CHAPTER FOUR

PATHWAYS TO AGROECOLOGICAL INTENSIFICATION OF SOIL FERTILITY MANAGEMENT BY SMALLHOLDER FARMERS IN THE ANDEAN HIGHLANDS

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Abstract
Small farmers in the high Andes (>2500m) of Bolivia, Ecuador, and Peru face increasing threats to their livelihoods due to land degradation, climate change, and overall decreases in agricultural productivity. The fragile nature of these agroecosystems and limited capacity of resource-poor farmers in the region to adopt the large-scale use of conventional fertilizer and pest control technologies suggest the need for agroecological intensification to restore soil functioning and ensure long-term sustainability in these systems. This review addresses soil fertility decline from a management perspective and considers six basic approaches to enhance nutrient cycling, crop nutrient acquisition, and long-term productivity. A mass balance approach first defines basic boundaries for nutrient cycling and suggests that erosion control and identification of alternative nutrient sources (e.g., peri-urban wastes, rock phosphate) are critical for reversing negative nutrient budgets. Meanwhile, short-term nutrient dynamics could benefit greatly from improved management of organic residues in combination with low-level inorganic fertilizer applications. There is also a need for greater understanding of soil physiochemical properties throughout much of the Andes and the impacts of management. Similarly, soil biological functioning is critical for successful agroecological intensification and there is great potential for both inoculative and management strategies to promote beneficial soil communities. Crop breeding for smallholder environments should complement strategies of agroecological intensification, taking advantage of high regional agrobiodiversity and experience from stress breeding programs in other regions. Finally, we suggest several means by which the spatial and temporal organization of farms may be improved to enhance overall agroecosystem function.

1. Introduction: Agricultural and Soil Fertility Issues in the High Andes

1.1. Cropping systems of the Andes
Agriculture in the tropical Andean highlands (>2500m) represents a diverse mix of cultures and cropping systems dating back several millennia (Sandor and Eash, 1995; Stanish, 2007). Today, these agroecosystems are largely managed by smallholder farmers in rural communities growing a mix of old and new world crops across a range of socioeconomic and environmental settings. Although potato (Solanum spp.) has long dominated food production in the region, other important crops include grains (e.g., maize, quinoa, barley, oats), legumes (e.g., fava beans, peas, Andean lupine—tarwi), other native tubers (e.g., oca, mashwa, and ullucu), and a wide array of vegetables (e.g., carrots, onions, cabbage). Livestock remains an integral part of these agroecosystems and includes native camelids (e.g., llama and alpaca), cattle, sheep, chickens, and guinea pigs (cuyes). Mixed crop-livestock farming
generally dominates areas below 3800 m; livestock becomes more important with altitude, as frosts become increasingly limiting to crop production. Generally speaking, there exists an altitudinal gradient of agricultural intensity, with more intensive management and the production of more diverse crops possible at lower altitudes and more extensive systems at higher elevations. Agroecosystems throughout the high Andes employ diverse cropping strategies and a range of farming intensities, from low-input sectoral fallow systems, which typically involve several years of cropping followed by 3–15 years of grazed fallow (Orlove and Godoy, 1986; Pestalozzi, 2000), to more intensively managed permanent structures such as terraces (andenes) and raised beds (wanku or suka) (de la Torres and Burga, 1986). More recently, industrial agriculture has introduced mechanized tillage and agrochemical inputs to enable continuous cropping across large expanses, particularly at lower altitudes. The distribution of these management practices varies considerably depending on cultural, geographic, and demographic factors. For example, higher population densities and relatively short distance to markets in peri-urban agricultural areas have led to more intensively managed, high-input commercial agriculture, while more geographically isolated regions in the Andes show greater emphasis on low-input, subsistence farming (Caycho-Ronco et al., 2009). Environmental constraints also play a critical role, as precipitation, temperature, and soil type are highly variable throughout the region and largely determine what crops can be grown.

1.2. Biophysical limitations and risks

Despite the diversity of agroecosystems in the tropical Andean highlands, agriculture is limited by a common set of environmental constraints throughout the region (Stadel, 1991). Climate plays perhaps the most important role (Fig. 1A and B). With little access to irrigation, most agriculture in the region is rainfed, leading to yield depressions when rainfall frequency is low and crop failure in drought years, with severe implications for overall yield stability. This threat is perhaps more critical for the relatively arid Altiplano, as well as inter-Andean valleys of Bolivia and the western slope of Peru, than in the northern Andes where annual precipitation is generally higher (Fig. 1A; Bottner et al., 2006; Geerts et al., 2006). Cool temperatures, especially at high elevations, limit growth and increase the risk of damage incurred by frost and hail. Meanwhile, the mountainous nature of the region results in many farms being dominated by sloping, rocky terrain with high inherent spatial heterogeneity in soils and microclimate (Buytaert et al., 2007; Zehetner and Miller, 2006). With a few exceptions, soils in the high Andes are generally thin, fragile, and highly nutrient limited. Although the volcanic soils (Andosols) of Ecuador and northern Peru (Fig. 2) can be more fertile due to their high soil organic matter (SOM) content and more favorable soil structure, this depends greatly upon weathering conditions and the parent materials on which they
formed. For example, allophanic Andosols represent some of the most fertile soils in the world, while non-allophanic Andosols, which dominate the Ecuadorean highlands (Poulenard et al., 2001), can have severe problems of phosphorus deficiency (due to high P-fixation), acidity, and aluminum toxicity (Dahlgren et al., 2004). Meanwhile, soils of the central Andes (southern Peru and Bolivia; Fig. 2) are generally low in SOM and nutrient content, coarser in texture, highly susceptible to erosion, and on average have a more neutral pH (Bottner et al., 2006; Cárdenas et al., 2008; Valente and Oliver, 1993). Despite these generalities, it should be noted that targeted management with manure and fallows on less vulnerable parts of farmed landscapes can lead to localized areas of high fertility that support impressive productivity (García, 2011). Also, in contrast to the highly weathered lowland soils commonly associated with tropical latitudes, many soils in the central Andes are similar to Ustic soils found in temperate regions (e.g., southern Europe, parts of North America), thus permitting some degree of knowledge transfer on management from these better studied regions.

It is generally accepted that crops face the greatest threat from specialist herbivores, both pests and pathogens, in their centers of origin (Jennings and Cock, 1977). The Andean region is no exception. For example, potatoes in the Andes face the dual threats of potato late blight and several species of potato tuber moths, weevils, and nematodes, each with the

**Figure 1**  Average annual precipitation (A) and temperature (B) for the Andean focus region (Ecuador, Peru, and Bolivia). The maps were generated using the WorldClim database (http://www.worldclim.org) following methods of Hijmans et al. (2005).
potential to cause total crop losses. In recent years, the severity of pest problems in the Andes has increased significantly, presumably due to the influences of agricultural intensification and climate change, among other factors (Parsa, 2010). Despite abundant research, solutions to these problems are lagging, particularly for neglected crops such as oca (*Oxalis tuberosa*), which are facing increasing farmer abandonment due to heavy pest infestations (Hersh, 2000).

1.3. Socioeconomic and cultural setting of Andean agriculture

In addition to constraints imposed by climate, soil type, and pests, many farmers in this region have limited access to a number of basic agricultural inputs such as fertilizer, pesticides, improved crop varieties, mechanized tillage, and irrigation. Although traditional agriculture may have been largely sustainable for centuries in the absence of these inputs (Dick *et al.*, 1994), recent pressures (e.g., population growth, market access, local attitudes,
climate change) have created more demand for their use (Sarmiento et al., 1993). Locally available inputs of organic matter have also become more limiting, due to increasing demand for fuel and fodder, as well as lower biomass production—driven by declining soil fertility and competing land uses (Orsag, 2009; Swinton and Quiroz, 2003). A long tradition of agriculture in the region, combined with the preservation of indigenous cultures and knowledge, has endowed many Andean communities with a sophisticated level of agroecological management (Sandor and Furbee, 1996; Winklerprins, 1999). However, due to rapidly shifting agricultural, climatic, and socioeconomical contexts, new information and increased knowledge exchange are needed to help farmers adapt to emerging challenges.

Access to agricultural inputs and external knowledge is especially limited for rural communities located far from population centers. Due to their isolation, imported products have a higher cost and technology transfer (both externally and locally) is often slow, while the distance to markets is so great that farmers have little incentive to invest in their land beyond what is needed for home consumption and local trade (Swinton and Quiroz, 2003). Poverty also represents a significant obstacle, as poor farmers have neither the monetary resources to invest in new technologies nor the economic luxury to assume the risk that is associated with these activities. These issues are particularly relevant for the Altiplano, where poverty levels greatly exceed the national averages for Bolivia and Peru, and over 60% of the population lives in rural areas (Quiroz et al., 2003). Labor shortages can also limit farmer investment in rural areas, as more farming families seek to diversify their incomes through off-farm employment (Zimmerer, 1993).

In addition to resource access, other factors influence farm productivity and farmers’ ability to adopt new technologies. For example, land tenure can greatly influence farmer decisions, as farmers are generally reluctant to invest in long-term agriculture improvements (i.e., soil conservation structures, proper management of SOM) on land that they do not own (Tenge et al., 2004). Ongoing shifts in land management from communal to private control represent another unique facet of Andean agriculture that effectively results in smaller management units and intensification of these fields (Cárdenas et al., 2008; Mayer, 1979). Despite the potential for more rapid innovation to occur under individualized management, growing evidence suggests that a lack of coordinated community decision-making about agricultural practices can exacerbate problems of soil fertility, livestock management, and pest regulation (Mayer, 1979; Orsag, 2009; Parsa, 2010). Local and cultural food preferences also affect farmers’ use of agricultural inputs and practices. For example, many farmers choose not to grow improved potato varieties or use agrochemicals for crops consumed at home or sold locally, as they feel that traditional practices and varieties yield superior taste and quality (Caycho-Ronco et al., 2009).
1.4. Current challenges and emerging threats

Despite a long agricultural history in the region, a number of issues in recent decades have emerged that threaten the long-term capacity of these agroecosystems to provide food and key ecosystem services. Population growth and the overall increase in food demand clearly play a role in agricultural intensification (Orsag, 2009; Winters et al., 1998); however, a number of technological and societal transformations have also contributed to degradation and the loss of soil fertility in the Andes (Córdoba and Novoa, 1997; Winters et al., 1998). The introduction of new technologies, such as mechanized tillage and chemical fertilizers, have aggravated SOM loss and erosion (Poulenard et al., 2001; Quintero, 2009; Sarmiento et al., 1993), while other forms of intensification (e.g., reduced time under fallow) can have similar impacts across a range of farming conditions (Pestalozzi, 2000; Sarmiento and Bottner, 2002). At the same time, local labor shortages and high emigration (more typical of rural areas) can lead to de-intensification and resultant increases in erosion, due to the associated deterioration of soil conservation structures or continued soil loss from fields with degraded vegetation and poor soil cover (Harden, 1996; Wiegers et al., 1999; Zimmerer, 1993). Soil degradation is often a self-perpetuating process, where declining crop productivity drives farmers to bring new and often more marginal lands under production (Kessler and Stroosnijder, 2006). These newly cultivated lands are often at higher elevations, on steeper slopes and/or on inappropriate soil types, and thus more susceptible to erosion and soil degradation (Córdoba and Novoa, 1997; Hořínek et al., 2002; Poulenard et al., 2001), and also possess lower yield potentials. Apart from issues of soil degradation and sedimentation, the colonization of natural areas threatens key watershed services (Buytaert et al., 2002, 2006; Hofstede, 1995) and regional biodiversity (Jaimes and Sarmiento, 2002; Lawler et al., 2009).

In addition to the direct consequences of human intervention in Andean landscapes, climate change presents a grave threat to highland farmers in the region (Perez et al., 2010; Valdivia and Quiroz, 2003; Valdivia et al., 2010). Although an increase in temperature and elevated CO$_2$ may increase potential crop growth in some areas (Buytaert et al., 2010a), higher variability in climate (particularly more erratic precipitation) along with reduced glacial water supply (Bradley et al., 2006) are causes for great concern. Additionally, warmer temperatures combined with stronger winds will likely increase evapotranspiration, thus further exacerbating issues of crop water stress. While overall changes to total precipitation are unclear, rains may start later in the year and are expected to become less frequent with higher intensity (Thibeault et al., 2010; Valdivia et al., 2010). Impacts of climate change on soils are perhaps less clear. While greater plant productivity in some areas could contribute to SOM, this may also lead to increased
soil nutrient depletion (van Groenigen et al., 2006). Decreased plant cover and increased variability in precipitation in some areas will likely result in greater erosion and subsequent nutrient loss. At the same time, higher temperatures will likely accelerate losses of soil C due to decomposition of SOM (Buytaert et al., 2010a; Davidson and Janssens, 2006) and can negatively impact soil decomposer communities (Briones et al., 2009).

