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The complexity of simple tillage systems

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SUMMARY

In the Central Peruvian highlands, potatoes are commonly cultivated by smallholder farmers in fields between 3500 and 4300 m asl. Severe climatic conditions, marginal soils and limited access to inputs and infrastructure define these challenging agro-ecological environments. To prepare an adequate seed bed for the potato and mitigate climatic, topographic and labour constraints, Andean farmers have developed distinct footplough-based tillage systems: *barbecho*, *chiwa* and *chacmeo*. A series of field experiments was conducted in 2005/06 and 2006/07 at four different locations to investigate the effect of three different tillage systems on potato tuber yield, varying factors such as cultivars and types and amounts of fertilizer applied. The objective was to improve understanding of the effect of these factors on potato yield and study the potential advantages and disadvantages of each tillage system.

The study showed that the type of tillage influenced a great variety of factors. Farmers often use a combination of tillage systems as a strategy to diversify possible risks, considering trade-offs regarding productivity *v.* yield stability, internal *v.* external resource use, labour requirement during peak times *v.* more uniform distribution or extensive *v.* intensive production. The *chiwa* and to some extent the *chacmeo* tillage systems resulted in relatively constant and stable yields for different environments and genetic materials, whereas the more intensive *barbecho* system sought to optimize growth conditions for the potato crop but was more liable to stress and required external resources. Currently, farmers often use the *barbecho* system to produce commercial cultivars for the urban markets investing the greatest share of internal and external resources. They use the *chiwa* and *chacmeo* systems to produce diverse native cultivars for their home consumption, valorizing their taste, cooking qualities and lower resource requirements.

INTRODUCTION

The Central Andean Highlands are the centre of origin of the potato crop (*Solanum* spp.), where over many centuries of potato cultivation several unique production technologies have co-evolved (Halloy *et al*. 2005; Caycho personal communication). Some of these technologies have become widely adopted, whereas others have remained restricted to their centre of invention. Reasons for this regional endemism of selected technologies are probably related to their specific adaptation to the conditions of the Andean highlands and potato cultivation. Nevertheless, with the potato crop expanding, particularly into highland regions of tropical and sub-tropical Africa and Asia, neglected technologies might become useful for regions with similar topographic and agro-ecological conditions.

In the Central Peruvian highlands, potatoes are commonly cultivated in fields 3500–4300 m asl. Andean soils are often of rather marginal quality and highly variable climatic conditions characterize the cropping environment. The risk of crop damage from diverse abiotic factors such as hail, drought and frost is generally high and therefore farmers consciously spread their options across environments through practices such as field scattering while, at the same time, adopting diverse livelihood strategies (Goland 1993; Zoomers 1999). Andean farming systems are generally mixed, integrating both livestock and high levels of inter- and intra-specific crop diversity based on species such as the potato (*Solanum* spp.), oca (*Oxalis tuberosa*), olluco (*Ullucus tuberosus*), mashua (*Tropaeolum tuberosum*), maca (*Lepidium meyenii*),

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quinoa (*Chenopodium quinoa*) and old world crops such as barley (*Hordeum vulgare*) and oats (*Avena sativa*).

The three commonly grown potato cultivar categories (improved, native-floury and native-bitter) are each represented by a different set of botanical species. Improved cultivars generally have *Solanum tuberosum* subsp. *tuberosum* within their pedigree. Native-floury cultivars are extremely diverse and belong to *S. tuberosum* subsp. *andigena*, *Solanum chaucha*, *Solanum goniocalyx*, *Solanum stenotomum* and *Solanum phureja*. Native-bitter cultivars are used for traditional freeze-drying and belong to *Solanum curtilobum*, *Solanum ajanhuiri* and *Solanum juzepczukii*. Improved cultivars are grown in almost all agro-ecologies ranging from sea level to altitudes of up to 4300 m asl and native-floury cultivars are usually cultivated 3500–4300 m asl, i.e. improved and native-floury cultivars are found in these regions without a sharp separation by altitudinal belts. Patchiness and altitudinal overlap are shaped by broad adaptability and multifaceted cropping rationales of farmers (Zimmerer 1998, 1999). However, native-bitter cultivars are mainly grown 4000 m asl.

The main planting season, called *qatun tarpuy* (big planting) in Quechua, starts with farmers planting with the first rains in October/November (spring, southern hemisphere). To prepare an adequate seed bed for the potato and mitigate climatic, topographic and labour constraints, Andean farmers have developed three distinct footplough-based tillage systems.

The footplough or *chakitaklla* is a tool of pre-Inca origin still commonly used throughout the Andes today (Cook 1918; Gade & Rios 1972; Rivero Luque 1990; Hocquenghem 2008). Depending on the region it consists of a shaft 0·8–2·5 m long made out of one or two wooden parts, a footrest on the left to increase the pressure for the digging and an iron share 75–300 mm wide and 200–500 mm long to cut into compacted soils.

