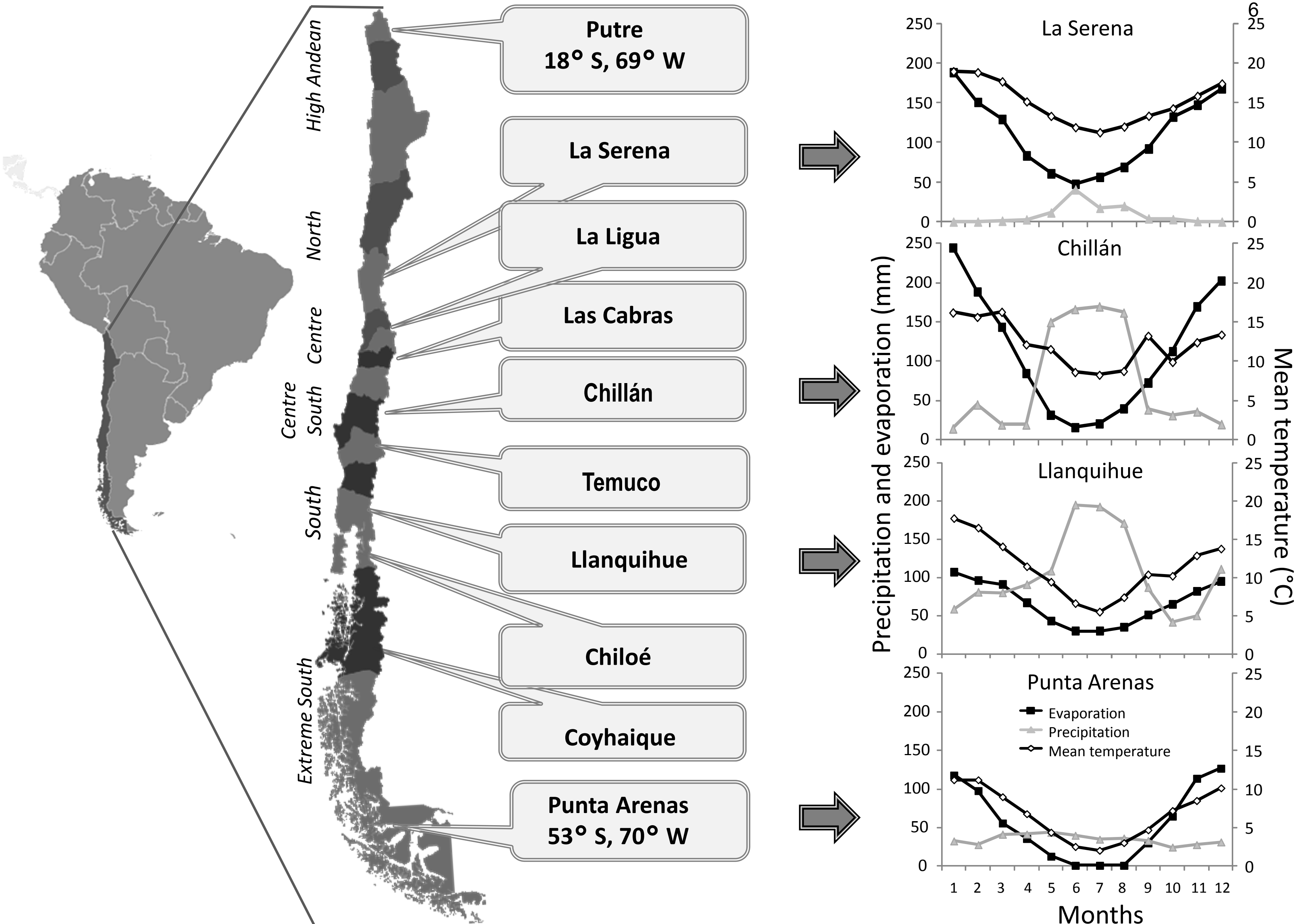

Fig. 2 Ten agro-zones where questionnaires were gone through with potato producers and weather data from some contrasting regions of Chile. White, black and grey symbols are mean temperatures, evaporation and precipitation, respectively (Novoa and Villaseca 1989)

avoiding early frost damage. Most of all growers produce their own seed potatoes. Owing to cooler temperatures late blight is less frequent in this environment. In Aysén planting and harvest dates are October and March, respectively, while in Magallanes these dates are October and April, respectively.

In the next decades agricultural systems will have the great challenge of closing the yield gaps of different crops in order to meet the projected food demand for a world population that it is expected to increase 35% by 2050 (van Wart et al. 2013). In addition, this challenge must be reached in a sustainable manner with higher resource use efficiency (nutrients, water and energy, among others) in order to minimize negative impact on environment. In this scenario, there is an increased interest to quantify the amount of CO_2 emission per unit of products. Some recent studies calculated emissions from agriculture and farming operations (e.g., Lal 2004; Hillier et al. 2009; Hillier et al. 2011). Potato production uses energy embedded in the seed potatoes, in the chemicals used (fertilizers and crop protection), in the tractor operations (tillage, planting, spraying, spreading and harvesting) and in irrigation, grading, store (un)loading and storage (Haverkort and Hillier 2011). All these factors involve the release of the greenhouse gas (GHG) carbon dioxide in factories producing the chemicals, farm implements, transport and power plants. Recently, Haverkort and Hillier (2011) using The Cool Farm Tool – Potato (CFT-Potato), which is a spreadsheet programme that allows the calculation of the amount of CO_2 equivalents that it costs to produce 1 t of potato, characterized four potato production systems in the Netherlands regarding their CO_2 equivalent t^{-1} and indentified main factors contributing to the footprint of each system. Chilean potato growers could vary greatly in the amount of CO_2 equivalents that it costs to produce 1 t of potato, not only owing to differences in crop management but also due to different actual yields reached among them. There is no information about this subject in the potato productions systems of Chile that allows potato growers adjust their management practices in order to reduce CO_2 emissions and use this characteristic as an advantage in the marketing of potato and its sub-products.

The main limitation of potato in Chile is late blight caused by *Phytophthora infestans* which is considered to be the most important factor reducing production. The population consists of the A1 mating type but is considered to be more aggressive than a decade ago. All important fungicides are registered in Chile and an early warning system based on networks of weather stations is being introduced to produce warnings of critical days of infection. Most small farmers do not spray at all due to a lack of resources (for example on Chiloe Island). Medium and big farmers spray on a calendar basis, even though the alarm system is being adopted by an increased number of farmers which may decrease or optimize the use of fungicides to control this disease. they spray non-optimal spray schedules with a knapsack sprayer. On Chiloe Island late blight has been very aggressive in some years resulting in complete crop failures. The extension to small farmers is organised by INDAP (an institute from the Ministry of Agriculture) which is very important to transfer knowledge on best practices to control late blight. In the breeding program of INIA late blight resistance is a very important trait. The recently introduced variety Patagonia-INIA has a good resistance to late blight and is being adopted by farmers.. Viruses are a cause of degeneration of seed. There is a good seed certification program in the country, but still certified seed is not massively used and most farmers plant farm saved seed for several years (3 or more) before introducing certified seeds. Nematodes are a problem in La Serena (in the north part of the country).

