

The compatibility of agricultural intensification in a global hotspot of smallholder agrobiodiversity (Bolivia)

Karl S. Zimmerer¹

Department of Geography, Earth and Environmental Systems Institute, Penn State Institutes for Energy and the Environment, Pennsylvania State University, University Park, PA 16802

Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved December 21, 2012 (received for review September 21, 2012)

Integrating the conservation of biodiversity by smallholder farmers with agricultural intensification is increasingly recognized as a leading priority of sustainability and food security amid global environmental and socioeconomic change. An international research project investigated the smallholder agrobiodiversity of maize (corn) in a global hotspot (Bolivia) undergoing significant intensification. Peach-based intensification was pronounced (300–400%) and prolonged (2000–2010) in study areas. Intensification and maize agrobiodiversity were found to co-occur within smallholder landscapes. Interactions of these field systems did not trigger land-change tipping points leading to landrace extirpation. By 2010 maize landraces in the study areas still demonstrated high levels of taxonomic and ecological biodiversity and contributed significantly to this crop's agrobiodiversity at national (31%) and hemispheric (3%) scales. Social and ecological resilience and in situ conservation of the maize agrobiodiversity by Bolivian smallholders was enabled through robust linkages to off-farm migration; resource access and asset capabilities among both traditional and nontraditional growers; landrace agroecology and food uses; and innovative knowledge and skills. The smallholders' resilience resulting from these linkages was integral to the conditional success of the in situ conservation of maize agrobiodiversity. Environment–development interactions both enabled smallholders' agrobiodiversity resilience and influenced the limits and vulnerability of agrobiodiversity. Scientific policy recommendations regarding land-use planning and sustainability analysis are targeted to specific Río+20 priorities for agrobiodiversity.

smallholder agricultural development | social–ecological resilience | food access | sustainability science | livelihood–landscape analysis

The potential compatibility of biodiversity in agricultural ecosystems undergoing intensification has become a major sustainability issue connecting food security, conservation, and global environmental–socioeconomic change (1–10). These connections were envisioned by the 2005 Millennium Ecosystem Assessment, reframing earlier in situ genetic resource conservation of the 1992 Convention on Biological Diversity and its successors [e.g., the Fifth Ordinary Meeting of the Conference of the Parties to the Convention on Biological Diversity, May 15–26, 2000 (CBD-COP 5) agrobiodiversity program] and by the 2001 International Treaty on Plant Genetic Resources for Food and Agriculture and have found their way into the prioritization by the recent 2012 United Nations Conference on Sustainable Development (Río+20) of the need to combine and improve sustainable agriculture, food security, and biodiversity conservation. [The final agreement of Río+20 (June 22, 2012) prioritizes this need, raising the call to incorporate biodiversity into land-use planning, which was a principal policy recommendation of the global scientific community's precursor conference (Planet under Pressure) in March 2012.] A central question of this new framing involves the identification of tradeoffs or potential synergies of land saving (farmland sustainability; refs. 11–17) and land sparing (wildland maximization; refs. 18–23). The two strategies need not be mutually exclusive. While agricultural intensification often leads to negative impacts including spillovers into wildlands (7), other intensified farmland types can be compatible with biodiversity

conservation, and sustainability (24–26). Importantly, smallholder farmers may serve integral roles in intensification initiatives targeted at both the conservation of biodiversity and potential food security (27).

Studies of agricultural intensification—the concentration of inputs per areal unit of farmland up to diminishing return of outputs (3, 28)—and its global impact on biological diversity have tended to focus on multispecies field systems (12, 29) and ecosystem services of food-producing landscapes (1, 2, 7, 16, 17, 30) with emphasis also on woodland habitats, insects, soil microorganisms, pollinators, and macrofauna (4, 5, 10, 31). Economic- and social-focused studies concentrate on market functions (cost-benefit, market pricing) and institutional governance (9, 11, 14, 15). Analysis of the global-change dynamics of agricultural intensification has focused less on the biodiversity and in situ conservation of landraces, which are subspecific taxonomic units of crops (akin to “unimproved” livestock breeds) consisting of genetically heterogeneous local or regional populations often referred to as “traditional” or “farmer” varieties and cultivars. Highly biodiverse landraces, which include the world's major domesticates (8, 32), function as the main planned component of crop agrobiodiversity, furnishing key agroecological and food resources to smallholder farms and communities as well as broader economic and sociocultural benefits in global conservation and food security (8, 28, 32–37). Geographically the biodiversity of landraces exhibits clusters in various global hotspots of smallholder agriculture ranging from traditional indigenous and peasant to peri-urban farming. Loss of landrace growing and use by smallholders, typically triggered by decommittal (reallocation, reduction, or elimination of inputs) of agrobiodiversity resources, provides a widespread signal of potential threats to global hotspots and food security (32–37). Increasingly, the dynamics of both landrace loss, which can deplete genetic diversity (genetic erosion), and the converse, in situ conservation through continued smallholder cultivation, have been assessed and analyzed (28, 33–36).

Empirical and model findings have overturned the view of agrobiodiversity farming as curating, per se (see ref. 38, p. 472), reinforcing the need to investigate landrace growing as coupled systems of smallholders' high-biodiversity land use subject to global environmental–socioeconomic change (28, 33–40). Recent findings are used to generate this study's four principal propositions. (i) Interactions of high-agrobiodiversity land use and global change-induced intensification are nondeterministic (28, 33–35) and require specification of intensive inputs (refs. 3, 28, 39 and *SI Text*) and spatial factors (28, 34). (ii) Intensification of field systems can impact agrobiodiversity through possible landrace-depleting

Author contributions: K.S.Z. designed research, performed research, analyzed data, and wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission.