High microclimatic heterogeneity, complex topography, and low resolution of global climate models generate substantial uncertainty regarding future climate predictions in the Andes and limit the ability of farmers and regional decision makers to anticipate and adapt to these changes (Buytaert et al., 2010b; Valdivia et al., 2010). Alterations to climate along with agricultural intensification may lead to increased pest pressure, as warmer weather can favor pest reproduction and weaken plant resistance due to increased water stress (Bale et al., 2002; Garret et al., 2006). Farmer surveys and preliminary evidence suggest that climate change is already yielding negative impacts on Andean croplands via enhanced water deficits, erosion, and SOM loss (Aguilera, 2010) and emphasizes the need to develop new agricultural strategies that improve ecological resilience and flexibility of agroecosystems.

1.5. Ecologically based intensification in the Andean context

The great challenges that lie ahead for the Andean region indicate the need for drastic intervention to counteract widespread degradation and help farmers adapt to rapidly changing conditions. Agricultural intensification based solely upon ‘green revolution’ technologies may not be adequate or desirable, given the complex socioeconomic setting and relative environmental fragility of the region. Great heterogeneity in climate, topography, soil type, and culture further hinders the implementation of broadly prescribed solutions (e.g., improved cultivars) and emphasizes the need for locally adapted technologies that address the specific constraints of each region. The unique cultural needs and ecological complexities of the Andes underscore the need for ecologically based approaches that seek to maximize long-term stability rather than short-term economic return. In the context of soil fertility, such agroecological intensification needs to focus on utilizing and augmenting the supply of locally produced and renewable soil fertility resources (e.g., manure, cover crops, compost) and optimizing nutrient use efficiency throughout the farm. Soil fertility and general management practices should aim to promote beneficial soil organisms, biological transformations that increase nutrient availability, and a greater coupling of nutrient cycles (especially N and P) with C turnover (Drinkwater and Snapp, 2007).

The Andean region offers a valuable test case for such agroecological intensification due to a number of key attributes: (1) a high diversity of crops, genotypes, management strategies, and growing environments
(e.g., NRC, 1989); (2) a burgeoning environmental consciousness and societal support for indigenous crop varieties and practices (Bebbington et al., 1993; Vargas, 2009); (3) a valuable history of local knowledge and agricultural extension; and (4) a relatively low population density that allows for additional flexibility in exploring alternative technology options. Taking into consideration the above ecological principles and unique assets of the region, this chapter seeks to evaluate past research on soil fertility in the tropical Andean highlands and explore the most promising options and potential synergies for agroecological intensification in the region. We consider promising soil fertility technologies and research from other parts of the world, with key economic and/or environmental similarities to the Andes, as potential sources of innovation. The review was conducted to generate recommendations for strategic on-farm interventions as well as promising areas of future research in soil fertility to advance sustainable agricultural development in the region.

2. Examining Soil Fertility and Management Strategies in Smallholder Systems

2.1. General concept of soil fertility

In this review, we employ an integrative definition of soil fertility that considers nutrient availability as well as the suite of physical, chemical, and biological aspects that characterize the soil environments and the ecosystem services they provide. Additionally, we consider co-limiting factors to crop growth as they have important implications for nutrient uptake and crop productivity. This section attempts to address soil fertility from a management perspective, considering six basic approaches for improving overall nutrient cycling, crop nutrient acquisition, and long-term productivity. These are: (1) a mass balance consideration of agroecosystem nutrient flows; (2) short-term nutrient dynamics; (3) physiochemical environment of soils; (4) the biological functioning of soils; (5) plant breeding for agroecological intensification; and (6) the spatial and temporal organization of farms. Alternatively, these approaches may be viewed as responses to common soil fertility problems in smallholder farms.

2.2. Approaches to examining soil fertility

2.2.1. Mass balance

One of the simplest, yet most valuable approaches for evaluating long-term soil fertility dynamics of agroecosystems is to consider an overall budget of nutrient input versus output (Cobo et al., 2010; Smaling and Fresco, 1993). This approach considers both intentionally managed imports (e.g., fertilizer,
manure) and exports (e.g., nutrients in crops or livestock produced for market), as well as unintended nutrient transfers (e.g., such as nutrient inputs in irrigation water and atmospheric deposition; and export due to erosion, burning, and nutrient loss via leaching or gaseous emissions). According to this perspective of fertility management, the nutrients entering a system must match or exceed nutrient outflow in order to maintain long-term yields (Fig. 3). Although N and P are the most limiting nutrients to agriculture in the Andes (Bossio and Cassman, 1991; Devaux et al., 1997), other nutrients such as K, S, and Ca may become limiting as well under a variety circumstances (de Koning et al., 1997; van de Kop, 1996; Vanek, 2010). Improved

Figure 3  Generalized nitrogen flow diagram for a typical smallholder field, incorporating spatial scales of nutrient sources. Rectangles represent the boundaries of the field (inner solid rectangle), household or farm management unit (outer rectangle), and boundary between the community scale and urban markets that supply inorganic fertilizer and other external fertility materials and also are a destination of marketed agricultural products and N export. Drawing shows that some N is cycled internal to the field and most crops and residue nutrients are cycled internally within farms or lost to erosion. Rangeland can represent an important fertility resource accessed via livestock grazing in extensive systems in the central Andes. Arrows represent approximate size of loss pathways.
management of soil fertility at this level needs to focus on improved nutrient recycling within agroecosystems and requires careful understanding of system inputs and losses. We recognize the mass balance approach as useful starting point that forces a consideration of system boundaries and long-term sustainability. However, we emphasize that whole system nutrient budgets often embody large uncertainties and neglect critical details of internal cycling and nutrient inputs via weathering.

Nutrient removal from agroecosystems via crop (or livestock) export often represents the most important mode of nutrient loss in cropping systems (Smaling et al., 1993; Vitousek et al., 2009) and understanding these losses is fundamental to ensuring long-term productivity. For example, crop export of K has been estimated to exceed other mechanisms of K removal (i.e., erosion, leaching) by an order of magnitude in some Andean cropping systems (de Koning et al., 1997; Vanek, 2010). Removal of N and P in crops can also be quite large, but not always the dominant mechanism of loss in the Andes. Given that the export of nutrients via harvest is ultimately desirable, as it relates to yield and the nutritional value of a crop, efforts to balance nutrient budgets are best focused on a variety of other, unintended mechanisms of loss.

Due to the steep terrain and general vulnerability of soils in the Andes, rates of erosion can be high (Alegre et al., 1990; Harden, 1988, 1993) and have garnered considerable attention in past years. Erosion represents a critical mechanism of nutrient loss for agroecosystems in the region. For example, rates of soil loss for agricultural fields in the Peruvian Andes have been estimated on the order of 10–100 Mgha⁻¹ yr⁻¹ (Felipe-Morales, 2002; Romero-León, 2005). Applying a conservative estimate for soil N content of 1 gN kg⁻¹ soil in the surface layer (Sandor and Eash, 1995) and a loss rate of 50 Mgha⁻¹ yr⁻¹, this translates into an annual loss of roughly 50 kgN ha⁻¹. This value is in accordance with losses reported elsewhere in the Andes and generally exceeds N losses associated with harvest of 10–30 kgN ha⁻¹ yr⁻¹ (de Koning et al., 1997). Nutrient losses due to erosion, however, may be considerably higher under some circumstances. In the Ecuadorian Andes, which tend to have higher SOM and nutrient content (Buytaert et al., 2007; Tonneijck et al., 2010), Harden (1988) estimated erosion rates as high as 800 Mgha⁻¹ yr⁻¹ on steep, highly susceptible agricultural land. Although this example represents an extreme case, it highlights the potential for erosion to rapidly offset nutrient balances in Andean agroecosystems. We also note that erosion losses for P may be even more important than for N, as they often exceed the limited ability of farmers to replenish P with manure or fertilizers. Perhaps a more critical consequence of high erosion rates is the loss of suitable substrate for crop growth. While nutrient stocks can be restored by fertilization, soil formation occurs slowly, with the global average estimated to be as low as 1 Mg soil formed ha⁻¹ yr⁻¹ (Pimentel, 2006). Thus, the implementation of viable soil conservation strategies is
critical throughout the Andes from both a nutrient balance perspective and more general goals of agroecosystem sustainability.

The susceptibility of soils to erosion depends greatly not only on topography, slope, climate, and soil type, but also to a large extent on management factors such as vegetation cover, cropping system, tillage, and livestock intensity (Coppus et al., 2003; Inbar and Llerena, 2000). Given the widely acknowledged role of agricultural disturbance in exacerbating erosion (Montgomery, 2007), a number of technologies have been put forth to conserve soils in the Andes and elsewhere. For steeper hillside farms, stone and earthen terraces represent one of the oldest approaches to soil conservation in the region and have proven largely successful in combating erosion (Goodman-Elgar, 2008; Sandor and Eash, 1995), yet these structures may no longer represent a viable option due to high labor requirements and altered political and socioeconomic conditions (Dehn, 1995; Posthumus and De Graaff, 2005). Terraces formed by live barriers are attractive as they require considerably lower initial investments, offer key byproducts (e.g., fodder, fuel, organic matter inputs), and can effectively control erosion (Craswell et al., 1998; Sims et al., 1999). Sims et al. (1999) working in Bolivia suggested that grasses (Phalaris sp.) offer the best erosion control in such systems, as they grow rapidly and provide fodder for livestock. However, competition for nutrients and water, along with high spatial variability within live barrier terraces, indicates that such technologies require additional study and/or modification (Dercon et al., 2006). Cover cropping offers another viable means to control erosion on hillside soils, by protecting the soil when and where crops are absent (Bunch, 2004; Sims et al., 1999).

The development of adapted cover crop technologies for erosion control in the Andes is highly desirable, as cover crops can also contribute significantly to soil nutrient and organic matter stores (Snapp and Silim, 2002; Wheeler et al., 1999). Despite the great potential for plant-based technologies to control erosion, maintenance costs (e.g., labor, seed) and knowledge requirements can limit their adoption by small farmers (Bunch, 2004; Posthumus et al., 2010; Snapp et al., 1998). Other erosion control strategies focus on reduced soil disturbance (tillage) in order to decrease labor requirements and conserve soils. For example, the Wacho rozado system from Ecuador (Sherwood et al., 1999) as well as the chiwa and chacmeo systems from the Central Andes (Oswald et al., 2009) all represent unique indigenous potatoes planting systems that seek to minimize soil movement on smallholder farms. Reduced tillage options have also been developed for larger farms that employ animal traction or mechanized tillage (Mamani et al., 2001; Quintero, 2009; Wall, 1999) and may be especially relevant for hillside farms in the northern Andes where mechanical tillage is more common and poses a greater threat. However, significant investment is still needed to work with farmers in developing locally adapted technologies and implements that minimize soil disturbance and provide viable
alternatives for small- and medium-sized farms in the region. At a watershed scale, erosion has been mitigated in some valley areas by recapturing eroded soil (and nutrients) as siltation of fields on river margins. This was a key feature of ancient spate irrigation practices in the Andes and elsewhere (Mehari et al., 2011; Zimmerer, 2011), and the same benefit is sought from gabion walls for soil capture along rivers promoted by some NGOs in the region (Pacheco et al., 1992). Despite advances in soil conservation technologies, the potential of reduced tillage and other strategies in the Andes needs to be further evaluated.

Other forms of nutrient loss can occur via leaching and gaseous emissions, particularly in the case of N. These losses not only threaten long-term yields but also can have highly deleterious impacts on regional water quality, downstream aquatic ecosystems, and greenhouse gas emissions (Matson et al., 1998). Such forms of nutrient export may be considerable in some agroecosystems are often the least understood by farmers and can be difficult to quantify. Management strategies to control them can involve reducing the availability of nutrients during times of low plant demand (see Fig. 4 and Section 2.2.2) as well as increasing SOM and the nutrient storage capacity of soils (Craswell and Lefroy, 2001).