The *barbecho* tillage system is predominantly used for improved and commercial native-floury potato cultivars. *Barbecho* consists of turning, breaking and loosening the soil before planting tubers, followed by two separate incidences of hilling. Between February and March, when the soil is still moist, it is turned with the footplough, leaving big clods. During the dry season (June–August) these clods are broken up with a hoe (*chiwaku*; *allachu*) and a more or less fine structured seed bed is prepared (Fig. 1). This same process may also be done with an oxen- or tractor-drawn plough, but in the central Peruvian highlands animal or mechanized traction is generally restricted to the wealthier farmers. *Barbecho* generates a relatively fine structured seed bed with a layer of tilled and loosened soil. For that reason, farmers prefer this tillage system for plain fields.

Chiwa is a type of minimal tillage that starts by making an opening in the pasture, lifting a sod of soil and depositing a potato seed 100–200 mm deep in the soil. Then the seed is covered with the same sod. In this manner, a field is planted in a relatively short time with a spacing of *c.* 250–400 mm between plants and 900–1100 mm between rows. After 4–6 weeks, a ridge with a height of *c.* 300 mm is built on top of the emerging plants with clods of soil dug up from the sites of the potato rows. Simultaneously, inorganic fertilizer or manure is applied. The operation of ridging is the first and only incidence of hilling. Depending on the region, the *chiwa* tillage system is also known as *tipka*, *chuki*, *qaqi*, *imicha* or *yakuycha*. The *chiwa* tillage system is better adapted to planting on slopes compared with *barbecho*. Planting on mountain slopes is a widely used technique in the Andean highlands to make best use of the undulating landscape and to avoid the effect of the night frosts that tend to be more severe in the plains, where the cold air can accumulate and damage susceptible crops, such as potato.

Chacmeo is also a type of minimal tillage and consists of turning two clods of soil on top of the pasture to form a row; seed tubers are planted in between the clods (above the former soil surface level) and hilling is practiced only once. Ridges are built with the *chakitaklla* during January and April. The seed potato is placed in the ridge above the pasture level so that the plant may use nutrients released through decomposition. The *chacmeo* tillage system is well adapted to slope planting compared with the *barbecho* system. In some regions, the *chacmeo* tillage system is also known as *chacma* or *suca*.

Very little is known about the biophysical advantages of these tillage systems and, with few exceptions (Bourliaud 1988), almost no references exist. However, each of the tillage systems has distinct features; some of which may potentially affect crop development, plant growth, tuber formation and finally yield (Table 1). These features may interact with the diverse agro-ecological conditions at these altitudes, as climatic and soil conditions can vary substantially even in small areas (Hervé 1994). Furthermore, the different potato species and numerous cultivars, their respective phenotypes and their distinct demand for growth conditions may also interact with the type of tillage system applied.

The experiment described in the present paper investigated the effect of the three different tillage systems on potato tuber yield and other yield parameters and their interactions with site-specific, agro-ecological factors, with genetic variability represented by the three potato cultivar categories and varying growth conditions influenced by different types and amounts of fertilizer applied. The objective was to improve understanding of the effect of these factors on crop yield and draw lessons concerning the potential advantages and disadvantages of each tillage system.

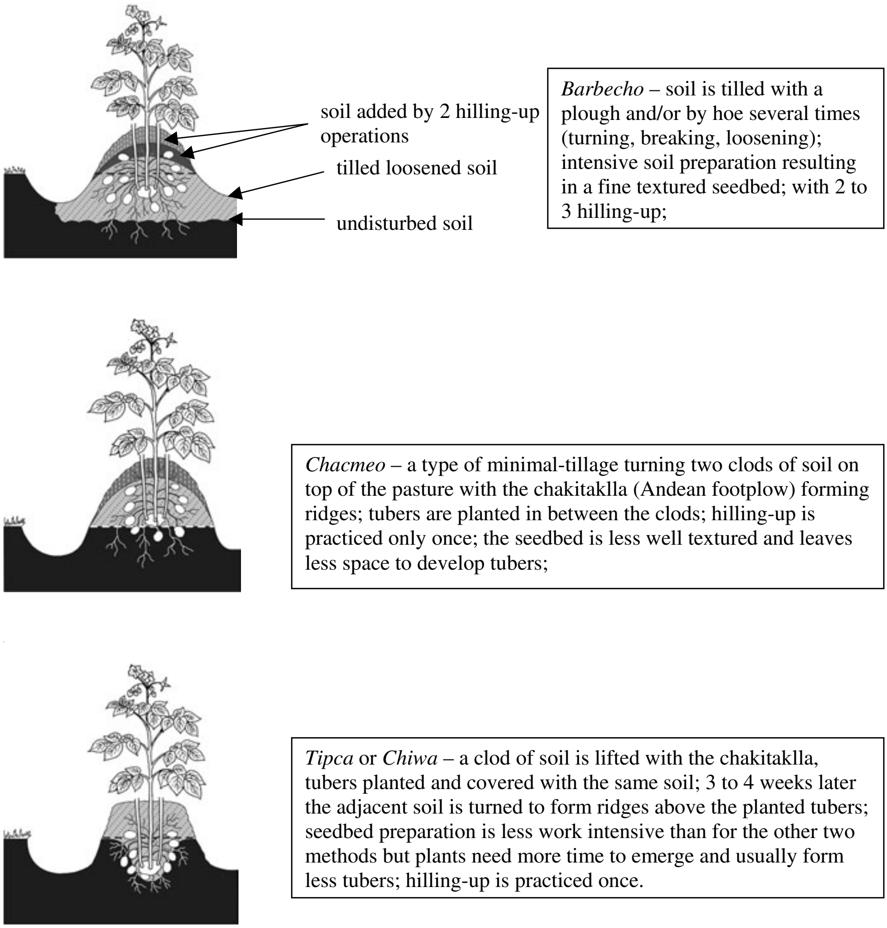

Fig. 1. Characteristics of Andean tillage systems for potato cultivation in high elevation zones.