¹E-mail: ksz2@psu.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1216294110/-DCSupplemental.

tipping points triggered by the decommitment of resources (e.g., the reduction of the growing area used for cultivation of agrobiodiverse crops), known to be a leading cause of landrace loss and potential genetic erosion (28, 33, 34), requires both multisite and longitudinal research designs with high spatiotemporal resolution. (iii) Trajectories of smallholder-grown agrobiodiversity amid intensification potentially indicate social–ecological resilience as well as possible limits resulting from environment–development interactions among land-use and livelihood factors (17, 28, 33–35, 41–43)*. (iv) Linkages (e.g., inputs) enabling agrobiodiversity may characterize ongoing changes of both traditional, high-agrobiodiversity land use and intensified cropping involving modernization and technological innovations (28, 33, 34). This study’s findings on the above propositions lead targeted insights to the corresponding priorities (assessment, adaptive management, capacity building, and mainstreaming) of Río+20 and current international agrobiodiversity conservation science highlighted in the conclusion.

This research investigates the agrobiodiversity of maize (corn) in the global hotspot of the Bolivian Andes amid the effects of land-change intensification, primarily commercial peach production. It merges time-based longitudinal research, focused on 2000–2010, with analysis of spatial variation (Table 1). Three study areas show variations in peach-based intensification (Table 1) as well as distinct degrees of extralocal market integration (agricultural products, labor migration) and infrastructure (irrigation) resulting from spatially differentiated development (Table 1 and *SI Text*). The village farm areas are representative of the 410-km² region of the Valle Alto (“High Valley”) in Bolivia’s tropical Andes Mountains (Fig. 1). Region-wide cultivation of Andean maize and complex use systems—both indigenous and nonindigenous—are known to have generated a global center of this crop’s agrobiodiversity comparable to the centers in Mexico and Central America (32, 44–51). Farmers in the study areas are bilingual Quechua-Spanish speakers with low-to-moderate incomes by national standards (52) and smallholder land-use systems (Table 1). The peri-urban location (35–50 km to the Cochabamba urban area, which has a population 1.1 million) has led to extralocal market integration and development of irrigation that is extensive but locally varied (Table 1 and *SI Text*).

Results

Intensification. By 2010 intensive peach production had expanded to cover 25–67% of smallholder-cultivated areas (Table 1). Global socioeconomic integration exerted a direct effect, because this intensification depended on the investment of international migration remittances in high-value peach growing. It also exerted effects through the expanding markets of the Cochabamba urban area. Inputs to intensive peach farming, approximately four times greater than inputs to maize growing (Table 2), combined capital, labor, skills and knowledge, and biological and agrochemical inputs including tree varieties, tree and field care, pesticides, fertilizer, weed control, tree and field monitoring, and manual harvest. Modern techniques in peach growing were conjoined with the cultural logic of traditional agriculture (*SI Text*). This intensification was smallholder-based, with the greatest relative area in Arbieta (99.5 fields/km²; Table 1). The graphical model (Fig. 2) estimates the spatiotemporal variation in proportional extent (left axis) and degree (right axis) of peach-based intensification showing the peak expansion mid-decade (*SI Text*). All surveyed peach

growers ($n = 128$) responded that their primary rationale was income generation. Land-user interviews ($n = 64$) showed that limiting factors to further peach growing were the availability of irrigation, capital, and labor as well as risks in production and marketing.

Andean Maize. High-agrobiodiversity Andean maize comprised 58–65% of land use in the study areas in 2000 (27, 51), before the major expansion of peach-based intensification. By 2010 maize growing was reduced significantly (17–53%, Table 1 and Fig. 2, 1a–3a). Maize cultivation was intensified from 2000–2010 through an increase in tractor tillage, fertilizer use, and dam-based irrigation, along with lessening of previous maize-fallow biannual rotation (Table 2). Field sizes (average 101.3 fields/km²) indicated smallholder-based maize growing in the study areas.

Ten types of Andean maize landraces were identified and classified in the sampling of fields and farms in the study sites (*SI Text*). These landraces were determined to represent an equal number of major Bolivian maize races (the taxonomic level that represents this crop’s principal subspecific categorization) (44, 46, 47, 53–55). In 2010 the cultivation of 10 maize landraces and races demonstrated the continuation of the taxonomic units present in the study areas in 2000 and earlier (30, 56, 57). This finding is supported also by the semistructured interviews ($n = 82$) confirming the continued cultivation of the types and numbers of maize landraces and races present since 2000. Numerical estimates also demonstrate the absence of area-scale extirpation between 2000 and 2010.[†] The ecological richness, evenness, and overall diversity of maize landraces demonstrated cross-site similarities (Table 3). Continued maize landrace biodiversity hinges on extensive phenologic variation of flowering and maturation among landraces (*SI Text*), reflecting agroecological usefulness and substantial genetic diversity (46, 58). Coupled with drought-tolerance traits, this phenologic variation enables staggered maize planting (August–December; Table 3), an effective drought-evasion and risk-reduction strategy. It also contributes to the reproductive separation of maize landraces. Maize landraces were allocated to sale, seed-saving, and food/beverage uses (Table 3), with the last comprising highly varied types of consumption (Tables S1 and S2). The range of consumption uses along with agroecological–phenologic variation were noted in interviews ($n = 64$) as predominant rationales for maize landrace growing.