Given that most small farmers are highly resource limited, improved nutrient recycling within farms offers an attractive means to close the gap, as many inputs (e.g., crop residues, manure, compost) are free and only require a limited amount of additional labor. For example, Osman (1999) suggested improved management of livestock manure and urine (e.g., composting, rapid incorporation to soil) as a means to reduce gaseous N losses and significantly improve the farm N budgets for small farmers in Peru. Additionally, for a

**Figure 4** Theoretical curves for plant nutrient uptake an availability under different fertility strategies (IF, Inorganic fertilizer; OR, Organic resources). Curves for plant demand and organic matter decay represent what might be seen during a typical growing season for a crop such as maize or potato. Twin peaks for IF represent two fertilizations (at planting and at peak crop demand).
number of reasons (convenience in threshing of grain, use of crop residues for forage and fuel) residues of quinoa, maize, lupine, and other grains are often removed off-field at harvest. On-field crop residue retention (or return) could contribute substantially to restoring nutrient balances and combating SOM depletion (Fuentes et al., 2009). Despite the promise of such simple interventions, many loss mechanisms are more difficult to control—particularly those associated with human urine and fecal waste. The safe recovery and application of human waste, which can comprise a significant portion of small farm nutrient budgets (Kamagne et al., 2006), often faces technological and cultural obstacles (Cofie et al., 2005; Karak and Bhattacharyya, 2011), resulting in persistent losses of key elements. Even under ideal management practices, losses are inevitable and alternative nutrient input sources are ultimately necessary to restore nutrient equilibrium on smallholder farms.

While organic inputs (i.e., manure, plant residues) and long fallows were traditionally used to restore soil fertility (Hervé, 1994; Sarmiento and Bottner, 2002), intensification of cropping systems (i.e., reduced fallow periods) has led to a growing reliance on synthetic fertilizers (when available and affordable) to make up the difference (Claverías, 1994; Wiegers et al., 1999). However, negative nutrient balances, reported for various highland Andean agroecosystems and driven strongly by erosion (de Koning et al., 1997; Osman, 1999; Vanek, 2010), suggest that the levels of fertilizer applied by farmers are often insufficient, likely due to inaccessibility (i.e., cost, availability) of these inputs to small farmers. Increased reliance on legumes and biological N-fixation offers perhaps the most obvious means to address long-term N deficits, as legumes already comprise a fundamental component of agricultural systems worldwide and their benefits are well understood by farmers. However, current N inputs from legumes are generally insufficient to meet crop demand and replenish soil N stores, and further integration of legumes into cropping systems (on- and off-field) is necessary to better meet typical farm N requirements (Snapp et al., 2005). Limitation of other nutrients, particularly P, is more complicated and may also have consequences for N-fixation (Chalk, 2000; Reed et al., 2007). Addition of P, K, Ca, and other potentially limiting elements to crop production generally depends upon the mining, refinement, and import of these nutrients from great distances, and thus costs are high. Improvement of rural markets and distribution networks for these fertilizers could thus help alleviate some issues of nutrient depletion, but the dependency of these inputs on oil prices and market fluctuations does not ensure that they are sustainable in the long-term. Rock phosphate represents a low quality, unrefined source of P that is relatively available in various parts of the Andes and offers promise for restoring P budgets in the region (Lorion, 2004). Other potential sources of nutrient inputs include peri-urban wastes from residential and commercial sources, but this largely depends on the proximity of farm to population centers and requires necessary infrastructure for
collection and transport of these materials (Harris et al., 2001). Longer-range transport of these resources may also be economically viable and highly advantageous under some circumstances for correcting nutrient imbalances and thus merits additional consideration.

2.2.2. Short-term nutrient dynamics and synchronization
The nutrient balance approach discussed above is a critical starting point for agroecological intensification and the long-term management of soil fertility. However, in addition to maintaining sufficient quantities, nutrients must also be present in plant available forms and at a time when plants need them. For example, in the case of Andosols in the northern Andes and other P-fixing soils, sorption of P limits its availability even when the P balances in a given year are highly positive (Dahlgren et al., 2004; Espinosa, 1991). Sorption may be irreversible unless management (organic residues, root/phosphate proximity, and timing of P application) addresses the low availability of P (Nziguheba et al., 1998). Synchronization of nutrient availability with plant demand is thus critical for maximizing crop productivity as well as for minimizing nutrient losses and associated environmental consequences (Cassman et al., 2002; Woomer and Swift, 1994). Inorganic fertilizers offer the distinct advantage of providing nutrients that are immediately available to plants and, in theory, allow for relatively simple regulation of soil nutrient availability to support crop growth. However, various economic and management constraints (i.e., labor, fluctuating costs, risk of crop damage associated with multiple field entries) typically result in suboptimal application of fertilizers from a soil fertility standpoint. Throughout the Andes, considerable research has examined the potential of synthetic fertilizers to increase productivity in various cropping systems. While high synthetic fertilizer applications may be representative of commercial fields in the region, it is much less common in smallholder agriculture that dominates the Andean highlands (Caycho-Ronco et al., 2009; Terrazas et al., 1998). Despite considerable emphasis on inorganic fertilizer research at regional universities, few studies have examined the issues of nutrient leaching and gaseous losses associated with inefficient fertilizer application (e.g., Machado et al., 2010). Evidence suggests that fertilizer application may greatly exceed crop demand in some circumstances, for example, at higher altitudes where potential yields are low and synthetic fertilizers represent a more recent introduction (NRC, 1989; Oswald, 2010). Thus, environmental and economic costs of fertilizer application may be substantial, but remain largely unknown for the high Andes.

Organic nutrient sources in the Andean highlands encompass both traditional manure and plant residue inputs and a number of innovations such as off-farm residues and manures, compost, and bioles (fermented liquid nutrient amendments). Considerable research has been devoted to these organic fertility inputs, and simple yield comparisons to synthetic fertilizer have been a common theme (e.g., Aguilera, 2010; García, 2011).
Organic inputs have some challenging aspects for soil fertility management. For example, compared to inorganic fertilizers, more must be transported and applied due to their lower nutrient contents. Additionally, the mineralization of plant nutrients from organic matter for plant uptake is often harder to predict, as amount and timing of nutrient release depend on a number of factors including organic matter quality, moisture, temperature, and the soil decomposer community receiving organic additions (Lavelle et al., 1993; Palm et al., 2001). The quality of organic resources (nutrient content and ease of decomposition) also tends to be more heterogeneous and can depend greatly on the source of material and timing of collection or application. Thus, additional labor and knowledge may be required to effectively manage organic resources, such that nutrient release is synchronized with crop growth. Despite these potential drawbacks, organic resources are the most important form of nutrient inputs for crop production in the Andean highlands (Caycho-Ronco et al., 2009; Terrazas et al., 1998) and offer several key benefits to farmers. First, organic resources are typically less expensive and more readily available to farmers than inorganic nutrient sources, especially in rural areas. Additionally, Andean smallholders have developed complex local knowledge that is well adapted to the use of manures and fallow residues and that may be readily transferable to innovations in organic inputs. Organic resource application also contributes to the maintenance of SOM in cropping systems (Fernandes et al., 1997), with vital implications for soil structure, water storage and movement, nutrient supply and retention, and the promotion of healthy soil biological communities (Craswell and Lefroy, 2001). Finally, they generally release nutrients more slowly and over time, potentially decreasing the susceptibility of nutrients to loss, as compared to synthetic fertilizers (Kramer et al., 2006).

Recognizing the inherent complexities of organic nutrient sources, researchers have invested considerable effort toward classifying and processing these materials in order to simplify management, provide a more predictable release of nutrients, and to enrich materials for reducing bulk and accelerating nutrient mineralization. For example, Palm et al. (2001) proposed a classification system for plant residues and organic materials commonly found in the humid tropics that is based on residue N content and the presence of recalcitrant compounds (polyphenols and lignin). This system identifies four organic matter quality classes with distinct recommendations of how best to apply the residues for optimal nutrient release. Although a few studies have examined the quality of organic resources available in the Andes (Couôteaux et al., 2008; Machado et al., 2010; Mahboubi et al., 1997), this information is limited and has not been adequately translated into targeted management recommendations for the Andean agroecosystems.

Efforts for processing organic materials prior to application have become commonplace throughout the world, as well as in the Andean highlands (Felipe-Morales, 2002; Herbas, 2000). Composting encompasses a broad
array of practices that involve mixing organic materials of different qualities (e.g., manure, plant residues, kitchen wastes, ash, sawdust) and a managed decomposition of residues to concentrate nutrients, remove pests and pathogens, homogenize materials, and form a more stable, yet nutrient rich substrate to apply to soil and stimulate biological activity (Litterick et al., 2004; Misra et al., 2003). Proper composting can also help prevent nutrient losses from high quality organic resources (e.g., urine and fresh manure), especially when materials are produced at a time that is inappropriate for field application. Other forms of composting, such as vermicomposting, rely on epigeic earthworms to breakdown organic materials, while concentrating and stabilizing nutrients in their casts. Although potentially more management intensive, this process yields a high quality soil amendment in a relatively short time and has received increasing attention in recent years, in part due to the beneficial byproducts associated with earthworm activity (Blouin et al., 2005; Cardoza, 2011). Anerobic methods of composting also exist in the Andes for the production of bioles, plant- or manure-based liquid fertilizers (Caycho-Ronco et al., 2009; Felipe-Morales, 2002). These contain nutrients in relatively available forms and are often applied to foliage or soil, as a means of rapidly correcting minor crop nutrient deficiencies. Organic materials can also be processed through non-biological processes. For example, burning of residues is common and provides the advantage of reducing biomass, suppressing pests, and increasing the availability of some key elements (e.g., K), but can also lead to high losses of others (e.g., N) and is generally ill-advised. A promising alternative for low quality, lignocellulosic residues (e.g., wood, wheat straw) is to pyrolyze or heat materials in a low-oxygen environment to produce biochar. Production and application of biochar supply some nutrients directly (Novak et al., 2009), but is perhaps more relevant for the indirect benefits to soil fertility, C storage, and biological functioning of soils (Chan et al., 2007; Noguera et al., 2010).

Despite a considerable research on the efficacy of synthetic and organic fertilizers in Andean crop production, relatively few studies have considered the combined application of these resources or integrated soil fertility management (ISFM; Vanlauwe et al., 2001). This approach recognizes the importance of organic matter inputs for supplying nutrients, maintaining SOM, and promoting healthy soil food webs (Craswell and Lefroy, 2001; Moore et al., 2004), but also allows for the strategic application of inorganic nutrients to meet crop nutrient demand at critical crop growth stages (Fig. 4). This strategy ultimately allows farmers to optimize the use of locally available organic resources with relatively small quantities of imported farm nutrients. Although this approach has been advocated by several researchers in the Andean region (Sarmiento et al., 2001; Valente and Oliver, 1993), few field trials have adequately addressed this approach (e.g., use of appropriate controls, equivalent nutrient additions) in the Andes and the potential is largely unknown.
In addition to considerations regarding the quality of nutrient resources and the dynamics of nutrient release, other factors such as climate, soil type, and management play a key role in determining optimal nutrient management strategies for a particular agroecosystem. For example, Bottner et al. (2006) compared the decay of buried crop residues between contrasting Andean environments (páramo soils of Venezuela vs. dry puna soils of Bolivia) and found that, despite having warmer and moister conditions, the finer texture and more acid soils of the páramo resulted in slower decay and a greater contribution of residues to SOM (Pansu et al., 2007). This suggests that the potential role of organic residues in meeting crop nutrient demand is distinct for these two systems and may be more important for crop productivity in the sandier, drier, SOM depleted soils of the Altiplano. Corroborating this idea, Chivenge et al. (2010), who reviewed ISFM trials across sub-Saharan Africa, found residue additions to contribute substantially more to crop yield in coarse (as opposed to fine) textured soils and suggested that organic matter additions may temporarily contribute to key SOM functions (i.e., water- and nutrient-holding capacity) in sandy soils with low SOM content. Another example comes from the Wachu rozado system from the northern Andes, where soil is inverted and potatoes are planted between two grass layers placed on top of one another (Sherwood et al., 1999). The organic matter in the grass layers begins to decompose and isolates the growing crop from the acidic, P-fixing Andosols, while providing a source of nutrients and an ideal growing environment for the potato. This system is well suited for the Ecuadorian páramo soils as means to improve nutrient availability, but may not be appropriate for other areas or soil types in the Andes. The great number of possibilities for such environment–management interactions emphasizes the need for developing locally adapted strategies that best utilize available nutrient resources and strategically manipulate the soil environment.