MATERIALS AND METHODS

A series of five separate field experiments were planted on the communal land of four different farmers' communities in the Central Andean Highland of the Huancavelica Department, Peru. The fields used had been in fallow from 3 to 5 years previous to planting. Two trials were established at 4010 and 4144 m asl, respectively, in the community of Dos de Mayo (18°05′26·9″S, 75°21′10·1″E) during the rainy season from November to May 2005/06. However, the trial at the lower site of Dos de Mayo was affected by water logging and poor seed quality. The harvest results were very variable and were not included in the overall analysis and evaluation of the experiment. In the following season, November–May 2006/07, two trials were planted on the land of the communities of Ccasapata (12°43′26·5″S, 74°45′6·8″E) at 3755 m asl and St. Rosa (12°43′55·6″S, 74°45′50·8″E) at 4102 m asl. Additionally, one more trial was implemented at the community of San Jose de Aymara (12°14′28·44″S, 75°03′59·3″E) at 3994 m asl. Soil characteristics of all trial sites are shown in Table 2 as well as the temperature and relative humidity measurements for St. Rosa and Ccasapata in Fig. 2.

Table 3 specifies the variables determining each trial design: tillage system (A), cultivars (B) and fertilizer applications (C). The trials at each site (except in Aymara) were planted in three separate blocks, each block prepared with a different tillage system. Cultivar and fertilization treatments were applied within each block, completely randomized with four replications. For statistical analysis, each block was first analysed as an independent experiment, and then the variances of the three experiments were compared. As the differences of the error variances did not exceed the factor 2·0, the three separate experiments at each site could be analysed as one trial (Gomez &

Table 1. *Key features of the three foot plough-based tillage systems*

	Barbecho	Chiwa	Chacmeo
Type of tillage	Full tillage	Minimal tillage	Minimal tillage
FTE* days (cultivation; 1 ha of potato)†	121	78	87
Labour intensity of the system	Intensive	Extensive	Moderate
Potato cultivars categories	Improved; commercial native-floury	Native-floury and native-bitter	Native-floury and native-bitter
Number of separate events of hilling	2	1	1
Use of inorganic external inputs	Common	Scarce	Scarce
Contribution to soil conservation	Limited	Positive	Positive

* FTE = full time equivalent.
† Source: De Haan *et al.* (2008).

Table 2. *Soil characteristics for four trial sites of the Central Andes of Peru*

	Dos de Mayo (4144 m)	Ccasapata (3755 m)	St. Rosa (4102 m)	Aymara (3994 m)
pH (1:1 soil:water)	4·7	4·4	6·5	3·9
Soil organic matter (g/kg)	133	47	83	98
Texture	Loamy sand	Sandy loam	Sandy clay	Loamy sand
Sand (g/kg)	554	440	520	580
Silt (g/kg)	320	390	120	340
Clay (g/kg)	126	170	360	80
Total N (g/kg)	3·9	2·6	4·4	3·1
P (mg/kg) (Olsen)	3·3	18·4	9·6	11·5
K (mg/kg)	83·7	111·8	72·2	89
Al/H^+ (me/100 g)	0·64	1·13	0·0	4·2

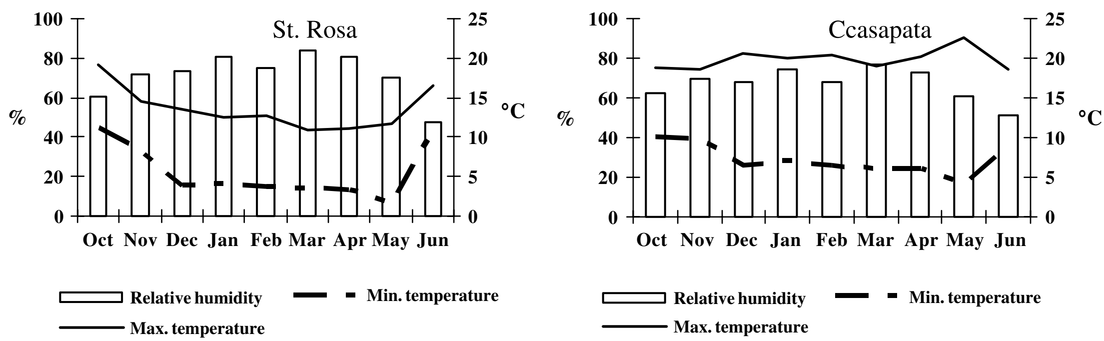

Fig. 2. Climate data for two farmers' communities representing potato cultivations in high elevations (St. Rosa) and on lower fields (Ccasapata).