Key factors were found to determine whether smallholders engaged in intensive peach farming also chose to grow maize. The farm-level capacity to grow maize in conjunction with peach-based intensification was pivotal to continued maize agrobiodiversity. Tested factors included direct land management (model 1), access to resources and socioeconomic conditions (model 2), and an overall combination (model 3) (detailed in *SI Text*). Logistic regression in model 1 showed the positive effect of resource endowments (78.3% predictive efficiency, $R^2 = 0.261$; Table 4). Other factors—access to nonland resources and socioeconomic factors, consisting of access to irrigation, migration, and household maize-growing experience—also exerted positive effects through the assets of favorable infrastructure, access to resources, and knowledge (model 2, Table 4 and Table S1). Land acquisition through purchase is related negatively because maize fields were less likely than peach sites to be obtained through purchase. Model 2 also demonstrates robustness in predicting maize growing (71.7% predictive efficiency; $R^2 = 0.354$). The positive effects of migration arose from monetary remittances

*Resilience is defined as the human social capacity to respond to disturbance-type changes within the domain of similar structures and functions (43). The concept of social–ecological resilience used in this study integrates a focus on the capacity-enabling linkages of smallholders’ in situ conservation with the limits and vulnerability involving potential agrobiodiversity tipping points, resource decommitment, and other depletions of agroecosystem services (41, 42).

[†]Of 256 households surveyed and interviewed in this study, 12 indicated they had discontinued a landrace between 2000 and 2010. Causes included resource decommitment involving irrigation ($n = 2$) and land ($n = 2$), along with decline of irrigation ($n = 2$) and soil quality ($n = 3$). All cases of maize cessation ($n = 12$) entailed discontinuing a single landrace that still was being cultivated by other smallholders in the study area, so that neither area-scale landrace loss nor genetic erosion were recorded.

Table 1. Demography and land use of study sites (Bolivia)

Village	No. of farming households [†]	Degree of irrigation [‡]	Level of international migration [§]	Total no. of fields surveyed	No. of farm households surveyed	Peach portion of farm area ^{*¶}	Maize portion of farm area [*]
Villa Mercedes/ Mamanaca	155	M	M	100	60	0.246	0.532
Santa Rosa	144	M-H	M-H	145	53	0.400	0.479
Arbieto	150	H	H	102	61	0.667	0.170

[†]Numbers of households were derived from the following estimates of farming populations: Villa Mercedes/Mamanaca, 698; Santa Rosa, 648; Arbieto, 673. Estimates include near-village farming residents and are based on 2001 census estimates (50).

[‡]M, medium (less irrigation infrastructure); M-H, medium-high (intermediate level of irrigation infrastructure); H, high (highest level of irrigation infrastructure).

[§]M, medium, 25–39% of family members migrated within the past 10 y; M-H, medium-high, 40–49% of family members migrated within the past 10 y; H, more than 50% of family members migrated within the past 10 y.

[¶]*n* = 146 peach fields. χ^2 tests show numbers of peach and maize fields significantly different among village farm areas at the level of $*P < .05$ and ratios of peach:nonpeach ratios are significantly different at the level of $P < 0.01$. Land tenure of a majority of peach and maize fields comprised smallholder field owners (60–80%); caretaking, rental, and modified sharecropping arrangements among smallholders were also used.

that enhanced access to inputs (land, water labor, technology). These remittances often were channeled through women farmers and migrant-designated field caretakers residing in the study areas (57.1%). The effect of combined factors (model 3) increased both the predictive efficiency (84.8%) and robustness ($R^2 = 0.518$). Thus a wide range of factors contributed to smallholders' ability to combine maize landrace growing and peach-based intensification.

Linkages enabling agrobiodiversity functioned in conditions in which maize and intensive peach growing occupied spatially distinct field sites (*SI Text*). Combined peach and maize growing were predominant, accounting for up to three-quarters of cropping in the study areas (Table 1). In certain locales (e.g., Arbieto, Santa Rosa) a comparatively higher proportion of farms pursuing intensification combined both types of land-use (65–70%

“combiners”), which, in addition to enhancing income, gave the benefits of self-provisioning maize and reducing overall cropping risk. Most combiner interviewees (84%) mentioned all three rationales in describing the compatibility of peach-based intensification and high-agrobiodiversity maize. Combiners were less frequent in study areas with fewer household resources (e.g., 30–35% combiners in Villa Mercedes/Mamanaca), where it is more common to pursue either peach or maize growing as “specialists.” High-density smallholder landscapes characterized the areas of both predominant combiners (320.2 fields/km²) and specialists (337.9 fields/km²). Knowledge of the key facets of agrobiodiversity management (phenologic variation, consumption uses) was found to be extensive, with insignificant differences among combiners (*n* = 52), peach specialists (*n* = 12), and maize specialists (*n* = 9) (*t* test, $P = 0.5128$).