2.2.3. Physiochemical environment of soils

Although the concept of soil fertility typically emphasizes the availability of nutrients for plant growth, the physical and chemical conditions of the soil environment play an important role in regulating nutrient processes as well as the ability of plant roots to explore the soil and assimilate nutrients. The physical status of soils concerns the structure of soils and how individual soil particles are arranged and combined to form soil aggregates. Aggregation in soils can have important impacts on a number of key soil properties. For example, aggregation directly impacts key soil functions related to soil porosity, aeration, water storage, and movement (Wu et al., 1990) and also affects the ability of roots to penetrate and explore the soil volume for water and nutrient resources. Soil aggregation also plays a fundamental role in SOM turnover and regulation of soil biotic communities (Brussaard et al., 2006; Six et al., 2002). In many soils, aggregates are closely associated with
organic matter, as larger aggregates (>50μm diameter) typically form around organic residues and/or are held together by microbial mucilages, fine roots, and fungal hyphae (Tisdall and Oades, 1982). Although SOM is a critical factor for aggregate formation in most soils, mechanisms of aggregation can vary depending on soil type (Bronick and Lal, 2005). For example, carbonates may dominate aggregation processes in Aridisols, while Al/Fe-humus complexes may be more important in Andosols (Bronick and Lal, 2005; Dahlgren et al., 2004). Soil ecosystem engineers (e.g., earthworms and ants) are key agents of aggregation in soil with favorable conditions for their activity (Lavelle et al., 1997). Texture also plays a role in aggregation, with organic residues relatively more important for aggregation in sandy soils as oppose to those dominated by clays (Bronick and Lal, 2005). Although proper management of soil structure is often critical for crop growth, few studies have looked at the effects of soil preparation and management on soil structure in the Andes. One exception is the relatively well-documented influence of management impacts on aggregation and soil degradation in the hardened ash (Cangahua) soils of Ecuador. This research indicates that Cangahua soils have highly unstable aggregates, are severely prone to crusting and erosion following cultivation, and should ultimately be left untilled with permanent vegetative cover (Buytaert et al., 2002; Podwojewski and Germain, 2005; Poulenard et al., 2001). Although not true for all soils (e.g., Cangahua soils), soil structure can generally be improved via reduced soil disturbance (e.g., tillage) and increased inputs of organic matter. The paucity of information on soil structure from other parts of the Andes suggests that further research on soil C and aggregate dynamics is needed to improve the long-term soil fertility management in the region.

The chemical environment of soils has perhaps received more attention (with respect to fertility) and refers to the ability of soils to maintain available nutrients and support basic plant growing processes. There exist a number of relevant chemical measures that influence soil fertility; however, soil pH (acidity) is probably the most important, as it affects multiple other chemical, biological, and physical processes of the soil. For example, acidic soils (pH<5) can have severe problems with Al toxicity and low nutrient availability (including P, N, K, and Ca). Along with pH, cation exchange capacity (CEC) is another important soil factor that relates to the ability of a soil to retain available plant nutrients, while in drier parts of the Bolivian Altiplano, soil salinity can also become a serious issue limiting agricultural productivity (Valente and Oliver, 1993). Although these factors are closely linked with site characteristics (i.e., soil type, parent material, and climate), management can greatly exacerbate or ameliorate these soil chemical properties. For example, tillage and fertilization during the cultivation stage in a sectoral fallow system of the Venezuelan páramo have been shown to decrease soil pH in these already acidic soils (Abadín et al., 2002; Abreu et al., 2009), and while pH can increase when soils are returned to fallow, it

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may not fully recover to the precultivation state for many years. Liming (e.g., application of calcium carbonate) is perhaps the most commonly prescribed means to increase the pH in acid soils, but required inputs can be substantial and the costs prohibitively high for most smallholder farms. Additions of ash and organic matter have also been shown to reduce acidity (Aguilera, 2010; García et al., 2010) and may represent a more affordable alternative for Andean farmers in some circumstances. Organic matter inputs have also been shown to increase CEC (García et al., 2010; Oorts et al., 2003) and can significantly improve other physical and chemical soil properties such as aggregation, water-holding capacity, and soil buffering capacity (Craswell and Lefroy, 2001; Kong et al., 2005). Biochar offers many of the same benefits of organic matter, but with potentially more immediate and longer lasting impacts. For example, biochar has been shown to increase soil pH, CEC, water-holding capacity (Chan et al., 2007; Jha et al., 2010; Karhu et al., 2011) and alter pore size distribution with multiple impacts for plant growth and soil biological communities (see section 2.2.4). As for soil structure, research concerning the characterization and management of soil chemical environments is notably lacking across much of the Andes and merits further emphasis in future research endeavors.

2.2.4. Biological functioning of soils

Understanding and managing biologically mediated nutrient cycling in soils are critical for sustaining the productivity of smallholder agricultural systems. Soil microbial and faunal communities ultimately depend upon carbon derived from plant residues, root exudates, and other processed, more stable forms of SOM as an energy source and habitat (Moore et al., 2004). In using these resources, symbiotic and associative rhizosphere organisms can: (1) provide plants access to nutrient pools that are typically unavailable to them (e.g., atmospheric N₂, recalcitrant P pools); (2) defend plants against pests and disease; and (3) enhance plant growth via hormonal or other physiological mechanisms. Here, we address two well-studied themes that link soil biology to agroecological intensification in the region. First, proper organic matter management by smallholder farmers is fundamental to soil biological communities, as SOM is a key substrate for promoting soil food webs and associated ecosystem services (Powlson et al., 2011). Second, inoculation of soil with carefully selected microbes from key functional groups (that can leverage substantial improvements in nutrient cycling or plant health) offers a promising and low cost means of improving soil functioning and system productivity. The hope (and hypothesis) is that improved management of SOM, along with the targeted introduction and/or promotion of beneficial organisms, can sustainably increase the productivity of crop rotations with relatively low levels of farmer investment.

In farmed soils, microbial and faunal communities reflect the quantity, quality, and diversity of plant C inputs, as well as the intensity and frequency
of soil disturbance (Carney and Matson, 2005; Thies and Grossman, 2006). Intensification on smallholder farms often leads to a decrease in the diversity of residue inputs and an increase in the tillage intensity, thus reducing the abundance and diversity of soil communities and the SOM which they depend on (Postma-Blauw et al., 2010). For example, in maize and wheat cropping systems of the Mexican highlands, residue retention and reduced tillage have been shown to foster greater overall bacterial populations, including beneficial actinomycetes and fluorescent pseudomonad bacteria (Govaerts et al., 2008). Improved residue management (greater quantity and diversity of inputs) has also been shown to increase microbial biomass and diversity when compared to a conventionally managed agriculture (with low residue inputs) in California (Briar et al., 2011). Root derived C can also contribute to SOM and soil aggregation and is a key resource for soil microbes, in addition to the direct role of soluble root exudates from living plants (Kong and Six, 2010; Puget and Drinkwater, 2001). A closer examination of different residue management strategies is particularly important for the Andean region where residues are predominantly removed for livestock, yet little is known about the consequences of this practice for soil biological functioning. In addition to management, temporal changes over the fallow cycle in the Andean region also drive microbial community dynamics and can provide benchmarks for the functional microbial and faunal diversity that managed fallows need to provide. For example, in the Bolivian Altiplano, Sivila and Herve (1999) found changes in the microbial communities along a chronosequence of fallowed fields, such that mycorrhizal spore counts increased with fallow age and SOM levels, but decreased following rotations of non-mycorrhizal quinoa and with the removal of Baccharis shrub vegetation.

The remarkable diversity and range of functions attributed to microbes and fauna in the rhizosphere of crops are now widely acknowledged, growing out of early knowledge of important plant symbionts such as rhizobia and mycorrhizae, to learning that microbes mediate many of the processes in soils that control plant growth (Murphy et al., 2007; Osorio-Vega, 2007; Rodríguez et al., 2006). Symbioses between legumes and rhizobia/bradyrhizobia, and associations between Frankia actinomycetes and trees such as the agroforestry species Alnus spp., currently account for most of the biologically fixed N on Earth (Freiberg et al., 1997). Legume species in Andean cropping systems include endemic Andean lupine (Lupinus mutabilis) infected by Bradyrhizobium lupini; vetch, pea, and fava bean infected by Rhizobium leguminosarum bv. viciae; and alfalfa and various endemic and introduced clover species (Trifolium spp.). Arbuscular mycorrhizae (AM) are another well-studied symbiont that infects the roots of most crop species. They expand the volume of soil explored by the plant and increase access to P and micronutrients, especially under dry soil conditions (Aroca and Ruiz-Lozano, 2009). In the Andes, potatoes, maize, cereals, and legumes like Vicia spp. are hosts for AM.
Interestingly, *L. mutabilis* and the Andean Chenopodium crops (Quinoa, Kañawa, etc.) do not host AM. Another potentially important symbiont, *Trichoderma*, is a fungal genus known to inhibit root pathogens (*Lorito et al., 2010*) via antifungal toxins and enzymes (see *Verma et al., 2007*). Other modes of action may also contribute, as some *Trichoderma* species inhabit the interface between the root cortex and soil as plant growth-promoting symbionts, inducing resistance to disease in the host plant with chemical signaling and occupying a niche at the root surface which crowds out pathogens (*Vinale et al., 2008*). *Trichoderma* may also improve nutrient uptake and induce positive responses to drought and pest stresses (*Lorito et al., 2010*).

*Rhizobia*, actinomycetes, AM, and *Trichoderma* are increasingly considered as part of a class of plant-growth-promoting microbes (PGPM) that act either in the rhizosphere or endophytically to improve plant growth via mobilization of scarce nutrients, hormonal action (e.g., auxin synthesis), and/or plant protection from disease and pest attack (*Martinez-Viveros et al., 2010*). Hormonal modes of action are likely important for PGPM impacts on crop growth in the Andes. For example, the production of indole acetic acid (IAA) promotes plant growth via effects on cell elongation and greater branching of root systems. *Oswald et al. (2010)* found that over half of the *Bacillus* and *Actinomyces* species collected in one Peruvian location produced IAA *in vitro* and may have improved growth of potato in a pot study. Other rhizosphere microbes degrade ethylene, a plant hormone that deters plant growth at high or persistent levels (*Hayat et al., 2010; Loon, 2007*). Microbes that improve access to P inhabit many soils and include phytate-mineralizers, which act on organic P substrates that form a substantial P reservoir in many soils (*Oberson et al., 2006*). Meanwhile, P-solubilizers can dissolve inorganic calcium phosphates and apatite minerals such as rock phosphate using organic acids and other mechanisms (*Rodrı´guez et al., 2006; Sharma, 2003; Takeda and Knight, 2006*). In addition to the root cortex (e.g., *Rhizobia* and AM), endophytic microbes colonize other plant parts such as xylem vessels where they may favor plant growth under stress conditions, including greater tolerance of drought and salt stress (*Compant et al., 2010; Hahn et al., 2008; Kane, 2011*). It should also be noted that there is frequent overlap of these functions within a single PGPM species (e.g., microbes that simultaneously synthesize auxin hormones and solubilize P; *Bashan and Bashan, 2010*). Despite advances in understanding of microbe-root interactions, most microbes inhabiting the rhizosphere and their functional genes may still be unknown. *Leveau (2007)* thus suggested that soil metagenomics, the attempt to directly sequence and derive functional information from DNA of the entire microbial community of a particular rhizosphere or soil, can help to probe novel and yet unknown modes of action for PGPM. Metagenomics could form part of a basic research agenda that may yield benefits for smallholders over the long-term, in contrast to direct trials of microbes as inoculants that we address next.
Interest in microbial inoculants grew naturally from knowledge of the beneficial effects of soil microbes for crops presented above. Nevertheless, it may be harder to improve beneficial soil communities via inoculation of seeds or soil than is suggested by experiments that test the effect of one microbial species on a crop of interest (Benizri et al., 2001; Oswald et al., 2010). Successful inoculants must exceed the positive impact of similar microbes already in the rhizosphere and also compete well enough to persist there. In vitro screening results are thus often not well correlated to field trials (Martínez-Viveros et al., 2010; Oswald et al., 2010). In spite of these challenges, microbial inoculants have shown promise in the Andes and in other smallholder systems. In order to understand where inoculants might contribute positively to agroecological intensification, research efforts should employ rigorous and standardized screening and on-farm trials and develop hypotheses about the soil and management conditions (e.g., degraded ones) where inoculants have greatest impact and those where their effects are redundant or inconsistent (Oswald et al., 2010).