Abiotic factors as limiting productivity are important, especially inadequate fertilization and drought due to lack of rain and irrigation.

The objectives of our research were to analyse the various potato production systems in Chile, from North to South from early and late ware potato crops and seed crops, data regarding crop management that allow us to analyse yield gaps, resource use efficiencies and foot-printing that make strategies possible of improvement of production and resource use. To this aim we made use of survey data and models of crop growth and carbon balances.

Materials and Methods

In the research presented here we followed three approaches: a survey of growers to identify the major characteristics of each cropping system, we used a crop growth model with weather and soil data and planting and harvest dates as input and we used the Cool Farm Tool – Potato to assess the amount of CO_2 associated with the production of one ton of potatoes.

Data collection

During May-July 2013, three to nineteen Chilean potato growers were interviewed per agro-ecosystem located at contrasting latitudes and climatic conditions (ten agro-ecosystem at latitudes ranging from 18° S to 53° S, Fig. 2, Table 2) with the aid of a questionnaire that contains all the questions relevant for the Cool Farm Tool – Potato (Haverkort and Hillier 2011). The survey concerned a total of 71 Chilean potato growers. Growers were selected such as to represent the broad range of potato crop systems of Chile varying in field size (smaller or larger than 10 ha per season grown), technology usage levels and aim of potato production (seed, early or late potato). In some areas the late crops were the exception in other areas early crops were the exception. In both cases growers grew such crop while sacrificing yields aiming at higher market prices. Growers had no difficulty to answer the questions regarding actual yields and crop management (soil, fertilization, pesticides, irrigation, harvest and post harvest operations). In each region, mean values of the crop management data were taken from growers with similar characteristics (farm size, degree of mechanization and productive purpose) were averaged.

The potential yield level was determined with the LINTUL-Potato simulation model using monthly weather data (maximum and minimum temperatures, solar radiation, precipitation and evaporation) acquired from meteorological stations located at each region and near to potato producers. Weather data (Table 2) from Coquimbo, Metropolitana, Bío-Bío, Araucanía, Valdivia, Osorno correspond to long term data (30 years) stored by the Institute of Agricultural Research of Chile. In the remaining regions

Table 2 Geographical and climatic information of localities where surveys were carried out and for which potential yield was calculated and the potato production systems present at each location. ASR: average daily solar radiation during the crop cycle of early planting potatoes. S, E and L represent seed production, early and late planting potato crops. *: producers with more than 10 ha of potato per season

Location	Zone	Latitud	Longitud	Altitude (m)	ASR $MJ/m^2/d$	Annual		Production system		
						Mean T °C	Precipitation (mm)	Seed	Early planting	Late planting
Putre	High Andean	18° 26' S	69° 60' W	2500	26.1	19.1	150	-	E	-
La Serena	North	29° 54' S	71° 15' W	32	16.0	13.5	104	-	E*	L*
La Ligua	Centre	32° 27' S	71° 16' W	58	18.4	14.4	341	-	E	L
Las Cabras		33° 34' S	70° 38' W	625	19.5	13.9	389	-	E	L
Chillan	Centre South	36° 03' S	72° 06' W	144	22.4	14.1	1025	-	E and E*	L
Temuco	South	38° 41' S	72° 25' W	200	22.5	10.2	1394	-	E and E*	L and L*
Llanquihue		41° 26' S	73° 07' W	88	20.9	10.7	2021	S*	E and E*	-
Chiloé		42° 29' S	73° 48' W	24	18.1	10.4	1942	-	E	-
Coyhaique	Extreme South	45° 34' S	72° 40' W	310	23.2	9.50	993	-	E	-
Punta Arenas		53° 10' S	70° 54' W	8	11.6	6.70	416	-	E	-

(Fig. 2, Table 2) weather data were obtained from a web site (agromet.inia.cl) supplied with online data from a network of agro-meteorological stations located at different latitudes of Chile. In these situations, evapo-transpiration (ETP) was not recorded by the weather stations; so here the ETP was obtained from Novoa and Villaseca (1989). The start and end of the simulations was determined by the planting and harvest date as indicated by the growers that were part of the questionnaire.

Calculations of CO_2 costs of production

The Cool Farm Tool – Potato (CFT-Potato, Haverkort and Hillier 2011) is a spreadsheet program that allows the calculation of the amount of CO_2 equivalents that it costs to produce one ton of potato. The spreadsheet was adapted from an original generic version of the tool, and completed for potato production in diverse production areas in the world applying different levels of technology. The CO_2 embedded in chemicals in their production and released from the soil after nitrogen fertilization in the CFT-Potato have been updated to consider more recent products and production methods. Energy costs of the operations in the original version taken from generic data provided by the American Society of Agricultural and Biological Engineers Standard, however, were altered (usually increased) where there was evidence from practical sources that the original figures did not apply. For example the figure of around 16 liters of diesel per hectare for potato harvesting in the original version was corrected to 60 liters per hectare based on observational data. Figures for typical potato operations such as windrowing were supplied. Irrigation with pumps powered by diesel or electricity from the grid, with a center pivot, a rain gun, drip irrigation and flooding and energy cost for extracting water from deeper sources were also added. We added data for grading, washing, store loading and unloading, the application of a sprout suppressant and storage with ventilation of ambient air or forged refrigeration. The CFT-Potato can be used by growers to calculate the actual costs of one ton of potato in terms of kg CO_2 and explore the repercussion of altered management options.

- Nitrous oxide (N_2O) emissions related to fertilizer application were estimated using the multivariate empirical model of Bouwman et al. (2002) which takes fertilizer type, rate, climate and soil characteristics into consideration, is employed. Although relatively small quantities of N are released from soil as nitrous oxide (around 1% of N applied according to IPCC Tier 1 (IPCC 2006)) - it is important to the GHG budget as it is 298 times more damaging than CO_2 over a 100 year horizon (IPCC 2006).

- NO and NH_3 were based on the model of FAO/IFA (2001), and converted to N_2O via the factor 0.01 as given in IPCC (2006). Leaching was assumed to occur at a rate of *0.3 * N applied* for moist climate zones only – and the conversion factor to N_2O of 0.01 was also employed

- Emissions of CO_2 from soil resulting from urea application or liming were also accounted for using the IPCC emissions factors (IPCC 2006), of 0.20 and 0.12 respectively.

- CO_2 emissions (or accumulation) from soils depend on climate, soil characteristics and tillage practices and crop residue management such as burning straw on one hand or incorporating green manure on the other, based on Ogle et al. (2005).

- The effect of manure and compost addition on soil C stocks were derived from those of Smith et al. (1997) i.e. about 0.04% change of soil organic matter concentration per ton dry matter of manure or compost.

- Averaging data from Audsley et al. (2009) for pesticides (fungicides, growth regulator, herbicides and insecticides), the tool uses the figure of 20.5 kg CO_2 equivalent per product application per hectare.