The social–ecological linkages detailed above have supported continued high-agrobiodiversity maize cultivation across a spectrum of time- and site-dependent intensification (Fig. 2). Land-change intensification did not trigger tipping points such as decommitment of resources potentially depleting landraces. The graphical model (Fig. 2) tracks land-change intensification of each study area (2000–2010), illustrating the compatibility of wide-ranging land use and intensity levels, even at uppermost points, with in situ conservation of maize landrace biodiversity. As a result the 10 maize landraces and races present in 2000–2010 comprised a significant share of this crop's biodiversity within Bolivia (31% of 32 maize races; ref. 46, pp. 45–131). This biodiversity also accounted for ~3% of the total number of maize races across the Americas (ref. 44, p. 185; ref. 47, p. 169).

The high concentration of landrace biodiversity has continued, although agroecological impacts suggest possible vulnerability. [A majority of interviewees referred to their awareness of changes in the agroecosystem (3, 10) that were seen as potentially limiting the cultivation of high-agrobiodiversity maize. Although important to recognize with regard to the resilience of smallholder agrobiodiversity (30), such changes have not resulted in extirpations of maize landraces in the study areas.] Interviewees reported that by 2010 water and soil deterioration (e.g., irrigation shortages) and reduced landscape complexity (e.g., canal woodlands) posed possible limits to high-agrobiodiversity maize growing through worsening ecosystem-service functions. Countering this possible decline is the increase in maize growing among Bolivian smallholders since 2010 because global changes have led to lessened intensification and migration (remittance decline) and pronounced climate variation (fruit-damaging frosts).

Discussion

Landrace cultivation and use in the Bolivian study sites have led to continued levels of maize agrobiodiversity that equal or exceed other

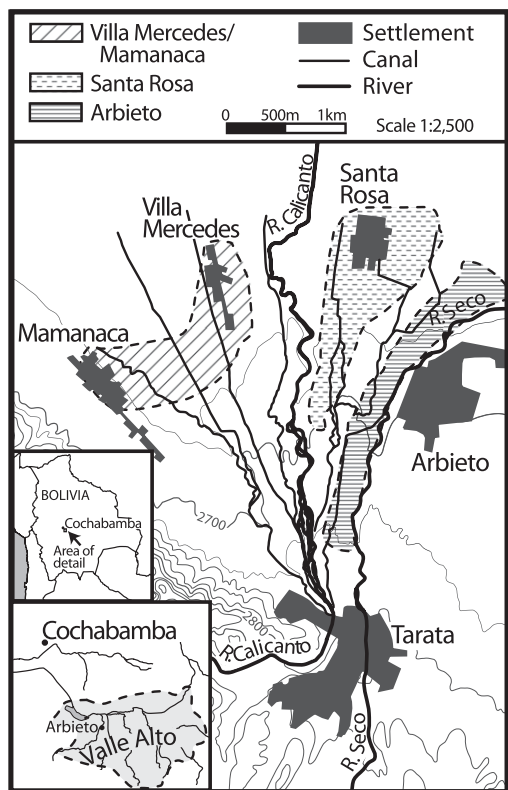


Fig. 1. Map of Bolivian study sites.

Table 2. Peach and maize intensification (2000–2010) and intensity levels (2009–2010)

Village	Year peach field start (mode)	Peach monetary input (US\$/ha/y)*	Peach labor intensity (d/ha/y)	Fallow frequency of maize fields [†]	Changes in maize cultivation and intensity levels [‡]	Monetary input for maize cultivation (US\$/ha/y)	Labor intensity for maize cultivation (d/ha/y)
Villa Mercedes/ Mamanaca	2006	\$2,577	130.10	0.244	T(3), I(1)	\$917	47.8
Santa Rosa	2001	\$2,645	104.92	0.060	T(3), I(1)	\$828	34.8
Arbieto	2006	\$2,900	125.60	0.067	T(3), I(2)	\$793	31.2

*Input and intensity levels of both peach and maize land use did not vary significantly among the study areas.

[†] χ^2 test shows difference between Villa Mercedes/Mamanaca and other two study areas (** $P < 0.05$); the latter do not differ significantly.

[‡]T, adoption of tractor tillage; I, maize intercropping; (3), adopted by more than 2/3 of surveyed households; (1), adopted by less than 1/3 of surveyed households; (2), adopted by 1/3–2/3 of surveyed households. Tractor tillage for maize increased sharply (2000–2010) and is widespread in all study areas.

global concentrations (32, 33, 36, 37, 50, 51, 59). In situ conservation has depended on smallholders deploying wide-ranging, indigenous and nonindigenous knowledge and innovative skills and techniques to combine landrace agrobiodiversity amid intensification. Intensification has been achieved primarily through arboriculture-based (peach) global land-change (60) and, to a far lesser degree, within high-agrobiodiversity maize fields (61). Interactions with migration exerted positive effects on both intensification and smallholder growing of biodiverse maize landraces, thus differing from migration-derived investments solely in the consumption goods (62). This study’s analysis of land-change systems and other global environmental–socioeconomic changes—intensification, development, and livelihood interactions—contributes an additional dimension to diachronic studies of landrace agrobiodiversity (63 and *SI Text*).

The capacity for continued cultivation and use of high-agrobiodiversity maize was fueled through the spatial configuration of land use, insofar as a discrete separation of field types occurs between high-agrobiodiversity parcels (maize) and predominant intensification sites (peach) within smallholder agriculture. In addition, the combined production-and-consumption values of maize require that nonseparable decisions be made related to land use and food. As a result, combined agroecological rationales (e.g., phenologic variation) and consumption desiderata (e.g., varied uses) contribute to an expansive range of preferences about

landrace choice and land use, thus benefitting the conservation of agrobiodiversity.