Research to date on microbial inoculation in the Andes confirms the need to select for both effective and competitive inoculant microbes. Differences in the effectiveness of Rhizobia strains for Andean legumes have been documented in several trials in the region (Barba et al., 2000; Conde et al., 2000; Lagacherie et al., 1983). Although high levels of endemic Rhizobia are generally thought to reduce the benefit of inoculation (Evans et al., 1996), Mnasri et al. (2007) found that a competitive rhizobium strain on beans could displace native strains even when native strains were abundant. Findings of Vanek (2010) in a Bolivian smallholder system suggest that N-fixation rates may be more limited by available P than by a lack of effective rhizobial symbionts. For a number of common legumes in the Andes, it appears that symbiont populations are maintained as long as legumes remain in the rotation (Meneses et al., 2000) and that continued inoculation may not be so important. Research on the potential for AM inoculants better illustrates the challenge of improving on endemic microbes and also supports the idea that gradients in soil fertility determine the impact of AM on crop nutrition. Mycorrhizae can be mutualistic, neutral, or even parasitic in their impacts on plant hosts (see Table 1), depending both on soil conditions (e.g., P availability) and on the particular AM species (Johnson, 2010; Moreno Diaz, 1988). In low-P experiments testing only the impact of one AM strain, crops typically benefit from mycorrhizal inoculation, a benefit the crop may already receive in a biologically diverse soil. For example, Davies et al. (2005a) found 44–57% increases in total dry matter with AM inoculation of a Peruvian potato variety in sterile, low-P soil. By contrast, results of field experiments with intact soil communities were mixed to positive (Table 1) because inoculant AM do not guarantee a favorable plant C investment compared to native AM species (Moreno Diaz, 1988; Rodriguez and Ortúñoo, 2007; Rodríguez et al., 2010). Trichoderma continue to be attractive...
Table 1  Example of impacts of mycorrhizal inoculation in sterile-control, greenhouse/nursery, and field inoculation of crops with mycorrhizae reviewed for the Andean region

<table>
<thead>
<tr>
<th>Source</th>
<th>Country</th>
<th>Crop</th>
<th>Sterile control/field/greenhouse</th>
<th>Colonization increase</th>
<th>Yield or disease benefit (+/−/0)</th>
<th>Interactions with other inputs/treatments; comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davies et al. (2005a)</td>
<td>Peru</td>
<td>Potato</td>
<td>Sterile control</td>
<td>+</td>
<td>+</td>
<td>Mixed cultures from the field outperform <em>G. intraradices</em></td>
</tr>
<tr>
<td>Ortuño et al. (2010)</td>
<td>Bolivia</td>
<td>Maize</td>
<td>Field</td>
<td>nd</td>
<td>+</td>
<td>Greater positive impact when combined with compost and poultry manure</td>
</tr>
<tr>
<td>Rodriguez and Ortuño (2007)</td>
<td>Bolivia</td>
<td>Onion</td>
<td>Field</td>
<td>+</td>
<td>−</td>
<td></td>
</tr>
<tr>
<td>Ibarra (2008)</td>
<td>Ecuador</td>
<td>Pepper</td>
<td>Field</td>
<td>+</td>
<td></td>
<td>Additive effect of AM inoculation at seeding and transplant and P addition</td>
</tr>
<tr>
<td>Orna (2009)</td>
<td>Ecuador</td>
<td>Tomato</td>
<td>Field</td>
<td>+/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moreno Diaz (1988)</td>
<td>Peru</td>
<td>Potato</td>
<td>Field</td>
<td>0</td>
<td></td>
<td>Greater positive impact when combined with vermicompost</td>
</tr>
<tr>
<td>Medrano Echalar and Ortuño, 2007</td>
<td>Bolivia</td>
<td>Onion seedlings</td>
<td>Greenhouse</td>
<td>nd</td>
<td>+/0</td>
<td>Mycorrhizal impact greater than addition of rock phosphate or wood vinegar</td>
</tr>
<tr>
<td>Arandia et al. (2007)</td>
<td>Bolivia</td>
<td>Onion</td>
<td>Greenhouse</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Ferrufino and Sanchez (2006)</td>
<td>Bolivia</td>
<td>Heart of palm</td>
<td>Nursery</td>
<td>+</td>
<td>+</td>
<td>Tropical trees, but shows viability of mycorrhizal root inoculation</td>
</tr>
<tr>
<td>Urgiles et al. (2009)</td>
<td>Ecuador</td>
<td>Tree spp.—tropical</td>
<td>Nursery</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Moreno Diaz (1988)</td>
<td>Peru</td>
<td>Potato</td>
<td>Seedbed</td>
<td>na</td>
<td>+</td>
<td><em>G. fasciculatum</em> outperforms other two strains</td>
</tr>
</tbody>
</table>
inoculants since they are strong rhizosphere competitors via their antibiosis and predation of other fungi, thus addressing a key challenge for inoculants (Schuster and Schmoll, 2010; Verma et al., 2007). Trials in Bolivia have found improved health and vigor of onion transplants when inoculated with a Trichoderma harzianum (Medrano Echalar and Ortuno, 2007). As for other inoculant research to date, trials on Trichoderma have focused frequently on greenhouse or horticultural production, whereas future efforts should evaluate their effectiveness in intensified smallholder crop rotations, especially where soil disease pressure is high and positive effects would be most expected.

Research on PGPM that improve crop access to P is of particular interest throughout the region and worldwide (Barroso and Nahas, 2005; Chen et al., 2006; Jorquera et al., 2008; Keneni et al., 2010; Oliveira et al., 2009) and may prove especially useful in P-sorbing volcanic soils (Andosols) in the northern Andes. In Peru, Oswald et al. (2010) demonstrated the P-solubilizing activity of 44% of Azotobacter and 58% of Bacillus bacterial strains isolated from the rhizosphere in a single potato field, while 28% of bacterial isolates from quinoa and one-quarter of rhizobial strains from fava bean in an Altiplano collecting area had P-solubilizing ability (Ortuno, 2010). Despite the apparently common occurrence of P-solubilizing bacteria in the Andes, their impact on crop growth is not always clear. While Faccini et al. (2007) found that P-solubilizing bacteria allowed equivalent potato yields with half the P fertilizer, other researchers in the northern Andes observed little impact of P-solubilizing bacteria on crop growth (Nustez and Acevedo, 2005; Rodriguez et al., 2010). Previous work in the region has largely focused on solubilizers of inorganic P forms, yet the prevalence of manure use in the Andes suggests that increased focus on mineralization of organic P by PGPM might be productive. Interestingly, P mineralizing and solubilizing bacteria may have utility in both low-P environments and also in intensified farming environments where fixation of applied fertilizer or manure P occurs (Chabot et al., 1996).

Plant growth-promoting bacteria with hormonal modes of action provide glimpses of fascinating mechanisms of plant microbe interaction that may prove useful in field settings. For example, inoculation with ethylene-degrading PGPM has been found to increase yield of pea, tomatoes, and peppers under in-season drought, by removing the ethylene stress signal to roots and allowing a quicker resumption of growth when soil moisture conditions improve (Arshad et al., 2008; Belimov et al., 2009; Mayak et al., 2004). These results suggest that some soil microbes play a mediating role in plant signaling to respond to stresses (Glick et al., 2007) and are especially relevant given the risk of in-season drought for smallholders in the Andes.

For the inoculant organisms reviewed here, domains of soil properties and management where inoculation is warranted need to be better characterized. For the example of AM inoculants, high P availability in soil can make mycorrhizal inoculation redundant or even inefficient for crops.
However, agroecological intensification by smallholders will likely occupy regimes of low-to-moderate soil fertility, as well as a mixture of inorganic and organic nutrient inputs. Here, AM may in fact be well suited to exploring available P pools with mutualistic outcomes for crop hosts (Douds et al., 2007). In support of this idea, Mader et al. (2011) found dramatic improvements in yields from the use of AM and PGPM, when strains isolated from low-fertility fields in Indian rice–wheat systems were used to inoculate low-fertility fields with degraded soils after flooding and rice cropping. Of course, highly degraded soils may also prove unresponsive to microbial inoculation, since soil C may be too depleted to provide for proper microbial function and additional restorative measures must be taken (e.g., organic matter inputs). Research on PGPM in the Andes may benefit by isolating microbes from environments that select for desired microbial traits as well as critical approaches to screening (Jorquera et al., 2008; Oswald et al., 2010). To avoid costly failures, this includes testing inoculants across gradients of soil fertility and degradation to define where they have greatest impact. It must also be noted that PGPM are highly multifunctional, with their modes of action depending greatly on other rhizosphere factors (Martinez-Viveros et al., 2010). Thus, producing a consistent inoculant effect with these associative PGPM can be challenging, and research on PGPM needs to acknowledge this possibility for prospective inoculant microbes. A useful concept readily adapted from the pathology of soil-borne plant diseases is that of soil receptivity and suppression for particular microbes or microbial symbioses. Studies by Oyarzun et al. (1998) and Herrera-Peraza et al. (2011) address this concept and exemplify how multivariate statistical techniques can relate microbial effectiveness to biotic and physicochemical properties of soils and soil management and offer promising insights for future research.

In addition to the direct effects of inoculation, research has focused on factors that catalyze or facilitate impacts of PGPM or native AM on crop growth. For example, Davies et al. (2005b) showed that simple additions of the flavonoid signal formononetin triggered greater soil sporulation of native AM fungi and increased in potato yield in Peru. Vanek (2010) found that mycorrhizal legumes in highland Bolivian crop fields had a higher ratio of uptake N:P and also AM colonization than did forage oat, suggesting that legumes promote mutualistic AM function in crop rotations. For Chilean Andosols, Borie et al. (2010) found that partially acidulated rock phosphate was particularly suited to mycorrhizal uptake and bypassed the P-fixation capacity of these soils. Additionally, biomass-derived charcoal (biochar) represents a means of altering the habitat for rhizosphere microbes in ways that can benefit crops and microbes alike. Pores in biochar derived from the original vessels of plant material may provide protection from drying and predation by other microbes and soil fauna, as well as changes in pH, which for acidic soils and for most biochars will create more neutral-pH
microsites that are favorable as bacterial habitat (Thies and Rillig, 2009). In reviewing impacts of biochar on AM, Warnock et al. (2007) documented neutral to very positive responses from char application on mycorrhizal colonization. As possible mechanisms for AM–charcoal relations, they advanced local alteration of soil physicochemical properties, indirect effects via impacts on other soil microbes, plant–fungal signaling interference, and protection from fungal grazers within charcoal. In addition to biochar, zeolites, nanoporous aluminosilicates of varied chemical composition, have the potential to increase the cation exchange and water-holding capacity of soils (Ramesh et al., 2010). The combination of small pore size and nutrient-holding capacity may make them especially active in microbially mediated nutrient transformations that prolong the availability of P, N, and other nutrients, especially via sorption of ammonium and other cations (Flores Macias et al., 2007; Ippolito et al., 2011).

While functioning as a source of carbon and nutrients to support decomposer food webs and improve soil physiochemical properties, compost and vermicomposts can also provide beneficial microbial inoculants to soils that can competitively suppress soil-borne diseases and have similar effects to inoculation with other rhizosphere microbes (Cardoza, 2011; Litterick et al., 2004; Quilty and Cattle, 2011). In addition, composts and other biomedias have been tested as vehicles to carry inoculant microbes into the soil (Seneviratne et al., 2011; Singhai et al., 2011). Rock phosphate or other minerals are sometimes mixed with the compost to foster their solubilization (Lange, 1994). In effect, compost may be thought of as a concentrated version of the effect desired in the whole soil for improving crop access to nutrients or protecting crop roots from disease. Despite some promising results with compost as inoculant promoters, their potential may be limited in rural, extensive smallholder farms in the Andes, where labor to produce compost may be at a premium and composting feedstocks have competing uses. However, in intensive areas of smallholder production near cities where waste feedstocks may be more available, composting as an integrated source of beneficial microbes and available nutrients for crops may hold greater promise.