Gomez 1984). Yield data were subjected to analysis of variance using SAS statistical software. The trial in Aymara was planted as a randomized complete block design for factor A, with factors B and C as split plots on A. Each treatment was replicated four times. The treatments and potato cultivars were the same for the four trials in Dos de Mayo, Ccasapata and St. Rosa. In Aymara, one fertilizer treatment was added. Hence, the trial results from Dos de Mayo, Ccasapata and St. Rosa were combined for statistical analyses to evaluate the effect of the different environments on yield, whereas the trial in Aymara was analysed separately because of its differences in design and treatments.

Table 3. *Treatment factors of a series of experiments conducted in the Central Andean Highlands of Peru during the rainy seasons 2005/06 and 2006/07*

Factor	Type	Level		Trial site
A	Tillage method	*Barbecho*	Tilled with plough	All
		Chacmeo	Tuber planted on soil surface, soil turned on top	
		Chiwa	Tuber planted below soil surface, soil turned after several weeks	
B	Cultivars	Improved cultivar	*Solanum tuberosum* spp. *andigena*	All
		Native-floury cultivar	*Solanum goniocalyx*	All
		Native-bitter cultivar	*Solanum curtilobum*	All
C	Fertilization	Organic	10 t manure/ha	All
		Inorganic	N–P–K 120–100–100 kg/ha	
		Mixed	5 t manure + N–P–K 60–100–100 kg/ha	Aymara

Plots consisted of six rows with 18 plants each, planted with a spacing of 0·90–1·10 m between rows and 0·30–0·35 m between plants, depending on the tillage system. General plot size ranged between 30 and 35 m^2. Fertilizer was applied at planting and hilling-up for all treatments installed in plots prepared with *chiwa*, *chacmeo* and *barbecho*. For all trials, the entire organic fertilizer and the P and K portion of the inorganic fertilizer were applied at the first application date and only the inorganic N fraction was split into two applications, with 60 kg/ha at planting and 60 kg/ha at hilling.

No pesticides were applied in the trials in the communities of Dos de Mayo, Ccasapata and St. Rosa. In Aymara, crops were protected against Andean potato weevil (*Premnotrypes* spp.) by applying phenylpyrazol (Regent) and potato leaf blight (*Phytophthora infestans*) by applying difenconazole (Score) and ethylene bisdithiocarbamate (Dithane M-45 WP NT) at label recommendations.

At harvest, the central rows of each plot were harvested to determine potato tuber yield and the number of tubers harvested. In Ccasapata and St. Rosa, plant emergence was recorded in 2006/07 and tuber sub-samples of each treatment were taken to be oven dried to determine their dry matter content. All trials were planted with the active participation of the respective farming communities.

RESULTS

Soil characteristics and plant emergence

The soils of the four sites had a high proportion of sand and relatively little clay, except for St. Rosa with about 350 g clay/kg (Table 2). Three soils were strongly acidic with pH values between 3·9 and 4·4, which is characteristic for the central Andean highlands. The soil at St. Rosa was almost neutral with a pH of 6·5. All soils had high contents of organic matter ranging between 50 and 130 g/kg, which again is a common feature of Andean soils at these altitudes. Plant available P was low to medium and K concentrations were in the medium range.

Plant establishment and survival were slightly higher in 2005/06 than in 2006/07 with densities of about 3·0 plants/m^2 at harvest compared with 2·8 plants/m^2, respectively. The type of tillage system had some influence with 5–7 % lower plant densities in the *chiwa* system particularly in 2005/06. However, more important in this respect was the choice of cultivar as the native-bitter cultivar had higher densities at harvest than the native-floury cultivar or the improved cultivar (data not shown). In Ccasapata, the lower site, more than 0·90 of all plants of all three cultivars planted in the *barbecho* system had emerged at 47 days after planting (DAP), whereas in the *chacmeo* and *chiwa* systems plant emergence was slower, reaching 0·90 about 2 weeks later (Fig. 3). In all tillage systems, the improved cultivar showed the fastest rate of emergence. The native-bitter cultivar and, to some extent, the native-floury cultivar were clearly slower especially in the *chiwa* system. At St. Rosa, 50 DAP plant emergence was 0·80–0·90 in *barbecho* and *chacmeo* for all cultivars. In *chiwa*, emergence was slower with cultivars reaching *c.* 0·80 at 59 DAP.