- Direct energy usage (petrol, diesel, electricity) on the farm for field operations (plowing-----harvest) and primary processing were taken from ASABE technical standards (ASABE 2006a,b)

- Country specific grid electricity emissions were taken from the GHG protocol‟s “Emission Factors for Cross-Sector Tools” (GHG protocol 2003). Hydro, wind or solar renewable electricity sources are also included using Ecoinvent figures (Ecoinvent 2007).

Calculations of potato yield and water need

The LINTUL crop growth model used in the present study – similar to the studies of Franke et al. (2011) from which this section was taken - calculates potato dry matter production from the amount of intercepted radiation by its green foliage and a conversion factor (radiation use efficiency, RUE) (Spitters 1990), following the approach of Kooman and Haverkort (1994) by calculating the temperature-dependent phenological development of a potato crop. Higher temperatures lead to earlier crop emergence and a more rapid initial leaf growth, resulting in increased interception of solar radiation at early stages of crop growth, a rapid maturation of the crop and a reduced length of the growing cycle from planting to harvest. Moreover, very high temperatures reduce photosynthesis and thereby biomass accumulation.

We simulated shoot growth, foliar expansion, biomass accumulation and tuber growth on a day-to-day basis. Climate input data required by the model includes daily minimum and maximum temperatures, incoming solar radiation and rainfall, reference evapotranspiration and carbon dioxide concentration. Management input data includes the depth and date of planting. Accumulated degree days from planting (with a base temperature of 2 ^{0}C) determines the time to crop emergence, leaf area development and the time of crop termination. The leaf area index (LAI) increases exponentially from crop emergence until a leaf area index of 0.75 is achieved. Thereafter, its development depends on temperature and water availability until a full crop cover is reached (LAI > 3). Daily biomass growth is calculated using the crop‟s LAI, light interception (using an extinction coefficient of 1 (Spitters and Schapendonk 1990)), and the RUE (1.25 g dry matter MJ^{-1} of intercepted radiation). In the model, photosynthesis capacity is reduced when the average day temperature falls below 16 ^{0}C or when the maximum temperature exceeds 30 ^{o}C and is completely halted at temperatures below 2 ^{0}C and above 35 ^{o}C (Kooman and Haverkort 1994). The harvest index for all cropping situations was set at 0.75 (Kooman and Haverkort 1994) and simulated yields are presented as tuber fresh matter, assuming a dry matter concentration of 20%.

Daily evapotranspiration (ET) for potatoes was calculated from the Penman-Monteith grass reference evapotranspiration (ETo) (Smith et al., 1996) multiplied by a crop specific coefficient (K_c) according to the procedure recommended by Allen et al. (1996). Daily ETo values were calculated using the daily maximum and minimum temperatures, relative humidity, wind speed, solar radiation and rain, as input parameters. Evaporation from the soil was quantified following Ritchie (1972), who calculated that a soil with an average water holding capacity that is wetted every four days by irrigation or rain has an evaporation rate that is one third of ETo until emergence of the crop. Thereafter evaporation from the soil decreases linearly with ground cover (calculated from LAI) to 10% of ET at full ground cover at the LAI value of 3.

To estimate ET, water use efficiency (WUE) by the crop and drainage, we calculated a water balance using the plant available water of the most prominent soil in any region. When rainfall was in excess of what the soil can hold it will not be available to the plant, as it may drain below the rooting zone (assumed to be 0.5 m deep throughout Chile) when running the models. Farmers were assumed to irrigate when 50% of the plant available water was depleted and may have irrigated just prior to an excessive rainstorm (then all precipitation is lost through drainage) or may have been about to irrigate when the event took place (then 50% of the plant available water is utilized and the rest lost through drainage). We therefore assumed that only daily rainfall that is not in excess of 25% of the plant available water was available for crop growth. We also assumed that water was available for irrigation when needed.

Results and Discussion

Actual and potential potato yields

The survey in the 10 agro-zones (Fig. 2) yielded 20 production systems going from North to South with seed and ware potato production systems and with small and not so small farms. These systems are shown on the abscissa of Figure 3 starting in the far North of the country on the left (Putre) and ending in the far South in Punta Arenas. The average yields of the surveyed growers was 31 t/ha (Fig. 3 a) which is higher than the official statistics of 24 t/ha; this shows some bias exists due to selecting somewhat better than average growers in such surveys. The subsistence production system of Putre in the high Andes and Las Cabras late planting (summer crop) system showed the lowest yields, well below 20 t/ha. High yields of around 50 t/ha were reported by large area early crop growers in Chillan and Llanquihue and the main crop growers at Chiloe Island. The seed crops in Llanquihue have lower actual yields than the main crop as the seed crops are harvested earlier to avoid aphids transmitting