The case of composting illustrates the need for inoculant technologies to be accessible for smallholders in the Andes. Cost and local access must be considered alongside technical optimization so that inoculant technologies can achieve maximum impact for smallholders, and thus research on inoculants from the region often includes analyses of economic and environmental costs and benefits. To avoid what Rosset and Altieri (1997) termed the threat of import substitution in smallholder sustainable agriculture, researchers have demonstrated promising results with local, on-farm methods for inoculating crops with AM using roots of infected crops, often with superior results to commercial inoculants (Davies et al., 2005a, Douds et al., 2007, Mäder et al., 2011). This approach is well suited to AM and Rhizobia,
where propagules like spores are necessarily associated with roots and may be more difficult with associative fungi and bacteria that have no intraradical structures. Regardless, such field-to-field approaches for inoculation carry risks for transmission of soil pathogens, which should be taken very seriously given their potential for drastic impact in the Andes.

While the role of soil microbial communities has been well studied in the Andes, the impacts of soil fauna in the region remain largely unknown, despite their significant impact on numerous key soil processes in diverse ecosystems around the globe. Soil fauna comprise a diverse group of organisms and alter soil functioning in a variety of ways. Soil invertebrates generally increase nutrient availability by (1) comminution of plant residues and accelerating decomposition and mineralization processes and (2) feeding on soil bacteria and fungi, thus releasing of nutrients bound within microbial tissues (Lavelle and Spain, 2001). The maintenance of healthy soil food webs (diverse and active soil fauna) has also been shown to control plant pathogens and may have important implications for crop growth (Blouin et al., 2005; Sanchez-Moreno and Ferris, 2007). Soil macrofauna, particularly those representing ecosystem engineers (e.g., earthworms, ants, termites), can drastically alter soil microbial communities via effects on soil structure, water movement, nutrient dynamics, and SOM (Lavelle et al., 1997). These activities can have varied implications for soil functioning but have generally proven to be beneficial for plant growth (Brown et al., 1999; Evans et al., 2011). Preliminary findings suggest that macrofauna can be quite relevant for at least some agroecosystems in the Andes. For example, Tonneijck and Jongmans (2008) examined biostructures and SOM distribution in páramo soils of Ecuador and concluded that bioturbation by earthworms was a fundamental process regulating the vertical distribution and turnover of SOM in these soils. Findings of Morales and Sarmiento (2002) suggest that soil disturbance associated with cropping reduces soil macrofauna abundance and diversity in Venezuelan páramo. Although some reports on soil fauna exist for other regions (Righi and van der Hammen, 1996; Zurita, 1997), information for highland Andean agroecosystems is notably scarce. Given the global importance of soil fauna and their potential to offer rapid and inexpensive indicators of soil health (Ferris et al., 2001; Velasquez et al., 2007), improved understanding of soil faunal activity and the factors affecting their abundance in agroecosystems remains a critical gap for sustainable soil fertility management in the Andes.

2.2.5. Plant breeding for agroecological intensification and climate change

Breeding of Andean crops to improve a large suite of desirable traits (for example, disease resistance, product qualities, or nutrient use efficiency) is a topic large enough to merit a separate review. Here, we focus on research efforts related to breeding for improved adaptation to two major edaphic
and climatic stresses, notably low nutrient availability and drought stress, both of which will reduce crop yields under the likely scenarios of climate change and soil degradation in the region. Great environmental and social heterogeneity in the Andes somewhat limits the broad applicability of crop breeding as an approach to agroecological intensification in the region. However, we suggest that careful consideration of this diversity and attempts to understand it can provide important opportunities for improving crop productivity and yield stability through breeding at both local and regional scales.

With a few exceptions highlighted below, there are substantial gaps in breeding and selection of highland Andean crops (native and introduced) for improved performance under nutrient or drought stress. At the same time, the range of variation of nutrient acquisition efficiency or drought resistance already present in existing native varieties is poorly documented. This lack of focus on stress tolerance for crops in the region may be traced to activities that compete for breeders’ attention. These include expenditures in resources and expertise toward assembling and maintaining important agrobiodiversity collections (e.g., potatoes, quinoa); emphasis on forage quality, market quality characteristics, and disease or pest resistance that are more easily selected for at experiment stations (Sciarascia Mugnozza et al., 1987); and a breeder bias toward wealthier farmers who have greater access to fertility inputs and irrigation. Nevertheless, substantial interest in abiotic stress breeding as well as a lack of adequate technical preparation for local staff to undertake novel breeding approaches was revealed by a 2006 survey of Bolivian plant breeding programs (Gabriel, 2006), thus suggesting high potential for new targeted breeding programs. Local biodiversity banks and contacts with the CGIAR center breeding resources offer tremendous opportunity to characterize existing genotypes for adaptation to low nutrient supply and drought stress, and select new genotypes in stress environments along gradients of soil fertility and/or degradation. It should also be noted that the lack of attention to breeding of Andean crops mirrors the worldwide “orphaning” of these plants in comparison to other crops (e.g., maize, soybean, rice).

With the exception of soils of the Altiplano that have been characterized as C- and N-limited, Andean valleys and particularly Andosols in the northern Andes suffer from P limitation (Cárdenas et al., 2008; Dahlgren et al., 2004; Valente and Oliver, 1993). Further, the soil P challenge in the Andes is one of availability rather than absolute supply, suggesting that improving P foraging ability of crops is a plausible strategy in this region. While N limitation is also important for nonlegume crops in Andean agroecosystems (prompting interest in N use efficiency for crops such as potatoes; Errebhi et al., 1999; Zebarth et al., 2008), we suggest that N deficiencies are more easily addressed through management (e.g., enhanced incorporation of legumes, see Sections 2.2.1 and 2.2.6) and merit less focus here.
Substantial breeding investments have improved P foraging ability in maize, bean, and soybean for lowland tropical P-limited environments (Beebe et al., 2006; Ramaekers et al., 2010; Zhu et al., 2005). One transferable element of these efforts is the concept that visible phenotypic characteristics of crops such as root hair length, basal root number, aerenchyma formation, and root shallowness (basal root gravitropism) predict P foraging ability and can be used to rapidly screen promising genotypes for trials under differential P availability (Ao et al., 2010; Beebe et al., 2006; Lynch, 2007). Other traits such as organic acid exudation are also important in mobilizing unavailable P and are known to occur in fava bean and Andean lupine (Hocking and Jeffery, 2004; Pease et al., 2006). Researchers have also focused on mechanisms of plant tolerance to aluminum toxicity in weathered soils of the lowland tropics (Beebe et al., 2009; Kochian et al., 2005), which is of lower prevalence in the highland tropics, but may be an important constraint to plant growth in Andosols of the Northern Andes (Dahlgren et al., 2004). The link between root characteristics and P foraging ability provides a logical entry point for efforts to evaluate existing varieties and improve P access of Andean crops such as fava bean, lupine, or maize.

At the inception of breeding for P foraging in common bean, landraces from a variety of geographic origins were compared for their P-foraging ability (Beebe et al., 1997). This process may provide a blueprint for testing germplasm of Andean legumes, quinoa, potato, and maize already gathered by Andean breeders, as well as promising accessions of crops from outside the region. Landraces selected by farmers in low-fertility environments may already have promising traits for P foraging, and little is known about how existing landraces are being selected by farmers as an adaptation to changing climate and weather shocks. In situ conservation of existing stress-tolerant varieties might be a useful complement to breeding approaches. However, crosses and selection based on this characterization would be an important further contribution of breeders, targeted toward gradients of fertility environments managed by subsistence farmers in the region.

As Noguera et al. (2011) suggest by their study of cultivar interactions with earthworm and biochar management, it will be important that regional breeding efforts shift focus from green revolution strategies that tested yields under high soluble fertility regimes to breeding that interfaces more effectively with the framework of agroecological intensification, for example, microbial symbioses, direct and successional plant impacts on the rhizosphere, biochar, and soil fauna (see previous sections of this review; Drinkwater and Snapp, 2007). For example, Snoek et al. (2003) reviewed breeding approaches for beans to improve rhizobial symbioses and N-fixation. Meanwhile, Boomsma and Vyn (2008) reviewed the mechanisms by which breeding maize for more effective symbiosis with AM could foster greater drought tolerance. Andean crop varieties could be bred for (or might already exhibit) better performance with mycorrhizae or organic nutrient sources, or even to
enhance biological control of soil pests (Degenhardt et al., 2009). The positive agroecological feedbacks from P foraging ability and other abiotic stress traits in smallholder systems should be recognized. For example, Henry et al. (2009) demonstrated that far from mining the soil for additional P, bean and soybean varieties that scavenged unavailable P covered soil better in a smallholder hillside context, reducing erosion P losses and creating a better P balance than P-inefficient varieties.

Unpredictable weather extremes, including frost and in-season drought, have always threatened crop productivity and food security in the Andes. However, increases in average temperature at high elevations due to climate change are predicted to exceed the global average (Bradley et al., 2006), so that evapotranspiration may increasingly outstrip the water-supplying ability of soil and both in-season and terminal drought stress may increase. There is already evidence that farmers perceive increased drought risk and are adapting their crop mixtures to climate change, for example, by increasing the proportion of early-maturing barley relative to other crops on the Bolivian Altiplano to avoid crop failure (A. Bonifacio, personal communication). Crop breeding for drought resistance and yield stability to confront climate change is already a worldwide effort, and much can be gained from linking Andean crop breeders to these global efforts (Khan et al., 2010). It should also be noted that plant traits targeted for agroecological intensification and climate change are also likely to be appropriate for possible alterations in the soils of Andean agroecosystems (discussed in Section 2.2.1), as most soil consequences of climate change are likely to occur through alterations to plant cover.

Mechanisms of drought resistance in crops encompass drought escape or earliness, dehydration avoidance (conservation of water in the plant, or ways to access more water in the soil profile), and drought tolerance (Khan et al., 2010). Drought resistance includes plant physiological mechanisms that improve yields under drought stress, such as deep rooting and osmotic adjustment of plant cells that allow photosynthesis and other metabolic processes to support plant productivity even under drought-stressed conditions (Blum, 2005; Chaves et al., 2003). Breeders and crop physiologists have elucidated these and other traits conferring drought resistance at a physiological level (Cattivelli et al., 2008), and are beginning to manipulate these traits with marker-assisted breeding and other molecular approaches (Araus et al., 2008; Miklas et al., 2006). Breeding methods for physiological drought resistance apply across crop species and could be useful for breeding efforts in the Andean region. Nevertheless, it should be recognized that drought tolerance mechanisms like osmotic adjustment have had limited success in explaining yield stability under drought, in comparison to avoidance of drought stress via plant size, earliness, or root architecture for water capture.

A number of studies in the region and elsewhere have examined differences in drought resistance among genotypes of Andean crops. For legumes, Siddique et al. (2001) tested a wide array of Mediterranean-type legumes
and concluded that earliness of flowering and pod formation (drought escape) was the dominant trait increasing yield under low rainfall. Studies on fava bean suggest that drought resistance and better recovery from drought are more due to stomatal closure and water conservation within the plant, rather than osmotic adjustment (Amede et al., 1999; Khan et al., 2010; Sau and Minguez, 2000). Analogous to root morphology traits used in screening for P foraging ability, Khan et al. (2007) suggested a number of physiological parameters of fava bean that are promising as physiological screening criteria for drought resistance. Drought physiology has not been greatly studied in *L. mutabilis* (see Carvalho et al., 2004), but Australian research on a number of old-world lupines showed that yield under drought stress was related to earliness and the speed of pod and bean filling rather than osmotic adjustment of cells (French and Buirchell, 2005; Palta et al., 2007). Others have argued that maximal water capture in the soil profile (e.g., deep rootness observed for *L. mutabilis*) and effective use of that water in plant productivity are more important under drought stress than a sole focus on photosynthesis per unit of water (Blum, 2009). Meanwhile, Tounieux et al. (2003a,b) examined six potato varieties under drought stress at tuberization in Bolivia and suggested that yield differences were not correlated with physiological parameters, but rather were due to reduced leaf area as well as the inability to translocate carbohydrates to tubers in sensitive varieties.