The social–ecological resilience of landrace agrobiodiversity reflected factors of land use as well as management of nonland resources and socioeconomic conditions (Table S1). Both innovation and continuation of the structures and functions of smallholder maize growing and use played key roles enabling in situ conservation (Table S2). Linkages identified in this study resemble the region-scale attributes ascribed to the in situ conservation of maize agrobiodiversity elsewhere in the Andean countries (47) and in Mexico and Central America (17, 33, 38, 50, 51, 63, 64). Analysis of the Bolivian study areas shows these key linkages operate amid recent and ongoing trends toward significant agricultural intensification and livelihood diversification. Evidence underscored the importance of “open systems” of smallholder know-how related to agrobiodiversity, as well as other skills, knowledge, and experience (17).

The overall viability of smallholder growing and use of maize landraces is faced with potential limits that are integral to sustainability analysis of agrobiodiversity (7; 41, p. 642; 42, p. 1737; 65). A decline in the capacity for maize landrace growing and use could worsen the social–ecological vulnerability of smallholders (66). Vital also to understanding smallholders’ conservation of agrobiodiversity is its functioning as a coemergent and relational property potentially contributing to sustainability (67). It emerges through cumulative responses whereby the continued production and consumption of maize landraces has been linked to changing land use and livelihoods (Table S1), but it also incorporates innovation (Table S2). This finding is in contrast to the understanding of maize landrace growing as the simple survival of a vestigial relict preserved through unaltered persistence or maintenance per se. Although the latter conditions may occur in remote or nearly unchanging communities (59), the formulation of in situ conservation as dynamic and coemergent is consistent with this study. Findings emphasize the importance of interactions with intensification amid broader development and global environmental–socioeconomic changes, including policies and strategies for conserving agrobiodiversity (i.e., relational-type interactions in agrobiodiversity conservation, both in situ and in gene banks; 3, 28, 33, 34, 35, 37, 59). The notable range of emergent functional linkages has helped enable both intensified land-change and conservation of Andean maize agrobiodiversity. Attention to coemergent linkages should be a basis of global, national, and local policies and land-use planning supporting in situ agrobiodiversity conservation and its potential compatibility with land-change intensification, food security, and sustainability.

Conclusion

Smallholders’ agricultural intensification under certain land-change conditions can be compatible with high, landrace-level agrobiodiversity in global hotspots. Principal conclusions concern each major proposition: (i) Agricultural intensification in smallholder communities is related to but is distinct from the use of land

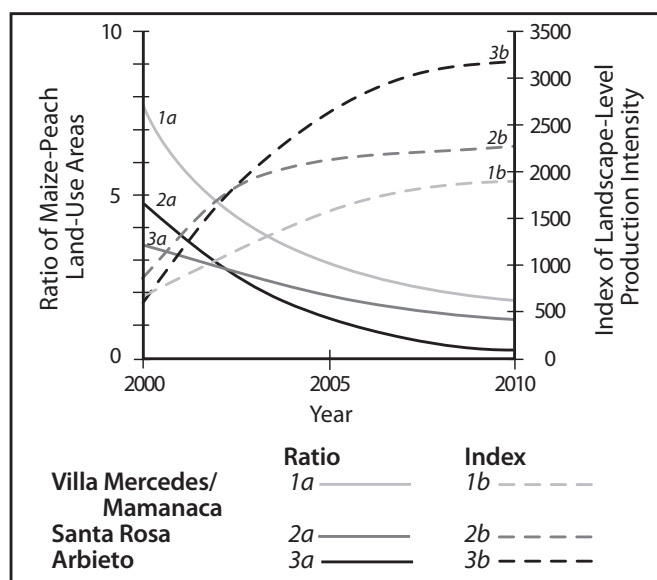


Fig. 2. Graphical model of land use with peach-based intensification and high-agrobiodiversity maize, 2000–2010. (Land-use ratios are on the left axis, and overall landscape intensification is on the right axis.)

Table 3. Ecological agrobiodiversity (landraces) and management of maize, 2009–2010

Village	Ecological richness (landraces/household)	Area-level ecological richness [Margalef index (33)]	Area-level ecological evenness [Pielou index (59)]	Area-level ecological diversity [Shannon index (36)]	Phenologic variation (planting months)	Frequency of sale*	Frequency of seed saving	Frequency of use for food
Villa Mercedes/ Mamanaca	1.35	1.69	0.67	1.28	Aug–Dec	0.31	0.31	0.39
Santa Rosa	1.37	1.86	0.61	1.34	Aug–Dec	0.31	0.27	0.42
Arbieto	1.43	1.89	0.71	1.33	Aug–Dec	0.34	0.22	0.44

Insignificant differences of all diversity indices were estimated using bias-corrected 95% confidence intervals based on 10,000 bootstrap samples. Insignificant difference of use-category frequency was based on χ^2 test ($P = 0.9349$).

*Marketing of maize in the study areas involves both grain and fodder.

for growing high-agrobiodiversity maize so that both elements occur within farm landscapes; (ii) high-resolution spatiotemporal research, both multisite and longitudinal, demonstrates that significant extents of high-agrobiodiversity landraces continue to be grown amid a range of intensification settings without triggering a critical level of resource decummittal; (iii) innovations and specific agrobiodiversity-enabling linkages, particularly the continued availability and quality of resources (arable land and water), market effects (including labor migration), extensive knowledge systems (combining indigenous and nonindigenous elements), and wide-ranging consumption uses, have been central to the social-ecological resilience of smallholder maize growing; and (iv) social-ecological linkages function as coemergent properties of changes in both traditional high-agrobiodiversity land use and, concurrently, “modern” cropping intensification and commodity production.