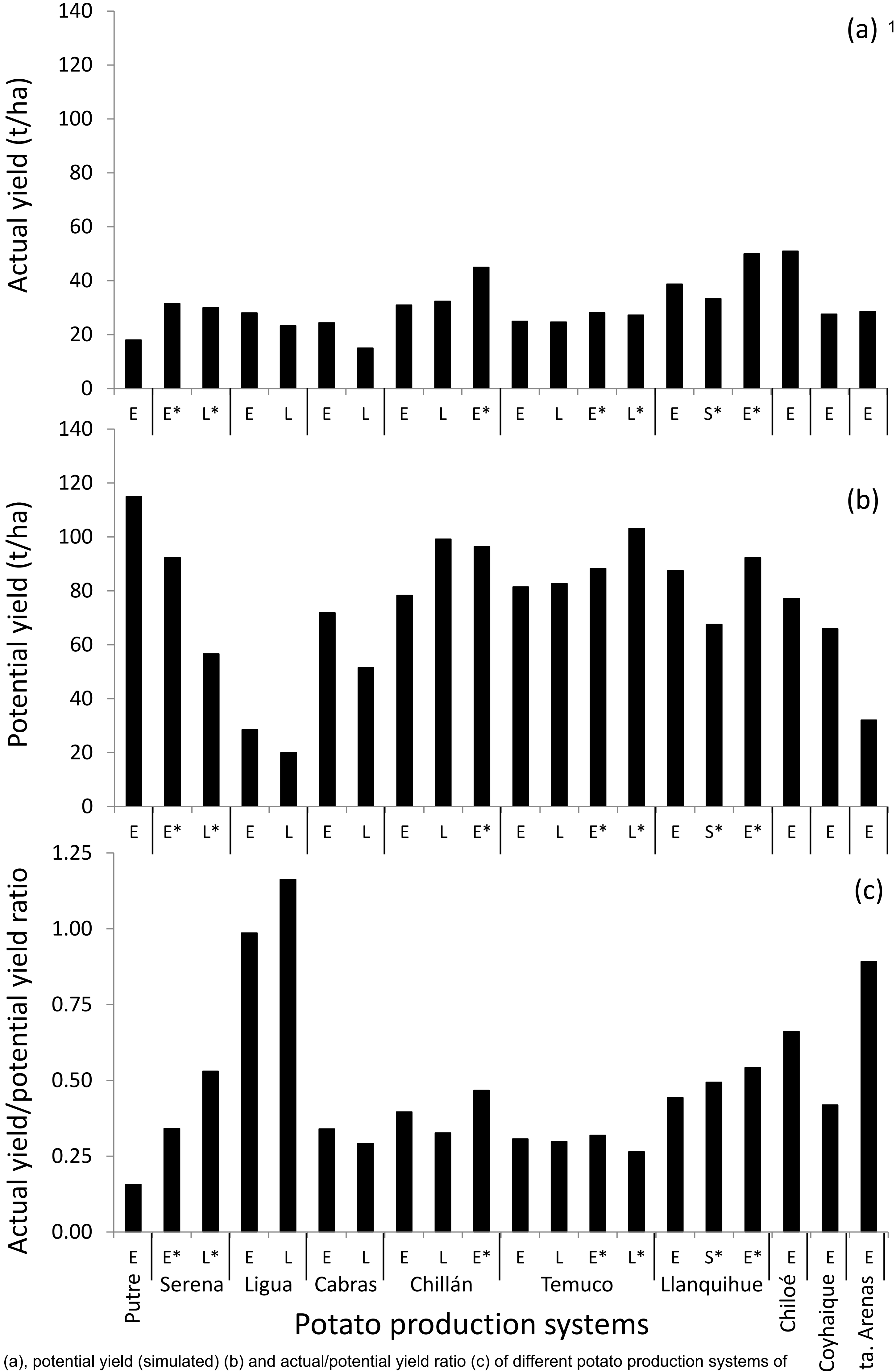

Fig. 3 Actual yield (a), potential yield (simulated) (b) and actual/potential yield ratio (c) of different potato production systems of Chile. E: early planting; L: late plating; S: seed producers; *: potato producers with more than 10 ha

viruses. In addition, there was a clear tendency of large area growers obtaining higher yields than the small holders. In La Serena, La Ligua and Las Cabras early (spring crops planted from June to September) and late planting crops (summer-autumn crops planted from January to March) were identified. In these systems the produce of a later planting and harvest may fetch a higher price but there is a clear tendency that later plantings lead to lower yields. This is due to a shorter growing season (owing to higher temperatures in summer crops) or less solar radiation per day (autumn crops) and physiologically young seed coming from crops harvested in the same location in November (two or so month old). Fig. 3b shows the calculated potential yield using temperature and solar radiation between planting and harvest dates used as model input. With the exception of highland Putre and La Serena there is a clear tendency of increasing potential yields going from the North to the Centre-South of the country (Ligua to Chillán with 24 to 91 t/ha, respectively) maintaining this yield to Llanquihue and then decreasing potential yields in the extreme South (Punta Arenas with 32 t/ha). This is mainly due to the greater length of the growing season in the Centre-South combined with long photoperiod in mid summer and consequently higher incident solar radiation (Table 2) of the spring crops.

In general, as expected, actual yields of potato production systems of Chile were lower (averaging across production systems 31 t ha^{-1}) than the potential yield (on average 74 t ha^{-1}) (Fig. 3a and 3b). Only in La Ligua and Punta Arenas the actual yields were close to the potential yields (Fig. 3c). Apparently in these areas it is easier for growers to obtain yields close to their potential than in areas where potential yields are much higher. On the latter, the actual yields on average were about 40% of the potential yield (gap = 60%) and it was observed a tendency to reduce this gap with increased actual yields (Fig. 4). Apparently high yields are associated with a higher level of technology hence a greater degree of approaching the potential yield which is consistent with what is shown in Fig. 3a that larger farms had higher yields.

Contrary to what was expected, there was no clear relationship between the length of the growing season – that shows a considerable variation between 87 and 185 days - and actual tuber yields (Fig. 5 a). The daily growth rate explained almost 70 % of the variation in reported actual yields (Fig. 5 b) by the interviewed growers. The daily growth rate is more determined by the average daily solar radiation between crop emergence and harvest (ASR in Table 2) and also by the radiation use efficiency which increases with level of technology such as the application of fertilizers, especially nitrogen and irrigation.

Actual and potential water use

Different amounts of water supplied through irrigation per growing season by farmers interviewed in the survey were observed (Fig. 6 a). In the High Andes (Putre) potato production is rain-fed only. Irrigated production systems and the amount of water used decline from North to South with still some irrigation in Chillán and hardly any in still more southerly located production areas. The pattern follows the one of increased precipitation during the growing season from North to South (Table 2). It is also

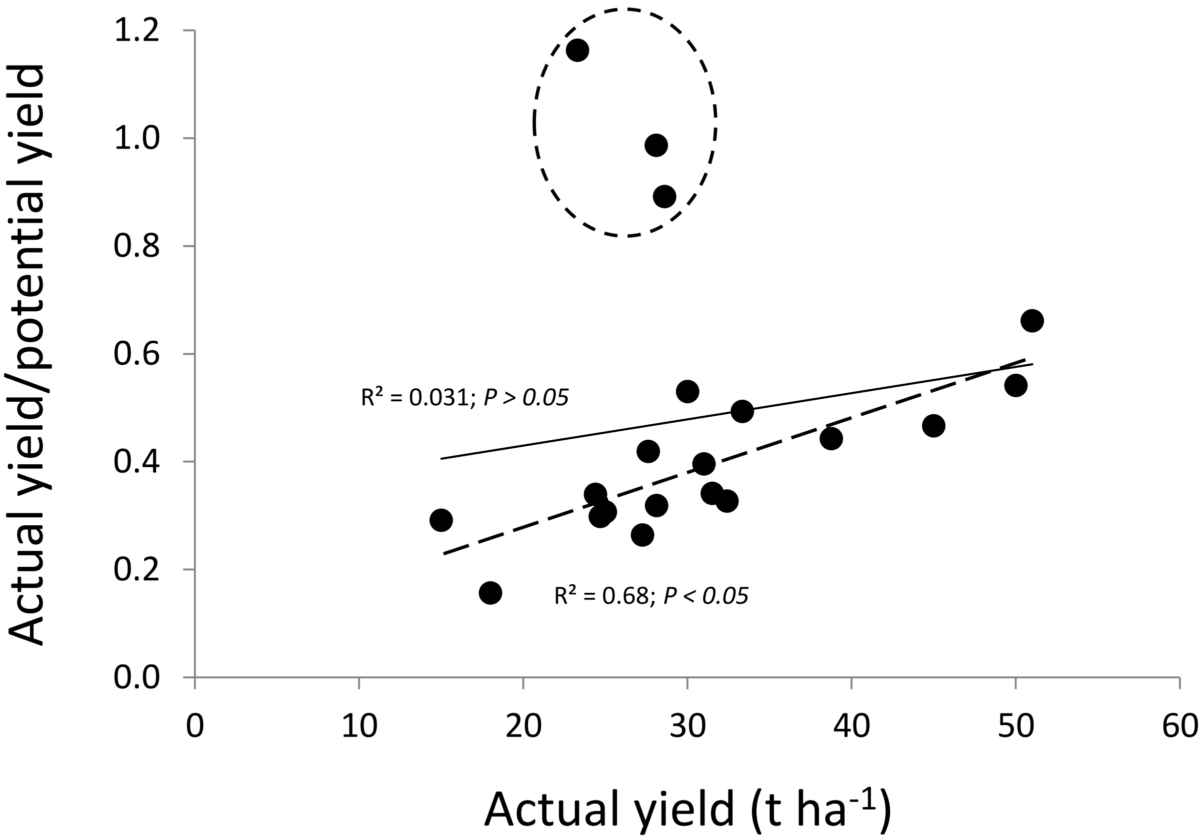

Fig. 4 Relationship between the ratio actual/potential yield and actual yield of 20 potato production systems in Chile. Encircled La Ligua and Punta Arenas systems with low potential yields. Solid line all data, dotted line data from La Ligua and Punta Arenas excluded