Regardless of physiological mechanisms of drought tolerance or avoidance, approaches to drought stress breeding for rainfed farming systems such as those in the Andes have recently emphasized the importance of selecting environments for breeding. Selection of varieties in environments with a particular drought stress, including the timing of the stress in the life cycle of the plant, is important to success in breeding for drought tolerance (Ceccarelli et al., 1991). For example, potatoes are highly sensitive to drought at tuberization (DallaCosta et al., 1997); breeding efforts for drought tolerance in maize focus on flowering and grain-filling stages (Banziger et al., 2006); and fava beans are most sensitive to drought at the pod set and early pod-filling phase (Khan et al., 2010). Ceccarelli et al. (1991) argued that the unpredictable stresses found in many smallholder farm environments mean that a suite of drought resistance traits must be selected for as a whole, a critique that has fostered an evolutionary strategy of breeding with farmer participation that is of interest to breeding efforts in the Andes (Ceccarelli et al., 2010). Nevertheless, it still makes sense to target the most vulnerable phases of crop growth for a given stress as a first priority in stress breeding, to foster mechanistic understanding of stress resistance and also since varieties that resist drought stress during these vulnerable phases will likely fare better in the average year when water becomes limiting.

Breeders working to select for stress tolerance in multi-environment trials have developed expertise in the efficient design and sophisticated interpretation of these trials, which often present challenges in teasing apart
genotype by environment interactions (Banziger et al., 2006; Bucheyeki et al., 2008; Setimela et al., 2005). One central and transferable concept from these efforts is that multienvironment variety trials can be grouped by “mega-environments” that embody similar soil types, climates, and agro-ecosystems (Setimela et al., 2005) within which other sources of variation in the trial (e.g., soil fertility and texture, drought stress) offer meaningful gradients to compare the performance of varieties. A classification scheme for Andean breeding environments and other smallholder environments worldwide would summarize similarities and differences between Andean and similar Mediterranean or highland climates elsewhere (e.g., east Africa, southern Asia) and soils that could supply germplasm for Andean breeding.

Crop modeling using the performance of different genotypes may also be a useful predictive tool in assessing impacts across environments. For example, Condori et al. (2010) used crop modeling with experimental validation in a number of environments across the Andes to assess the performance of major potato varieties. This showed that crop growth modeling could be used to predict the performance and usefulness of potato and bitter potato cultivars with a wide range of characteristics, given weather data and a number of scenarios of frost risk, and has applicability in rapid assessment of new stress-tolerant crop varieties across rainfall and temperature gradients in the Andes, and in the generation of hypotheses and research designs for multienvironment trials.

A very different approach to breeding for sustainability, which must be fit carefully to rotations in the Andean region, is the development of perennial cereals such as those being tested in the United States and Australia. These could dramatically reduce erosion and improve soil structure, water use from fluctuating precipitation, and benefits of rhizosphere processes (Bell et al., 2010; Cox et al., 2002).

Last, we reiterate the importance of the efforts to collect and preserve crop genetic diversity within the region for potato, quinoa, lupine, and other Andean crops, and stress that in order for this genetic resource to have maximal utility in confronting abiotic stresses for the region, it needs to be more than just a repository of agricultural heritage. Andean germplasm banks (and those elsewhere) should be screened and used in recurrent breeding and other efforts that generate new, stress resistant varietal options for smallholder farmers in the face of climate variability and change.

2.2.6. Spatial and temporal organization of farms
The above sections have focused on a variety of input-based technologies and improved management options that offer promising advances to improve soil fertility, productivity, and yield stability in the Andes. However, these technologies have largely been considered in isolation, overlooking how farming practices might be integrated to advance overall benefits for smallholder farmers. The spatial and temporal integration of
agricultural practices at multiple scales plays a fundamental role in optimizing agroecosystem productivity and environmental services. For example, the temporal integration of crops and livestock at the plot scale is a widespread and highly successful practice, commonly observed in sectoral fallow systems of the Andes (Molinillo and Monasterio, 2006; Pestalozzi, 2000). The cropping period provides the majority of the food, while fallow components serve the dual purpose of supplying fodder for animal production and the recovery of soil nutrient stores, hydrologic function, and biological communities (Sarmiento, 2000; Sarmiento and Bottner, 2002; Sivila de Cary and Hervé, 1994). Combining these two phases on the same plot of land yields higher productivity than either practice would in isolation. Similarly, the production and transfer of manure from pasture areas to crops represent another common, spatial integration of livestock with cropping systems at the farm scale (Caycho-Ronco et al., 2009; Giller et al., 2006) that improves overall productivity via redistribution of nutrients and organic matter to where they are most needed. While integration of agricultural production strategies may be common in the Andes, there remains considerable room for improvement. Further, there is a growing need to reinforce these concepts, as agricultural intensification (i.e., shortened fallows, use of agrochemicals) may be disrupting the balance and benefits associated with long-established integrative practices (Claverías, 1994; Mayer, 1979).

In both fallow-based and continually cropped systems of the Andes, crop rotation represents a widely utilized form of temporal diversification at the plot scale (Caycho-Ronco et al., 2009; Tapia, 1994). Crop rotation (including the use of cover crops) can provide key benefits for pest and disease control, improved nutrient use, and to soil restoration (Liebman and Dyck, 1993; Smith et al., 2008; Snapp et al., 2005) and offers an indispensable tool of sustainable management. A number of crops (e.g., Brassica sp., Crotalaria sp.) are included in rotations specifically for their pest suppression effects (Kirkegaard and Sarwar, 1998; Wang et al., 2002); however, less strategic rotations of common crops from divergent plant families can also help to break pest cycles, with more diverse rotations proving the most effective (Miller et al., 2006). Even simple maize and soybean rotations have been shown to outperform monocultures of either crop (Crookston et al., 1991), though mechanisms are not always clear. Although there has been some research on rotations in the Andes, much of this work has focused on residual fertility for crops following heavily fertilized potatoes (e.g., Condori et al., 1997). Research by Nieto-Cabrera et al. (1997) looking specifically at the role of crop sequence in the Ecuadorian Andes found potatoes and quinoa production to increase significantly following plantings of L. mutabilis, presumably due to additional N inputs associated with the legume. Other benefits of legumes were noted for fava bean in Bolivian potato systems, where application of residues has been suggested as a valuable tool for the management of plant-parasitic nematodes (Iriarte et al., 1999).
A promising area for improved spatial integration at the plot scale is the implementation of polycultures, or intercropping. Combining multiple species within the same field may complicate management in some cases but can increase overall yield through increased species complementarity of resource use (Fornara and Tilman, 2008). For example, Li et al. (2007) found a maize–fava bean intercropping systems in China to outyield (produce more than either crop would in monoculture) due to differing rooting depth and timing of nutrient uptake (reduced competition) as well as improved availability of P resulting from organic acid production by fava bean roots (facilitation). In this same cropping system, increased competition for available N by maize forced fava beans to fix more N from atmospheric sources, thus augmenting overall N inputs to the system via N-fixation (Li et al., 2009). Just as for crop rotation, increased spatial diversification in Andean agriculture can also help alleviate pest issues, but through increases in predation/parasitism of pests and decreased density of resources (Gianoli et al., 2006; Poveda et al., 2008). Although offering clear potential for cropping situations, such benefits of intercropping have been demonstrated in multiple ecosystem types and seem to be especially well suited for grassland systems (Fornara and Tilman, 2008; Oberson et al., 1999). Such practices could perhaps be most easily implemented during non-cropping stages of sectoral fallow systems, as management requirements are minimal and risks to farmers relatively low. However, there is also great potential for more intensified crop–pasture rotations. The idea of improved fallows and pastures (where species composition is intentionally managed) for the Andes has been suggested previously (Barrios et al., 2005; García, 2011; Sarmiento et al., 2001), but principally with a focus on leguminous plants. Others have suggested mixtures of legumes and grasses as an option to maximize N-fixation and productivity for fodder production (Bartl et al., 2009; Bentley et al., 2007). Such mixtures could incorporate exotic plants that are well adapted to local climates (e.g., cold tolerant, able to set seed before arrival of the dry season; Wheeler et al., 1999), as well as native species that could help reduce farmer investment and ensure survival (Bartl et al., 2009; Nezomba et al., 2010). Further, improved fallows (with optimal varieties and species mixtures) combined with strategic fertilization (particularly P additions) could greatly enhance N-fixation, fodder production, and SOM stabilization, ultimately accelerating the recovery of soil functioning and nutrient reserves.

Another means of enhancing spatial integration at the plot and farm level is through agroforestry practices. Although potential for tree growth in some parts of the Andes (i.e., very dry regions and/or high elevations) may be low, evidence suggests that for large parts of the Andean highlands trees may have been much more common than at present (Chepstow-Lusty and Winfield, 2000; Hensen, 2002), and that potential for agroforestry technologies may be higher than often acknowledged (Cotler and Maass, 1999; Mahboubi et al., 1997; Reynel and Felipe-Morales, 1990). For example, Mahboubi et al. (1997) compared tree survival of candidate species in the Bolivian Altiplano.
and found several species (e.g., the native *Buddleja coriacea*) to tolerate conditions well at elevations as high as 4200m, with a greater number of tree species suitable for lower elevations. They also suggested that residues obtained from these trees (all except *Eucalyptus* sp.) could provide valuable nutrients to enhance crop growth. Comparisons of contour row species near Cochabamba, Bolivia, suggest that woody species can grow well and also provide effective erosion control (*Sims et al.*, 1999). Additionally, the incorporation of legumes (particularly woody species) into grass contour barriers has been suggested as an effective means of contributing to soil fertility and rapid erosion control, while reducing plant resource competition (*Mutegi et al.*, 2008; *Sims and Rodriguez*, 2001). Along with contour hedgerows, alternative options for integrating woody species into agroecosystems include fodder banks, wood lots, cut and carry systems, and/or windbreaks at field margins (*Reynel and Felipe-Morales*, 1990; *Young*, 1997), as well as trees intermixed in the field, a highly successful strategy for lower elevation hillsides used in the Quesungual agroforestry system of Honduras (*Fonte et al.*, 2010; *Hellin et al.*, 1999). Ultimately, the incorporation of trees into the landscape offers great potential to provide farmers with supplementary fuel, fodder, and soil fertility amendments (*Barrios et al.*, 2005), while contributing key ecosystem services (e.g., erosion control, climate change mitigation, improved water dynamics) and enhancing regional biodiversity (*Antle et al.*, 2007; *Otero and Onaindiam*, 2009; *Smukler et al.*, 2010). It should be noted, however, that proposed agroforestry technologies must seek to minimize the potential negative impacts of trees, such as increased competition with crops for light, water, and nutrients; greater labor requirement; and promotion of crop pests (e.g., birds). Based on the relative paucity of materials encountered in our literature search, research to date has yet to fully explore the full potential of tree-based options in the Andes. Although the flexibility of agroforestry practices in the Andean highlands is perhaps more limited than their lowland counterparts, large potential exists and future research needs to address these possibilities.

In addressing spatial organization of farms, soil heterogeneity frequently represents a major challenge for soil fertility management. Andean agroecosystems often have extreme and diverse topography which can generate steep and somewhat predictable fertility gradients over the landscape (*Buytaert et al.*, 2007). However, fertility gradients are also generated by anthropogenic factors at the farm scale, with improved nutrient status typically found closer to the household (*Tittonell et al.*, 2005; *Vanek*, 2010). In farming systems of the east African highlands, *Vanlauwe et al.* (2006) suggested that fields further from the farmer homes (outfields) should receive greater nutrients investment, as they are likely show a greater response to fertilizer additions. However, in more mountainous regions such as the Andes, outfields may represent fields with steeper slopes and/or rockier sites, where soils do not have the same yield potential as flatter infield sites and increased nutrient applications might be at greater risk to loss, via erosion (*Vanek*, 2010). In either situation, there may be distinct soil fertility management strategies that
reflect differential labor inputs associated with far versus near farm plots. For example, in the Andes it may be better to apply manure and compost generated near the home to infield plots, so as to minimize transport labor. At the same time more distant plots, especially those prone to erosion, are perhaps better candidates for cover crops and/or improved fallows combined with strategic fertilizer applications in order to generate vegetative cover and organic matter inputs on-site, and thus avoid transport. Such fertility gradients are equally important at smaller scales as well and perhaps more manageable. For example, Dercon et al. (2006) demonstrated that erosion within contour hedgerows in Ecuador generated gradients of SOM, P, texture, such that fertility was lowest on the upper portion of slopes and highest at the bottom, where live barriers slowed runoff leading to soil deposition. Crop yield within terraces varied significantly, with up to fourfold differences for wheat growing at the top versus the bottom of a single terrace. They conclude that erosion control is critical in slowing the formation of such gradients. However, it may also be necessary to improve organic matter management (via manure or plant residue additions) on the upslope portions of the terrace to restore SOM and the capacity of these soils to provide and retain nutrients.