General yield observations

Results from the harvests of three trials (Dos de Mayo, Ccasapata and St. Rosa) were combined for their analysis and showed interactions among all factors (site × tillage × cultivar × fertilizer). In order to present and evaluate the data in a comprehensive way, first general observations are shown and subsequently more interactions added to eventually explain the whole complexity of the results. Furthermore, the trial sites were divided into three environments according to their altitude: low (Ccasapata, 3755 m asl),

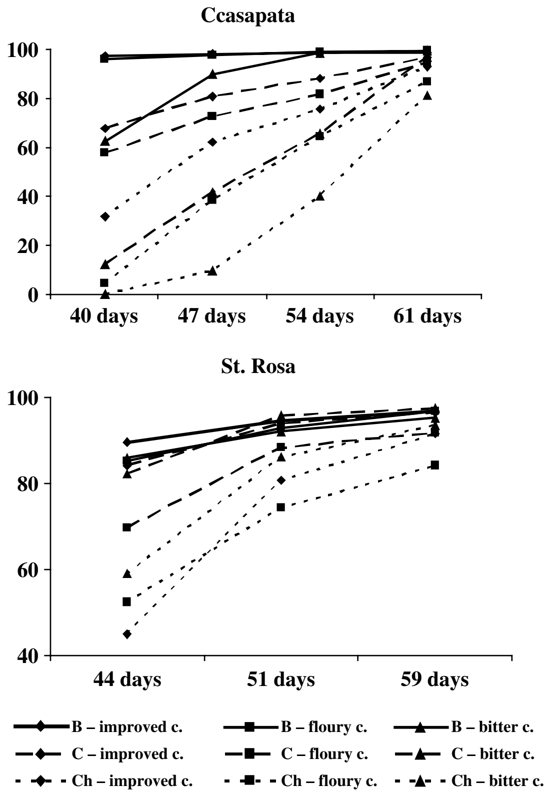

Fig. 3. Plant emergence in percent of three potato cultivars planted with three different tillage systems at two sites during the rainy season 2006/07. B, *Barbecho*; C, *Chacmeo*; Ch, *Chiwa*; c., cultivar.

intermediate (Aymara, 3994 m asl) and high (Dos de Mayo, 4102 m asl and St. Rosa, 4144 m asl). As mentioned earlier, the trial at Aymara was analysed separately. Nevertheless, in its general features the results confirmed findings of the other trials, adding some extra information due to the more detailed study of the response to fertilizer.

Sites

Trials established at lower and intermediate altitudes had greater overall tuber yields (on average 2–4 t more of fresh tubers/ha) compared with the trials at higher altitudes. Differences in yield among the treatments were smaller and less variable for trial sites at high altitude compared with low altitudes (Tables 4 and 5).

Site, tillage system and cultivars

At the low and intermediate sites (Ccasapata and Aymara), potatoes planted in *barbecho* produced greater yields than the ones in *chacmeo* or *chiwa*. At the high sites (Dos de Mayo-alto and St. Rosa), the results were more variable but tuber yields from land prepared with *chiwa* or *chacmeo* were as great as or even greater than yields from *barbecho*. Improved cultivars showed the highest yield potential, out yielding the native cultivars in the *barbecho* system at the low and intermediate sites but not at the high-altitude sites. Under *chiwa* tillage, the yield levels and actual tuber yields of all cultivars were similar at the lower and upper sites (except the native-bitter cultivar in Ccasapata), whereas under *chacmeo* tillage the improved cultivars had greater yields at the lower sites and similar yields at the upper sites as compared with the native cultivars.

Site, tillage system, cultivars and fertilizer

Inorganic fertilizer application always increased yields compared with organic manure irrespective of the site, type of tillage or the cultivar used, except in *barbecho* with the improved cultivar in Ccasapata and in *chacmeo* with the native-floury cultivar in St. Rosa. The reasons for these two exceptions are unknown. However, yield increases differed and ranged from 3 to 10 t/ha depending on the interactions among the different factors. Percentage yield increments were generally lower in the *barbecho* system and greater in the *chiwa* system at the low and intermediate sites compared with the high ones. For *chacmeo*, increments were more variable and no clear trend could be established. They were similar at the lower and intermediate sites (except for the native-bitter cultivar), but differed at the higher sites, being greater at Dos de Mayo compared with St. Rosa. The trial at Aymara showed that an additional yield increase could be achieved with a mix of organic and inorganic fertilizer applications rather than pure organic or inorganic regimes. Although only half the rate of the organic and inorganic fertilizer amounts was applied, yield increments ranged from 2 to 10 t/ha compared with the full inorganic rate.

Yield components – number of tubers/m² and mean weight/tuber

Average tuber weight, number of tubers/m² and dry matter content of tubers were determined for the trials in Ccasapata and St. Rosa (2006/07). Tuber numbers and average tuber weight were clearly influenced by the tillage system, the growth conditions (site and type of fertilization) and the potato cultivar.