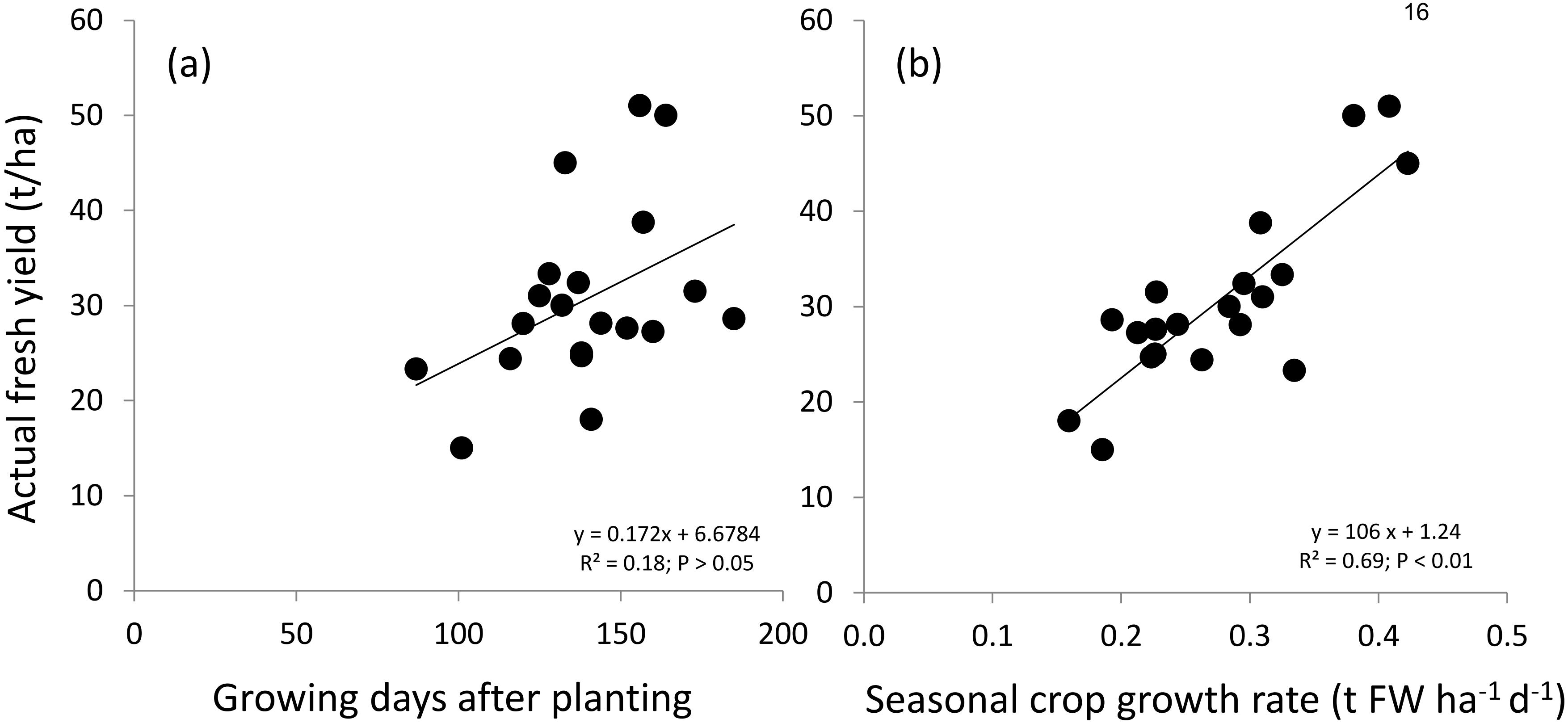

Fig. 5 Relationship between actual fresh yield and growing days after planting (a) and between actual fresh yield and seasonal crop growth rate (b) in different potato production systems of Chile