These conclusions provide policy and strategic insights on the fundamental targets of the 2012 Rio+20 prioritization of sustainable intensification, biodiversity conservation, and food security, building on four core areas of agrobiodiversity conservation science in the 2000 CBD-COP 5. First, assessment of agrobiodiversity must incorporate a diachronic analysis of trajectories of intensification-change including spatiotemporal characterization and monitoring for the planning of high-agrobiodiversity smallholder land use. Second, adaptive management can be aided, potentially to a large degree, through the analysis of new pathways of smallholder intensification that are determined to be compatible with the conservation of landrace biodiversity by operating within land-change thresholds. Third, building capacity for agrobiodiversity conservation depends on enabling smallholders’ social-ecological resilience through diverse production and consumption linkages (including agroecological factors and both traditional and nontraditional

growers). Fourth, the mainstreaming of agrobiodiversity conservation requires a greater focus on coemergent processes whereby adjustments of landrace-containing land use are recognized as dynamic, linked, and potentially compatible with agricultural intensification.

Methods

In-depth field projects undertaken with Bolivian collaborators in 2003–2005 and 2007–2012 used interdisciplinary designs to compile and analyze high-resolution spatial and longitudinal data integrated with long-term 1987–2012 datasets (*SI Text*) (30, 56). A Geographic Information System (GIS) database incorporated high-resolution imagery (1:2,500 topographic maps and 1:8,000 aerial photographs in 1993 and 2001) that was analyzed using ArcGIS tools.

Detailed surveys of land use and intensification were conducted in the study areas using a structured random design to address production inputs and outputs of peach and maize ($n = 347$ fields) and the suite of farm-level management, varietal choices, on- and off-farm livelihood activities, food and consumption decisions, and water and soil management, especially irrigation, for 174 households. Farm survey results were used to estimate spatial extents and levels of intensification. Logistic regression modeling was designed to investigate factors among intensive peach-growing smallholders ($n = 128$) predicting whether they also grew maize. These factors were chosen to represent conditions of land change (model 1) and development (model 2) (*Table S1*) and a composite model (model 3) (*SI Text*). Coordinated methods were designed for field-level sampling, identification and standard taxonomic classification of maize, and biodiversity estimates (*SI Text*).

A total of 88 semistructured interviews averaging 30–40 min were conducted in Quechua and Spanish. Interviews with diverse groups were completed in each study area (*SI Text*). Both semistructured interviews and farm surveys involved components asking land users and officials to estimate the areas devoted to intensified peach growing and maize growing and the characteristics of changes in these areas.

Table 4. Logistic regression of factors within farms ($n = 128$) in combination of field-level intensification (peach) and high agrobiodiversity (maize)

Variable	Model 1	Model 2	Model 3
Constant	−1.89** (0.25, −2.89)	0.60 (2.02, 0.30)	−2.49 (2.63, −0.95)
Household field area	0.65* (0.18, 1.67)		0.46 (0.51, 0.90)
Livestock number	0.18 (0.12, 1.42)		0.17 (0.17, 1.0)
Crop fallow	38.04 (399.54, 0.08)		19.51 (299.55, 0.09)
Irrigation shares		0.099 (0.083, 1.18)	0.11 (0.13, 0.90)
Migration extent		0.55** (0.21, 2.65)	0.56** (0.24, 2.31)
Field acquisition		−1.02 (0.84, −1.21)	−1.59 (1.03, −1.55)
Household age		−0.057 (0.043, −1.30)	−0.02 (0.05, −0.41)
Nagelkerke’s R^2	0.261	0.354	0.518
Predictive efficiency (%)	78.3	71.7	84.8
χ^2 test	9.77*	13.79**	21.96**

Coefficients given for each estimate. SEs and z values are shown in parentheses. * $P < 0.05$; ** $P < 0.01$.

ACKNOWLEDGMENTS. We acknowledge the contributions of G. Ávila, N. Tapia, F. Delgado, M. Bell, P. Howe, R. Hedberg, D. Retchless, Q. Di, L. Schneider, L. Rojas, T. Hosse, B. Moats, T. Bassett, J. Centellas, T. Rudel, A. Cáceres, B. Barham, D. Lewis, D. Praeger, A. Guarachi, E. Carter, F. Gonzales, J. Burt, and A. Burnicki. Institutional collaborators included the Pennsylvania State University Colleges of Agricultural Sciences and Earth and Mineral Sciences, Earth and Environmental Systems Institute, and the Pennsylvania State University Insti-

tutes for Energy and the Environment; Agroecología Universidad Cochabamba, ARLL, Centro de Estudios Superiores Universitarios, and PROINPA (in Bolivia); Consortium for Sustainable Development in the Andean Ecoregion and CIP (in Peru); and Centro Internacional de Mejoramiento de Maíz y Trigo (in Mexico). Research in phase I (2002–2005) and phase II (2007–2012) was funded through National Science Foundation Grant BC 0240962 (University of Wisconsin-Madison) and National Science Foundation Grant HSD 0948816 (Pennsylvania State University).