The native-floury cultivar produced, on average, more tubers/m² than the improved and the native-bitter cultivar but had also the lowest mean tuber weight for all treatments and sites (Fig. 4*a*, *b*). It produced up to 60 % more tubers at the lower site than at the higher one and had fewer tubers in *chacmeo* at both sites compared with *barbecho* or

Table 4. *Fresh tuber yields in t/ha of different potato cultivars planted in plots prepared with three distinct tillage methods at three sites during the rainy seasons from November to May 2005/06 and 2006/07.* s.e.d. *listed for significant effects only*

	Site											
	Dos de Mayo-alto				Ccasapata				St. Rosa			
Cultivar	Improved cultivar	Native-floury cultivar	Native-bitter cultivar	Mean (sites × tillage × fertilizer) s.e.d. 1·1; (135 d.f.); $P<0{\cdot}001$	Improved cultivar	Native-floury cultivar	Native-bitter cultivar	Mean (sites × tillage × fertilizer) s.e.d. 1·1; (135 d.f.); $P<0{\cdot}001$	Improved cultivar	Native-floury cultivar	Native-bitter cultivar	Mean (sites × tillage × fertilizer) s.e.d. 1·1; (135 d.f.); $P<0{\cdot}001$
Barbecho												
Manure	7	8	5	7	20	17	13	17	6	8	9	7
NPK	16	20	14	17	27	17	18	21	9	13	16	13
Mean	12	14	10		23	17	16		8	10	12	
Chacmeo												
Manure	9	9	6	8	12	9	10	11	7	9	12	9
NPK	20	18	15	18	17	15	13	15	13	8	17	13
Mean	14	14	11		15	12	12		10	9	14	
Chiwa												
Manure	8	10	7	8	8	6	6	7	10	11	9	10
NPK	12	14	13	13	18	16	10	14	16	14	16	16
Mean	10	12	10		13	11	8		13	13	13	
s.e.d. (sites × types of tillage × cultivars) = 1·3; (135 d.f.); $P=0{\cdot}003$												
s.e.d. (sites × types of tillage × cultivars × fertilizer) = 1·8; (135 d.f.); $P=0{\cdot}015$												
Overall sites												
Manure	8	9	6		13	11	10		7	9	10	
NPK	16	18	14		21	16	14		13	12	16	
s.e.d. (sites × fertilizer × cultivar) s.e.d. 1·1; (135 d.f.); $P=0{\cdot}035$												

Table 5. *Fresh tuber yields in t/ha of different potato cultivars planted in plots prepared with three distinct tillage methods at Aymara, rainy season from November to May 2006/07.* S.E.D. *listed for significant effects only*

Cultivar tillage	Improved cultivar	Native-floury cultivar	Native-bitter cultivar	Mean S.E.D. 1·1; (2 D.F.); $P=0.005$	Mean (tillage) S.E.D. 1·4; (2 D.F.); $P=0.009$
Barbecho					18
Manure	16	13	13	14	
NPK	17	15	15	16	
Manure + NPK	29	23	20	24	
Mean (no significant differences)	21	17	16		
Chacmeo					14
Manure	11	8	7	9	
NPK	17	14	14	15	
Manure + NPK	23	19	17	20	
Mean (no significant differences)	17	14	13		
Chiwa					11
Manure	7	7	9	7	
NPK	12	12	11	12	
Manure + NPK	17	14	15	15	
Mean (tillage × cultivar) S.E.D. 1·1; (2 D.F.); $P=0.030$	12	11	12		
Mean (cultivar) S.E.D. 0·6; (2 D.F.); $P<0.001$	17	14	13		

chiwa. Mean tuber weights were similar for the improved and the native-bitter cultivar for the three tillage systems but in *barbecho* and *chacmeo* they were considerably lower at the higher site than at the lower one. In *chiwa*, mean tuber weights were alike at both sites.

Inorganic fertilization resulted in increased tuber numbers for the native cultivars in all tillage systems but for the improved cultivar only in the *chiwa* system. Mean tuber weights were increased for the improved cultivar in all treatments but not for the native-bitter one. The native-floury cultivar generally showed increased mean tuber weights except for the two treatments (Ccasapata – *barbecho* and St. Rosa – *chacmeo*), which were mentioned before as having no yield increases associated with inorganic fertilization (data not shown).

Tuber dry matter yields

The proportion of tuber dry matter was determined to compare fresh tuber weights with actual dry matter production (Fig. 4). The improved and the native-bitter cultivars had 2–4 % higher dry matter contents at the lower site (Ccasapata) compared with the higher site (St. Rosa); only the native-floury cultivar had similar contents at both sites (except in the *barbecho* system). Likewise, tubers grown in the *chiwa* system had the highest content of dry matter at both sites compared with *chacmeo* and *barbecho* for all cultivars. Both native cultivars had considerably higher dry matter contents compared with the improved cultivar. Inorganic fertilization reduced the dry matter content as compared with organic fertilization, especially for the native-floury cultivar and to a lesser extent for the improved and native-bitter cultivars (data not shown).

Therefore, the magnitude of the differences in dry matter tuber yield among potato cultivars grown in three distinct tillage systems varied from those observed with fresh tuber yields (Table 6). In particular, the differences in yield between the improved cultivar and the two native cultivars were altered. For example, in Ccasapata the improved cultivar produced 20 % more fresh tubers in *chacmeo* but yields were similar for all cultivars considering dry matter production. In St. Rosa, the native cultivars produced *c*. 30–50 % more fresh tuber yield in *barbecho* than the improved cultivar but *c*. 100 % more dry matter tuber yield. Likewise in *chiwa* (St. Rosa) all cultivars had similar fresh tuber yields but for dry tuber weight the native cultivars out yielded the improved cultivar by 44 and 30 %, respectively.