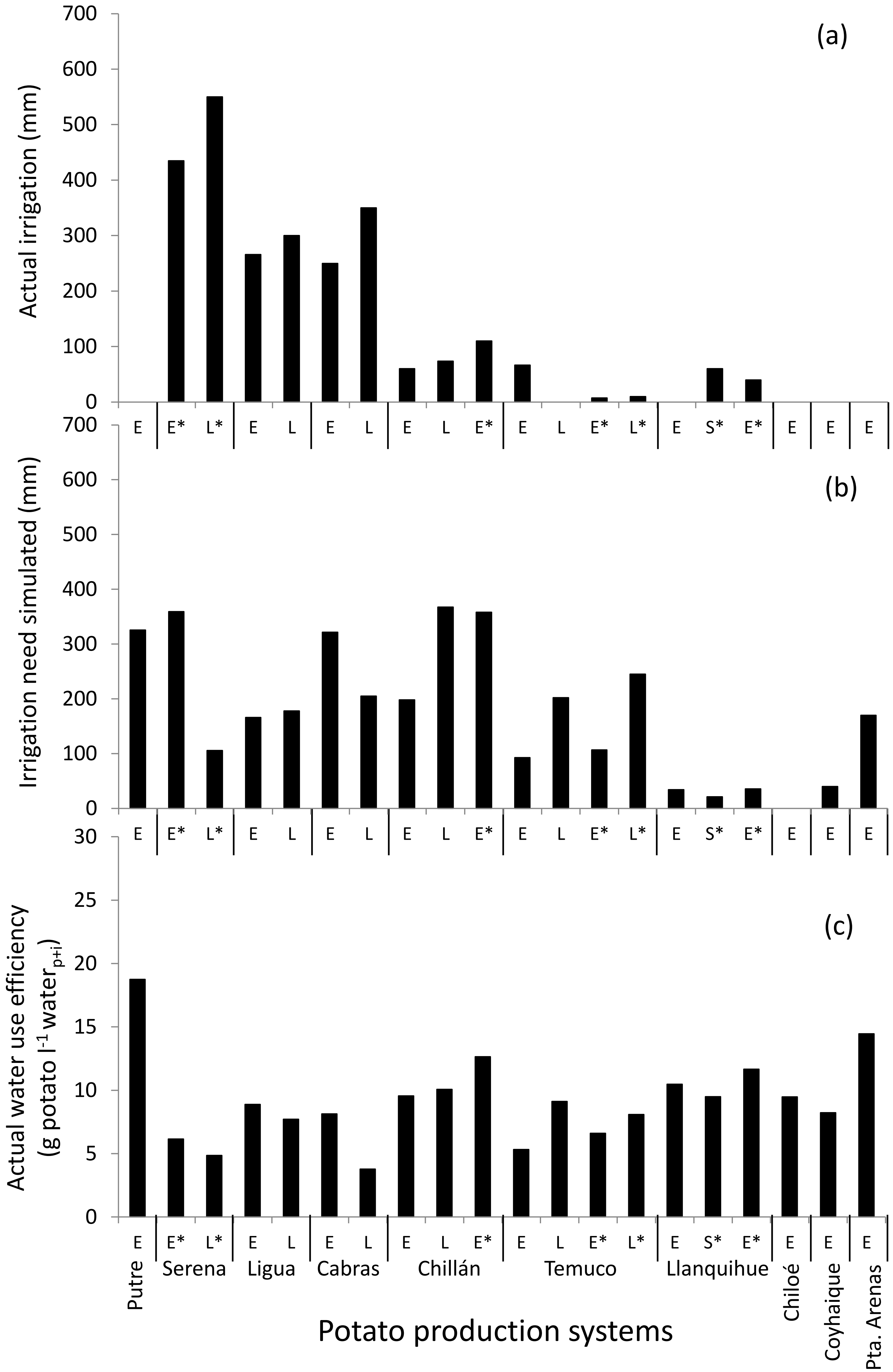

Fig. 6 Actual irrigation (a), simulated irrigation need (b) and actual water use efficiency (fresh yield/(irrigation + precipitation)) (c) in different potato production systems of Chile. E: early planting; L: late plating; S: seed producers; *: potato producers with more than 10 ha

clear that large holdings apply more water than small holdings and in Temuco and Llanquihue only large holdings irrigate and small holders do not irrigate at all. This phenomenon partly explains the higher yields of growers with larger holdings. When observing the calculated amount of water transpired by a crop achieving its simulated potential yield (Fig. 6 b) it is obvious that in many locations there is a clear precipitation deficit that is not met by irrigation. In most areas in the world where adequate irrigation is common practice, growers approximately apply twice the amount of the calculated water needed (Haverkort unpublished data). In the dry North of La Serena, La Ligua and Las Cabras growers indeed apply about twice the calculated amount, whereas in the rainy spring-summer areas – especially the late crops in Temuco irrigation falls far behind the crop requirements. Even the cool location in Punta Arenas has a precipitation deficit of almost 200 mm, but farmers here do not irrigate.

Actual water use efficiency, the ratio between actual fresh yield and the amount of water supplied by rain and irrigation, was clearly different among potato production systems in which water use efficiency ranged between 19 (Putre) and 3.7 (Las Cabras) g potato l^{-1} of water available during the crop cycle (Fig. 6 c). Putre and Punta Arenas showed the highest water use efficiencies owing to low levels of precipitation and lack of irrigation. Potato production systems of La Serena and late planted potatoes of Las Cabras showed the lowest water use efficiencies averaging 5.8 g potato l^{-1} due to an ample amount of irrigation. The resource use efficiency clearly decreases with an increase in the resource availability. The rest of the country showed an averaged water use efficiency of 9 g potato l^{-1}. In Llanquihue with low irrigation need (Fig. 6 b) to reach the potential yield (83 t/ha, Fig. 3 b) the potential water use efficiency was calculated to be 24 g potato l^{-1}. This agro zone showed a considerable gap in water use efficiency showing the scope for improved crop management practices to increase actual yields.

Nutrient use efficiency

Across the 20 potato production systems a large variation was found in the amount of fertilizers applied ranging from 295 to 1010 kg ha^{-1} of fertilizer for Putre and La Serena (late planting), respectively (Fig. 7 a). In addition, Llanquihue and Chiloe showed higher fertilization rates averaging 958 kg ha^{-1}. In the rest of the country, the average fertilization rate was the 672 kg ha^{-1}. The high fertilization rates in the south is mainly due to the high amount of phosphorus applied to crops (300-450 kg P_2O_5/ha) owing to the high phosphorus retention capacity of these soils (volcanic soils). A significant ($P < 0.01$) relationship was found between actual yields and the total amount of fertilization applied during the crops cycle (Fig. 7 b). However, this relationship explained only the 45% of the variation in actual yield.

The crops variation in actual yields and rate of fertilization yielded great differences in the nutrient use efficiency (NUE) of the main macronutrients nitrogen, potassium and phosphorous, ranging from 56 to 445 g potato produced per g^{-1} nutrient applied (Fig. 8 a). The NUE values for the three minerals were significant ($P < 0.01$) and negatively related (R^2 = 0.46, 0.58 and 0.55 for N, P_2O_5 and K_2O, respectively) to the reported nutrient application rate (Fig. 8 a). The nutrient use efficiencies varied