- Jackson L, Bawa K, Pascual U, Perrings C (2005) agroBIODIVERSITY: A New Science Agenda for Biodiversity in Support of Sustainable Agroecosystems. DIVERSITAS Report No. 4 (DIVERSITAS, Rome).
- Jackson LE, Pascual U, Hodgkin T (2007) Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agric Ecosyst Environ* 121(3):196–210.
- Zimmerer KS (2010) Biological diversity in agriculture and global change. *Annu Rev Ecol Syst* 35:137–166.
- Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. *Science* 277(5325):504–509.
- Vitousek PM, Mooney HA, Lubchenco J, Melillo J (1997) Human domination of earth's ecosystems. *Science* 277(5325):494–499.
- Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. *Nature* 418(6898):671–677.
- Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. *Ecol Lett* 8(8):857–874.
- Gepts P (2006) Plant genetic resources conservation and utilization: The accomplishments and future of a societal insurance policy. *Crop Sci* 46(5):2278–2292.
- Pascual U, Perrings C (2007) Developing incentives and economic mechanisms for in situ biodiversity conservation in agricultural landscapes. *Agric Ecosyst Environ* 121(3):255–268.
- Tomich TP, et al. (2011) Agroecology: A review from a global change perspective. *Annu Rev Environ Resour* 36:193–222.
- Narloch U, Drucker A, Pascual OA (2010) Payments for agrobiodiversity conservation services for sustained on-farm utilization of plant and animal genetic resources. *Ecol Econ* 70(11):1837–1845.
- Perfecto I, Vandermeer J (2010) The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proc Natl Acad Sci USA* 107(13):5786–5791.
- Carvalho LG, et al. (2011) Natural and within-farmland biodiversity enhances crop productivity. *Ecol Lett* 14(3):251–259.
- Perrings C, et al. (2006) Biodiversity in agricultural landscapes: Saving natural capital without losing interest. *Conserv Biol* 20(2):263–264.
- Omer A, Pascual U, Russell N (2010) A theoretical model of agrobiodiversity as a supporting service for sustainable agricultural intensification. *Ecol Econ* 69(10):1926–1933.
- Scherr SJ, McNeely JA (2007) Biodiversity conservation and agricultural sustainability: Towards a new paradigm of 'ecoagriculture' landscapes. *Philos Trans R Soc Lond B Biol Sci* 363(1491):477–494.
- Jackson LE, et al. (2012) Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions. *Glob Environ Change* 22(3):623–639.
- Fischer J, et al. (2011) Conservation: Limits of land sparing. *Science* 334(6056):593, author reply 594–595.
- Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. *Science* 333(6047):1289–1291.
- Green RE, Cornell SJ, Scharlemann JP, Balmford A (2005) Farming and the fate of wild nature. *Science* 307(5709):550–555.
- Matson PA, Vitousek PM (2006) Agricultural intensification: Will land spared from farming be land spared for nature? *Conserv Biol* 20(3):709–710.
- Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci USA* 108(9):3465–3472.
- Flynn DFB, et al. (2009) Loss of functional diversity under land use intensification across multiple taxa. *Ecol Lett* 12(1):22–33.
- Brussard L, et al. (2012) Reconciling biodiversity conservation and food challenges for a new agriculture. *Curr Opin Environ Sustain* 2(1–2):34–42.
- Pretty J, Toulmin C, Williams S (2011) Sustainable intensification in African agriculture. *Int J of Agric Sustain* 9(1):5–24.
- Godfray HCJ, et al. (2010) Food security: The challenge of feeding 9 billion people. *Science* 327(5967):812–818.
- Tscharntke T, et al. (2012) Global food security, biodiversity conservation and the future of agricultural intensification. *Biol Conserv* 151(1):53–59.
- Brookfield H (2001) *Exploring Agrodiversity* (Columbia Univ Press, New York).
- Vandermeer J, van Noordwijk M, Anderson J, Ong C, Perfecto I (1998) Global change and multi-species agroecosystems: Concepts and issues. *Agric Ecosyst Environ* 67(1):1–22.
- Zimmerer KS (2010) Woodlands and agrobiodiversity in irrigation landscapes amidst global change: Bolivia, 1990–2002. *Prof Geogr* 62(3):335–356.
- Swift MJ, Izac A-MN, van Noordwijk M (2004) Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? *Agric Ecosyst Environ* 104(1):113–134.
- Perales H, Brush SB, Qualset CO (2003) Dynamic management of maize landraces in Central Mexico. *Econ Bot* 57(1):21–34.
- Brush SB (2004) *Farmers' Bounty* (Yale Univ Press, New Haven, CT).
- Zimmerer KS (1996) *Changing Fortunes: Biodiversity and Peasant Livelihood in the Peruvian Andes* (Univ of California Press, Berkeley, CA).
- Nabhan GP (2009) *Where Our Food Comes From: Retracing Nikolay Vavilov's Quest to End Famine* (Island, Washington, DC).
- van Heerwaarden J, Hellin J, Visser RF, van Eeuwijk FA (2009) Estimating maize genetic erosion in modernized smallholder agriculture. *Theor Appl Genet* 119(5):875–888.