DISCUSSION

Soils with low pH and low clay contents are relatively common in the central Andean highlands. These properties affect nutrient availability and might limit crop productivity. Decomposition processes at high altitudes are slow, because of low temperatures, seasonal drought and natural acidity of the soils, resulting

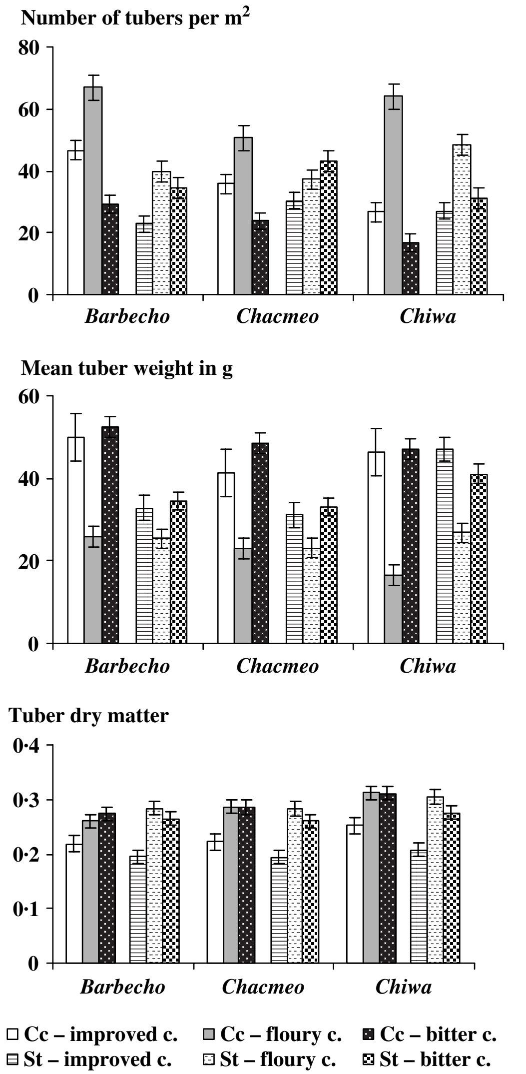

Fig. 4. Tuber numbers/m², average tuber weight in g and percent of tuber dry matter for three potato cultivars grown in different tillage systems at two sites in the Central Andean highlands, rainy season 2006/07. Cc, Ccasapata; St, St. Rosa; c., cultivar.

in an accumulation of organic substance that improves several soil characteristics, such as nutrient and water retention, soil temperature and structural stability of soil aggregates (RuiJun & FuXing 2005; Tang *et al.* 2007). Nevertheless, availability of nutrients, especially nitrogen and phosphorus, is often low, which is one of the reasons why farmers grow at most three to four crops (sometimes only one) before leaving the field fallow or as a natural pasture to recuperate for at least 3–4 years before cultivating it again. For the same reason, farmers always grow potato as the first crop in the rotation cycle. It has a high nutrient demand and it is the most important crop for their subsistence and is therefore provided with the best nutrient supply after fallow. In this context, the tillage system, the way to prepare the soil for planting, is a major component of the solution space farmers make to achieve best use of limited resources such as labour, land, soil fertility, seed or fertilizer for crop production. The term solution space refers to all combinations of values of critical management variables that deliver positive results when a particular technology is used (Reece & Sumberg 2003).

The current experiment showed interactions for the four factors site × tillage × cultivar × fertilization, indicating that the three tillage systems provided different growth conditions to specific potato cultivars in different altitudinal zones. Soil tillage has a direct effect on nutrient mineralization rates and availability of (soil and fertilizer) nutrients for plants but also on water retention capacity and soil temperature and therefore on plant development and yield (Malhi *et al.* 2006; Oorts *et al.* 2006). The cultivars clearly showed different degrees of adaptation to these growth conditions at the different altitudinal levels, expressed as variations of their tuber yield. For example, yields differed considerably between sites, showing increments of 40–160 % in Ccasapata but only of 50–90 % in St. Rosa. Inorganic fertilization was most efficient, producing the greatest rates of increment when applied in *chiwa* at the lower and intermediate sites (Ccasapata, Aymara) as compared with organic fertilization. A possible explanation would be that in *chiwa* the potato plant used most of its reserves to grow from its planting depth, 200 mm below the original soil surface, through the additional soil layer (ridge) turned on top before reaching the sunlight and consequently had an instant high demand for nutrients. These nutrients were more readily available, and in greater quantities, with inorganic than with organic fertilization. Conversely, increments in *chiwa* in the upper fields were lower because other growth factors than nutrient supply, such as water retention, storage of light energy, temperature, etc., might become more decisive.