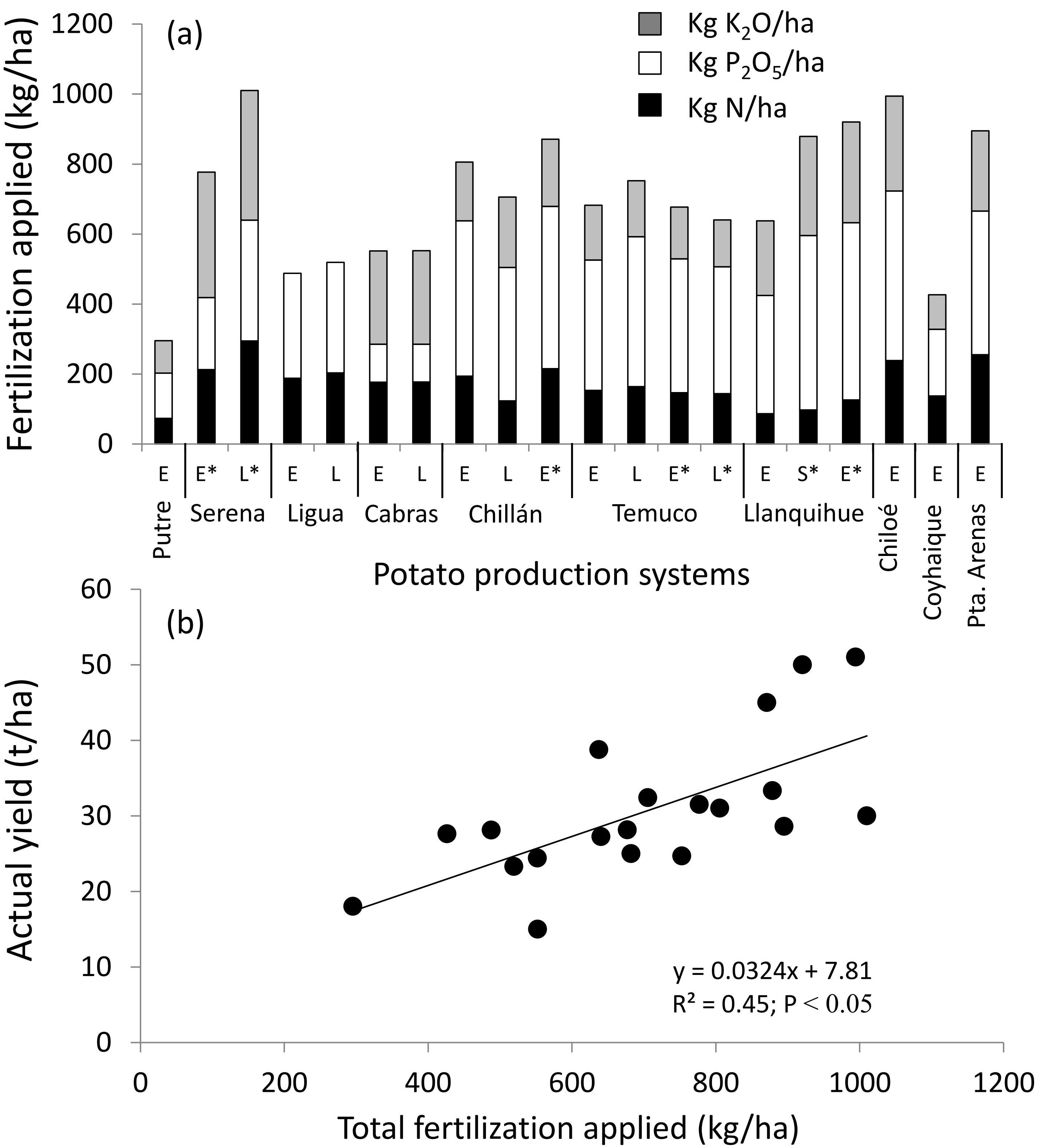

Fig. 7 Amount of N, P2O5 and K2O applied (a) and relationship between actual yield and total fertilization applied during the crop cycle (b) of different potato production systems

considerably in Chile with N use efficiency ranging between 445 and 85 g per gram N; P use efficiency ranged from 225 to 58 g potato per gram P_2O_5 applied and K_2O use efficiency ranged between 280 and 56 g potato per gram K_2O applied. The very high figures are indicative of low application rates and here the soil may be mined for these minerals. The wide range of mineral use efficiencies reflects the wide range in actual yield levels that finds its origin in the differences in yield potential and management practices such as the use of certified seed, irrigation and the application rates of fertilizers per se. On the other hand, no relationship was found between actual yield and NUE values (Fig. 8 b).

Amount of CO_2 per ton of potato and main sources of emissions

The total amounts of CO_2 emitted per ton fresh potato in the 20 cropping systems surveyed are shown in Figure 9. The subsistence cropping system at Putre clearly had the lowest CO_2 foot print of around 50 kg CO_2 per ton potato. This was to be expected as here the use of inputs was low, yields were low but consequently the resource use efficiency was high. Contrastingly, the high input La Serena late crop showed the highest footprint of over 200 kg CO_2 per ton. This high level is mainly due to electricity used for pumping irrigation water of the late crop that grows into early summer with daily high evapotranspiration rates. The late crop also received more fertilizer, especially nitrogen – probably to compensate for leaching associated with the high irrigation level. The same holds for the other late crops in the dry North such as at La Ligua and Las Cabras. The seed crop in Llanquihue had a much higher emission than the ware potato crops due to lower yields but higher levels of inputs, especially pesticides. Chiloé and Punta Arenas showed a low level of CO_2 emission due to the fertilizer manufacture process but yet high levels of fertilizer induced emissions in the soil are observed due to the fact that di-ammonium phosphate instead of triple superphosphate is used.

In general, total CO_2 emissions were correlated ($R^2 = 0.56; P < 0.01$) with CO_2 emission originating from fertilization (Fig. 10). The relationship between the above mentioned variable was enhanced ($R^2 = 0.85$) when data of La Serena (dashed circles) were excluded, considering their high CO_2 emission from irrigation with electricity (averaging 42 kg CO_2/t) in these production systems. No relationship was found between total CO_2 emission and actual yield (data not shown). Averaging across all potato production systems the total CO_2 emission per ton of fresh potato produced was 122 kg CO_2 /t. Main sources of emission (75%) were those related to fertilizer production (35%), fertilizer induced field emission (25%) and seed production (15%).

Concluding remarks

In Chile potatoes are grown in a wide range of ecological zones between 18 and 53 degrees South, between 0 and 3000 meter altitude and as summer, spring, autumn and winter crops; where the growing season is sufficiently long growers may opt for early and late plantings. The purpose may be seed potato production or subsistence such as in Putre or pure cash crops providing capital such as in the case of La Serena. Processing into French fries, crisps or flour is low and important quantities of