Organization at larger scales is also important for optimizing the efficiency of farm management and ensuring a range of ecosystem functions at the farm and landscape level. Although climate, topography, and soil type largely determine where different crop and livestock elements are placed, there is likely to be some room to better organize farms and landscapes for increasing farm efficiency and the production of ecosystem services and reducing labor. For example, active landscape management in the Andes has been observed whereby farmers strategically disperse their crop fields as means of distributing risks and improving overall yield stability (Goland, 1993). At the same time, the physical arrangement of crops and other farm attributes can greatly influence less obvious agroecosystem functions in a variety of ways. The maintenance of biodiversity and pollination services probably offers the clearest case for the role of landscape organization in the provision of agroecosystem services. Pollinators are critical for the production of numerous crops around the globe (Klein et al., 2007), including a number of important Andean crops (e.g., onions, fava beans, Andean lupine), and are greatly influenced by landscape structure and composition (Ricketts et al., 2008). Pest control agents are also impacted by the landscape (Bianchi et al., 2006), but often in counterintuitive ways (Parsa et al., 2011). Perhaps more relevant for soil fertility, landscape diversity can influence soil fauna biodiversity and distribution. For example, patches of native vegetation may function as a reservoir or refuge of earthworms for adjacent agricultural plots, thus maintaining their diversity, abundance, and activity on farmed plots (Marichal, 2011). The composition of management attributes at the farm level can also impact key ecosystem services such as C storage, N loss, and erosion control (Robertson and Swinton, 2005; Smukler et al., 2010).
3. Additional Considerations for Soil Fertility Interventions

3.1. Need to incorporate co-limiting crop growth factors

While the availability of nutrients, optimal soil physical, chemical and biological conditions, and appropriate cultivars are critical for agroecosystem productivity, these factors alone are not sufficient to ensure high crop yields. As mentioned earlier, water represents a fundamental limiting constraint for much of the Andes, particularly for rainfed agroecosystems of the Altiplano. The technologies advocated here for improving nutrient balances thus need to consider impacts on crop–soil water dynamics. For example, the use of live barriers for erosion control, N-fixation, and/or fodder production can create competition for water and may ultimately impact crop yields (Dercon et al., 2006; Pansak et al., 2007). At the same time, enhanced inputs of organic matter may improve nutrient availability and soil faunal activity with beneficial impacts for water infiltration and storage (Capowiez et al., 2009). Along with water, other co-limiting factors include light, temperature, as well as pest and disease. For example, mulch-based technologies that work well for lower elevation, dry tropical sites (Erenstein, 2003; Fonte et al., 2010) may not be appropriate for cooler, high elevation sites where a residue layer may inhibit growth by maintaining cooler soil temperatures (M. Scurrah, personal communication). Pests and disease factors present still more complex considerations for soil fertility practices, as their responses to environmental change are less predictable and often difficult to control. Although there is some indication that improved soil fertility and biological functioning improve plant resistance to pests (Bennet and Bever, 2007; Blouin et al., 2005; Thamer et al., 2011), a number of management practices could potentially exacerbate pest problems (Alyokhin et al., 2005; Conklin et al., 2002; Parsa, 2010). While the relative importance of each of these co-limiting factors depends on the environmental and management context, all factors are essential to consider when developing agroecological options to improve soil fertility.

3.2. Integrating local needs and knowledge into soil fertility research

Limited adoption of new agricultural technologies has long been a challenge for scientists and development professionals who work to refine and validate these technologies, and lack of adoption is often conceptualized as an important obstacle to improving livelihoods in rural communities (Ashby et al., 1997). Some researchers have examined the way that implementation
costs, lack of short-term payoffs, insufficient or unstable land tenure, or access to information can hinder adoption (Bayard et al., 2006; Tenge et al., 2004). While these economic and information limitations to adoption certainly play a role, scientists studying extension and rural development suggest that adoption or adaptation of new exogenous technologies will only result when greater attention is given to existing knowledge structures and perceived needs of farmers, as well as processes by which farmer learning and innovation take place in rural communities (Bentley, 1989; Deugd et al., 1998; Paredes, 2010). As mentioned earlier, many farming communities in the Andes benefit from a long history of agricultural knowledge and often possess an intimate and complex understanding of their land (e.g., Sandor and Furbee, 1996). Despite this attribute, there often exists a general disconnect between farmer needs and researcher objectives (Horton, 1983). This can lead to low adoption rates and, further, suggests the need for greater farmer involvement in the development of new management strategies (Altieri, 2004; Barrios and Trejo, 2003; Bentley et al., 2007). While increased farmer interaction is critical, farmers are not always able to express their demands in the same knowledge system used by researchers (Bentley et al., 2007). Thus, learning from both sides and mutual involvement in the research process are critical for the development of relevant agroecological intensification strategies that have a high probability of acceptance among farmers (Ashby et al., 1997; Winklerprins, 1999). At the same time, farmer involvement alone may not be sufficient for the development of successful technologies. There exists a clear need to develop flexible strategies that allow for farmers to better understand the mechanisms behind new technologies and adjust them to their local needs as well as to adapt them to rapidly changing socioeconomic and environmental conditions (Bentley et al., 2007). Further, new technologies need to account for community dynamics and local decision-making processes, as well as regional policies and political structures. Ultimately, the integration of local knowledge and farmer needs into the research process is fundamental for developing practical soil fertility technologies that have a high probability of adoption and achieving regional impact.

4. Conclusions and Recommendations

4.1. Outlook for agroecological intensification in the Andean context

The Andean region faces key challenges in coming years, yet offers a number of unique attributes that may allow for successful agroecological intensification and betterment of rural livelihoods throughout the region. As discussed earlier, this region is endowed with a large native crop diversity and
demonstrates a strong interest in maintaining local varieties and indigenous management techniques (Brush et al., 1995). Further, many smallholder agroecosystems in the Andes already display considerable within-farm spatial and temporal diversity, complex crop rotations (or fallow sequences), and diverse crop mixtures, suggesting that farmers are already accustomed to key principles of sustainability and perhaps more flexible in their farm management strategies. Such attributes combined with well-developed local knowledge have the potential to facilitate innovation and improve adaptation to new conditions. Despite these attributes, the region faces many challenges and the need for change is clear. While increased reliance upon agrochemical inputs and ‘green revolution’ technologies represents one alternative to traditional practices that has occurred elsewhere, this route may not be economically or ecologically viable in the Andes due to the relative fragility of soils and landscapes, low yield potential, and the minimal financial resources of rural farmers. Modifying classic short-term, yield-driven definitions of agricultural success may allow us to develop more appropriate development strategies for the region. The success of a particular intervention must consider not only short-term yield and economic returns but also long-term stability of yields, ecological resilience, and the environmental consequences of a given practice. Taking these factors into consideration, agroecological intensification, as discussed here, has the potential to significantly improve the productivity and stability of Andean agriculture.

This chapter attempts to take a pragmatic approach to soil fertility management options in the Andes. We consider a balance of applied research, with more immediate prospects to improve livelihoods of Andean farmers (e.g., ISFM, cover cropping), versus innovations associated with more basic science that are less certain and have a longer return on investment, but may yield potentially greater impacts (e.g., metagenomics, perennialization of crops). Although we focus principally on ecologically based interventions, we also consider the prudent use of agrochemicals, new cultivars, and mechanization as valuable tools to help farmers increase overall agroecosystem function on their farms. From the above discussion of past research and technology options in the Andean highlands, we attempt to offer a brief and targeted list of the most promising areas for research and implementation. We want to emphasize that there exists no single technology that is likely to lead to successful agroecological intensification of Andean farms across all sites. Rather, we propose that a suite of technology options is likely required and the precise combination likely varies by climate, soil type, as well as political and cultural setting. For each technology, we stress the importance of supporting farmers in experimentation and adaptation to their local needs. In this review, we aimed to sort through the various options and offer researchers and extension workers the basic information and guidelines for future research and implementation projects that will contribute to poverty alleviation, improved food security, and environmental sustainability (for a more
detailed list of recommendations, see http://mcknight.ccrp.cornell.edu/projects/andes_cop/andescop.html).

4.2. Recommendations for future research and interventions

1. **Soil conservation**: There is a clear need for continued investment in soil conservation, particularly for hillside soils and areas where mechanized tillage has become more common. Erosion prevention strategies should focus on barriers with low capital and labor investment (e.g., live barriers) as well as improved management of fallow plots (e.g., cover cropping). Better understanding of how current management practices impact erosion processes and participatory development of new small holder technologies are needed to combat erosion losses and maintain more positive farm nutrient balances.

2. **Biomass production**: Organic matter has become highly limiting in Andean agroecosystems (particularly in the Altiplano) due to competing uses of fuel, fodder, and soil fertility amendments, thus indicating a need for greater farm level biomass production. Efforts to address this issue should emphasize the incorporation of N-fixing species both within crop fields (e.g., polycultures, live barriers) and at field margins as a means to enhance soil fertility and improve the overall farm N balances with minimal farmer inputs.

3. **Alternative nutrient sources**: Large scale nutrient imbalances suggest the need for the identification of new potential sources of nutrient inputs. Waste streams of existing industries (e.g., poultry, floriculture) and rock phosphate offer promising fertility sources for many farming communities. Improved market access and transportation of these materials (as well as conventional agricultural inputs such as fertilizer) to more isolated farmers would contribute greatly to restoring farm nutrient balances.

4. **Improved management of organic residues** would help to improve nutrient-use efficiency, while contributing to soil biological functioning and SOM storage. Further, the strategic application of inorganic fertilizers with organic resources offers a particularly useful tool for controlling nutrient release from a variety of organic materials and rapidly correcting nutrient imbalances, thus allowing farmers to maximize the potential of locally available organic resources.

5. **Soil ecology**: Continued research must strive to understand and optimize soil microbial and faunal communities and their activity through proper management (e.g., residue or charcoal additions, rotation) and inoculative strategies. For microbial inoculants, rigorous and standardized screening in the lab must be accompanied by field testing under diverse conditions to fully evaluate the potential of these organisms to contribute to improved crop performance. Soil metagenomics and other basic
research on plant–microbe relations in the rhizosphere may also offer longer-term contributions to principles and solutions for research.

6. **Targeted breeding efforts** should take advantage of the high agrobiodiversity associated with the local domestication of multiple indigenous crops in the Andes and seek to optimize interactions with key root symbionts (e.g., *Rhizobia*, mycorrhizae, soil fauna) and alternative nutrient sources that form the basis of agroecological intensification. Additionally, breeding efforts should draw upon approaches from other crops and regions with severe edaphic and/or climatic constraints to more rapidly improve the productivity and stability of key orphan crops, including supporting crops such as fava bean and Andean lupine.

7. **Improved spatial and temporal organization of farms** would contribute to more efficient use of land and the improved provision of ecosystem services (e.g., C sequestration, N-fixation, erosion control, pest control). Research on diversification at the plot level should explore promising plant synergies between functionally distinct species in order to enhance crop utilization of resources. Additionally, improved understanding of soil fertility gradients and options for strategic management of within-farm heterogeneity would help farmers to improve overall farm productivity and yield stability in Andean agroecosystems.

8. **Long-term and basic soils research**: There is a need for basic research and detailed soil maps to improve our understanding of soil physical, chemical, and biological processes in the Andes and the potential impacts of new management strategies throughout the region. Additionally, long-term agricultural research and monitoring is notably lacking in the region, yet would greatly improve our ability to understand the more far-reaching impacts of land management and global change.

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**REFERENCES**


Ortuño, N. (2010). Desarrollo de bioinsumos para la producción sostenible de hortalizas con pequeños agricultores para una soberanía alimentaria en los Andes. CIAT, Colombia.