Manure is essential for the potato crop to be able to use the nutrient supply from inorganic fertilizer effectively. Manure, especially in these adverse agroecologies, has other functions than being only a source of nutrients, often resulting in synergistic effects of organic and inorganic fertilizers. Some reasons substantiating this observation are (i) that organic fertilizer provides specific micronutrients that limit plant growth but are not provided by the 'normal' mineral NPK application (Mallory & Porter 2007), (ii) that soil organic carbon contents are often

Table 6. *Dry matter weights of tubers in t/ha of different potato cultivars planted in plots prepared with three distinct tillage methods at two sites during the rainy seasons from November to May 2006/07.* S.E.D. *listed for significant effects only*

Site	Improved cultivar		Native-floury cultivar		Native-bitter cultivar	
Cultivar tillage	Ccasapata	St. Rosa	Ccasapata	St. Rosa	Ccasapata	St. Rosa
Barbecho						
Manure	4·3	1·1	4·7	2·3	3·6	2·3
NPK	5·9	1·8	4·1	3·6	5·0	4·1
Mean (cultivar × tillage) S.E.D. 0·28; (90 D.F.); $P<0·026$	3·3		3·7		3·8	
Chacmeo						
Manure	2·7	1·3	2·7	2·6	2·9	3·1
NPK	3·8	2·5	4·0	2·2	3·7	4·2
Mean (cultivar × tillage) (no significant differences)	2·6		2·9		3·5	
Chiwa						
Manure	2·2	2·1	2·0	3·5	2·0	2·7
NPK	4·1	3·2	4·7	4·3	2·9	4·3
Mean (cultivar × tillage) (no significant differences)	2·9		3·6		3·0	
Mean (site × cultivar) S.E.D. 0·22; (90 D.F.); $P<0·001$	3·8	2·0	3·7	3·1	3·4	3·5

S.E.D. (sites × types of tillage) = 0·25; (18 D.F.); $P<0·001$.
S.E.D. (sites × types of tillage × cultivars × fertilizer) = 0·54; (90 D.F.); $P=0·024$.

associated with increased water supply capacity of the soil (Liebig & Doran 1999; Barzegar *et al.* 2002), (iii) that soil organic matter increases cation exchange capacity (Black & White 1973), which improves nutrient retention and nutrient availability for the plant or (iv) that application of organic carbon stimulates microbial activity, thereby nutrient mineralization and availability (Tu *et al.* 2006; Srivastava *et al.* 2007) and (v) increases the suppressiveness of soils for plant pathogens (Tamm 2006).

The improved and the native-floury cultivars produced greatest yields when grown in favourable growth conditions, i.e. at the lower sites in a well-prepared seed bed (*barbecho*) and with inorganic fertilization. When these conditions were not met such as at the higher sites, yield reductions were notable. The cultivars produced fewer and smaller tubers, although the native-floury cultivar still showed better adaptation to these conditions than the improved one. A similar effect could be observed when these cultivars were grown in *chacmeo* or *chiwa* at the lower sites; yields were reduced and fewer tubers produced compared with the *barbecho* system. Reasons for this could be the physical and spatial restrictions due to the smaller growth space surrounded by untilled soil in these systems and/or the prolonged and more energy-consuming time to emergence, which renders the young plants more susceptible to stress during early growth.

The bitter cultivar produced relatively constant yields in all three tillage systems at the lower and upper sites (except in Ccasapata), indicating a limited yield potential in more favourable growth conditions but a better yield stability in more marginal conditions compared with the other cultivars. It produced more tubers/m^2 at the higher site, indicating a better adaptation to these growth conditions.

The effect of the type of tillage on the dry matter content of potato was striking. The *chiwa* system increased tuber dry matter content by up to 2%, more pronounced for the native cultivars and less for the improved cultivar. Furthermore, there were other genetic and site-specific differences. The native cultivars produced 5–10% more dry matter than the improved cultivar and there was a tendency for higher dry matter contents at the lower site than the upper one. Hence, an evaluation of the dry matter yields of the different cultivars showed that the yield advantage in fresh tubers of the improved cultivar was mainly due to its better water harvesting capacity but not to an increased dry matter production compared with the native cultivars. At the lower site dry matter yields of the cultivars were similar within the respective tillage systems, whereas at the upper site the native cultivars, especially when fertilized with organic manure, often out yielded the improved cultivar. These facts clearly support farmers' statements that tubers from local cultivars grown in *chiwa* or *chacmeo* and fertilized with organic manure are of a better quality and have a better taste (starchier) than the ones from improved cultivars produced in *barbecho* (Caycho personal communication).

The experiment showed that the tillage system interacted with and influenced a variety of factors. Therefore, farmers have to make complex decisions considering productivity *v* yield stability, internal *v* external resource use, labour requirement during peak times *v* a more uniform distribution or extensive *v* intensive production. The *chiwa* and to some extent the *chacmeo* technique seemed to reduce risks generating relatively stable yields for different environments and genetic material, whereas the *barbecho* system sought to optimize growth conditions for the potato crop but was more liable to stress and the use of external resources, which might affect crop productivity considerably. Presently, farmers often use the *barbecho* system to produce potatoes of improved cultivars for the market, which has specific quality requirements (size, form, colour, disease free, etc.), investing the greatest share of internal and external resources. They use the *chiwa* and *chacmeo* systems to produce native cultivars for their home consumption, valorizing their taste, cooking qualities and lower resource requirements.

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