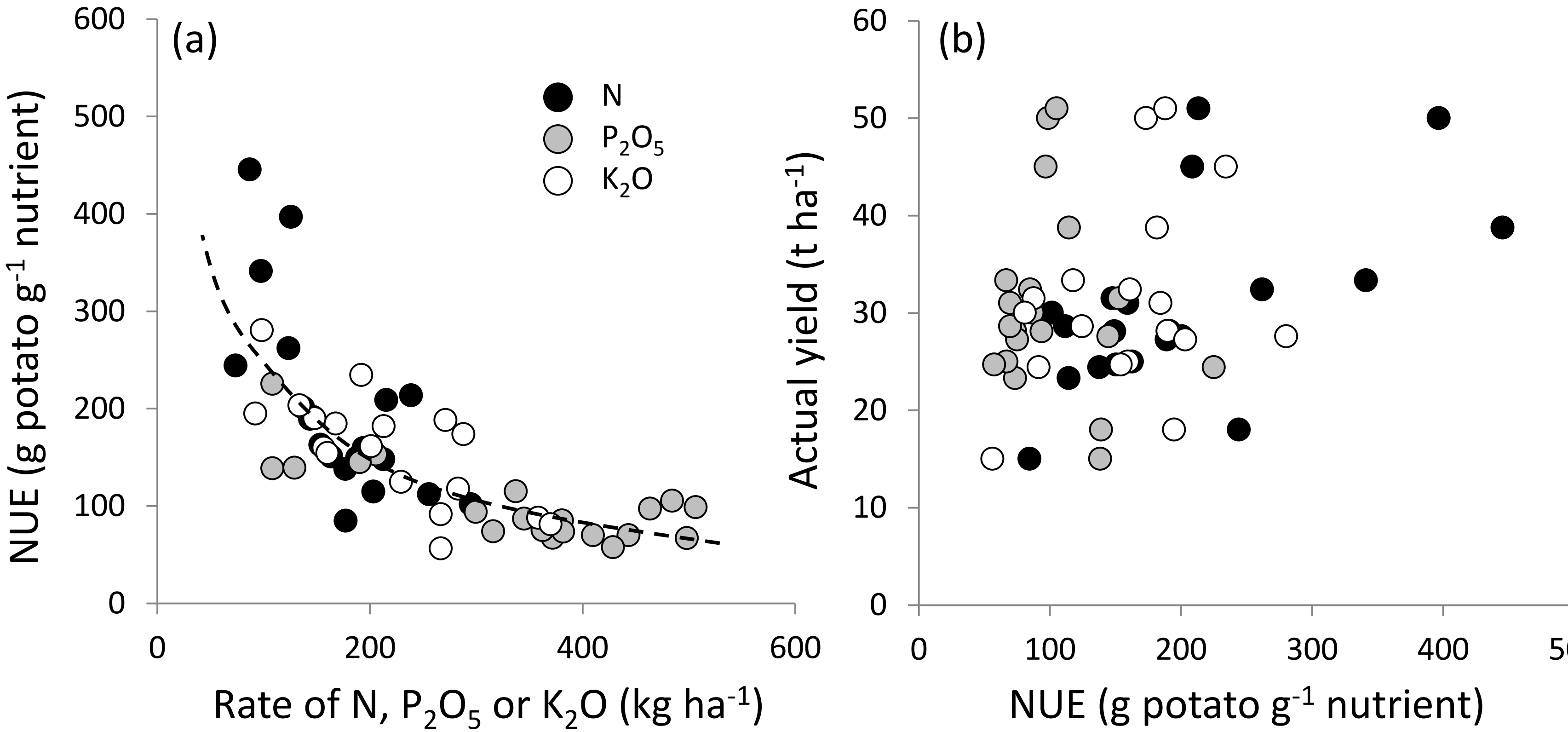

Fig. 8 Relationship between nutrient use efficiency (NUE, g potato g-1 N, P2O5 or K2O) and nutrient application rate (a) and between actual yield and NUE (b) of different potato production systems

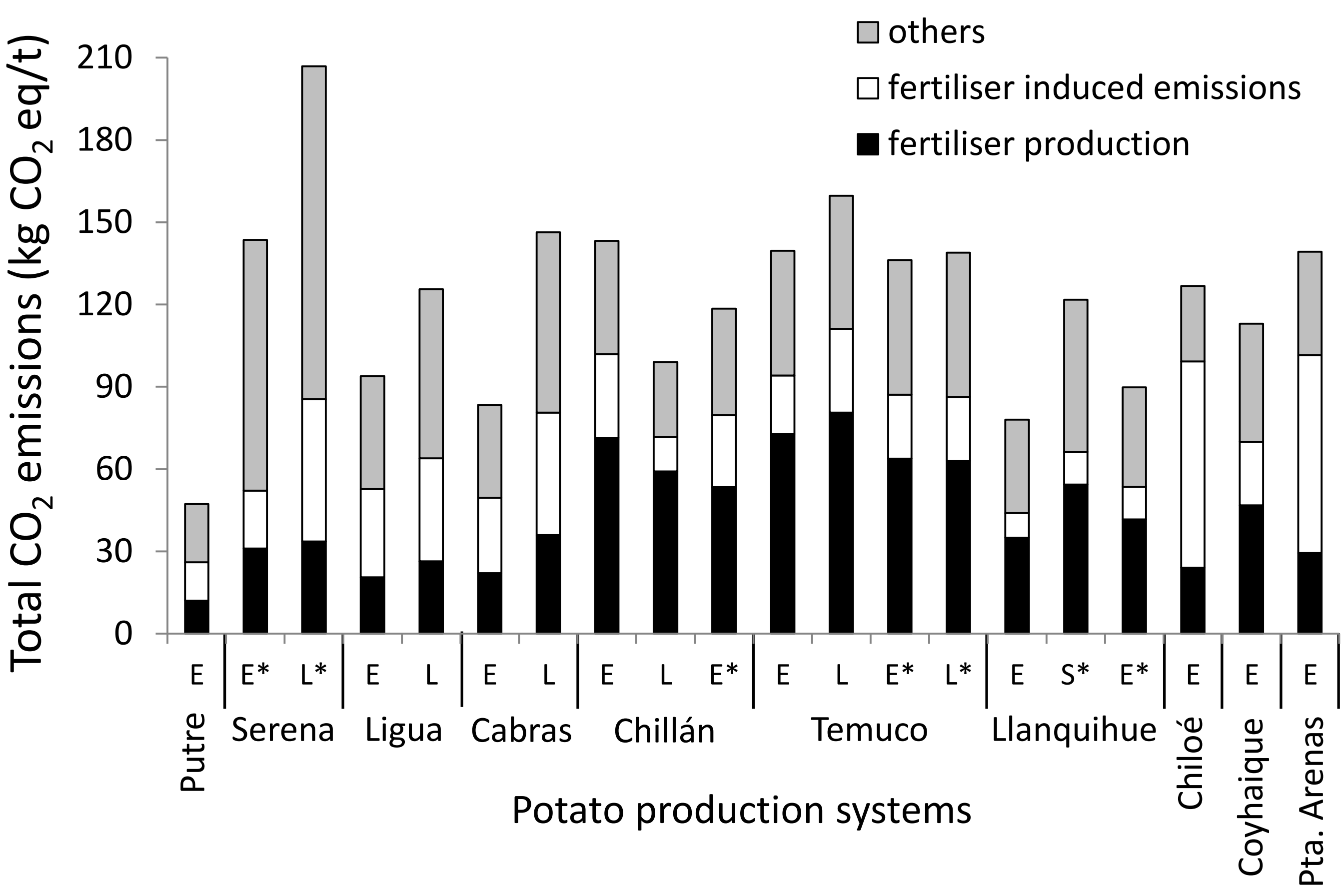

Fig. 9 CO2 emission per ton fresh potato in different potato production systems (a). E: early planting; L: late plating; S: seed producers; *: potato producers with more than 10 ha

frozen and powdered products are imported. The levels of technology differ from subsistence practices – all operations by hand and low levels of chemical inputs – to highly mechanized large holdings in the centre and South of the country. Consequently the ecological footprints, the resource use efficiencies vary considerably: land use efficiencies vary between 17 and 50 t/ha, whereas water use efficiencies may reach high levels, but this is mainly due to lack of irrigation. The nutrient use efficiencies vary considerably in Chile with some very high figures which are indicative of low application rates leading to soil mining and depleted. The wide range of mineral use efficiencies stems from the ample range in actual yield levels found that have its origin in the differences in yield potential observed and in management practices found as using or not certified seed or irrigation and adequate dose and timing of fertilizers and biocides. The energy use efficiency as reflected in the production costs in terms of CO_2 costs per ton of potato varies strongly between the low input subsistence system (55 kg CO_2 per ton) and the high input irrigated spring crops in La Serena (140 kg CO_2 per ton). The majority of the production systems have CO_2 costs between 90 and 150 kg which is common for most parts of the world.

The description, yield gap analysis, ecological foot prints and benchmarking of the potato production systems in Chile allows strategies for improving footprints and profitability and may yield information about future investments in research, development and production of the crop. For low footprints all inputs need to be optimized as then the resource use efficiencies will all increase. In contrast to e.g. North America where land management, inputs of certified seed and chemicals for fertilization and crop protection and center pivot irrigation systems are all optimized, in Chile often one or more of these are sub-optimally used thereby negatively affecting the others. It shows that there is considerable scope to make potato production more efficient, less costly and potentially sufficiently competitive to allow local processing thereby substantially adding value to the potato supply chain in Chile.

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