- Jarvis DI, Hodgkin T, Sthapit BR, Fadda C, Lopez-Noriega I (2011) An heuristic framework for identifying multiple ways of supporting the conservation and use of traditional crop varieties within the agricultural production system. *Crit Rev Plant Sci* 30(1–2):125–176.
- Dyer GA, Taylor JE (2008) A crop population perspective on maize seed systems in Mexico. *Proc Natl Acad Sci USA* 105(2):470–475.
- Kirch PV, Zimmerer KS (2010) *Roots of Conflict: Soils, Agriculture, and Sociopolitical Complexity in Ancient Hawai'i*, ed Kirch PV (School for Advanced Research, Santa Fe), pp 3–30.
- Young OR, et al. (2006) The globalization of socio-ecological systems: An agenda for scientific research. *Glob Environ Change* 16(3):304–316.
- Kates RW, et al. (2001) Environment and development. Sustainability science. *Science* 292(5517):641–642.
- Clark WC (2007) Sustainability science: A room of its own. *Proc Natl Acad Sci USA* 104(6):1737–1738.
- Folke C, et al. (2004) Regime shifts, resilience, and biodiversity in ecosystem management. *Annu Rev Ecol Syst* 35:557–581.
- Sánchez JJ, Stuber CV, Goodman MM (2000) Isozymatic diversity in the races of maize of the Americas. *Maydica* 45(1):185–203.
- Brandolini A (1970) *Genetic Resources in Plants – Their Exploration and Conservation*, eds Frankel OH, Bennett E (F. A. Davis, Philadelphia), pp 273–309.
- Ramírez ER, Timothy DH, Diaz E, Grant UJ (1960) *Races of Maize in Bolivia* (National Academy of Sciences and National Research Council, Washington, DC).
- Goodman MM, Stuber CW (1983) Races of maize, VI: Isozyme variation among races of maize in Bolivia. *Maydica* 28(2):169–187.
- Vigouroux Y, et al. (2008) Population structure and genetic diversity of New World maize races assessed by DNA microsatellites. *Am J Bot* 95(10):1240–1253.
- Perales HR, Benz BF, Brush SB, Qualset CO (2005) Maize diversity and ethnolinguistic diversity in Chiapas, Mexico. *Proc Natl Acad Sci USA* 102(3):949–954.
- Brush SB, Perales HR (2007) A maize landscape: Ethnicity and agrobiodiversity in Chiapas Mexico. *Agric Ecosyst Environ* 121(3):211–221.
- van Etten J, Fuentes López MR, Molina Monterroso LG, Ponciano Samayoa KM (2007) Genetic diversity of maize (*Zea mays* L. ssp. *mays*) in communities of the western highlands of Guatemala: Geographical patterns and processes. *Genet Resour Crop Evol* 55(2):303–317.
- INE (Instituto Nacional Estadística) (2001) *Resultados del Censo de 2001 – Nivel de Hogares [Results of the 2001 Census – Household Level]* (INE, Cochabamba, Bolivia).
- Ávila GA, Brandolini AG (1990) *I Maíz Boliviano [Bolivian Maize]* (Instituto Agronomico per L'Oltremare, Florence, Italy).
- Ávila GA, Guzman L, Céspedes M (1998) *Catálogo de Recursos Genéticos de Maíces Bolivianos [Catalogue of Bolivian Maize Genetic Resources]* (Centro de Investigaciones Fitogenéticas de Pairumani, Cochabamba, Bolivia).
- Ávila GA (2008) *El Maíz y Su Mejoramiento Genético en Bolivia. [Maize and its Genetic Improvement in Bolivia]* (Academia Nacional de Ciencias de Bolivia, La Paz, Bolivia).
- Zimmerer KS (2011) The landscape technology of spate irrigation amid development changes: Assembling the links to resources, livelihoods, and agrobiodiversity-food in the Bolivian Andes. *Glob Environ Change* 21(3):917–934.
- CIDRE Club 2/3 (1991) Informe de Avance No. 8. Proyecto Múltiple Laka Laka [Progress Report No. 8. Multi-Purpose Laka Laka Project] (CIDRE, Cochabamba, Bolivia).
- Buckler ES, et al. (2009) The genetic architecture of maize flowering time. *Science* 325(5941):714–718.
- Jarvis DI, et al. (2008) A global perspective of the richness and evenness of traditional crop-variety diversity maintained by farming communities. *Proc Natl Acad Sci USA* 105(14):5326–5331.
- Keys E, McConnell WJ (2005) Global change and the intensification of agriculture in the tropics. *Glob Environ Change* 15(4):320–337.
- Bray F (1994) Agriculture for developing nations. *Sci Am* 271(1):30–37.
- Jokisch BD (2002) Migration and agricultural change: The case of smallholder agriculture in Highland Ecuador. *Hum Ecol* 30(4):523–550.
- van Etten J (2006) Changes in farmers' knowledge of maize diversity in highland Guatemala, 1927/37–2004. *J Ethnobiol Ethnomed* 2(12):12.
- van Dusen ME, Taylor JE (2005) Missing markets and crop diversity: Evidence from Mexico. *Environ Dev Econ* 10(4):513–531.
- Turner BL II, Robbins P (2008) Land-change, science, and political ecology: Similarities, differences, and implications for sustainability science. *Annu Rev Ecol Syst* 33:295–316.
- Eakin H, Bojórquez-Tapia LA (2008) Insights into the composition of household vulnerability from multicriteria decision analysis. *Glob Environ Change* 18(1):112–127.
- Rammel C, Stagl S, Wilfing H (2007) Managing complex adaptive systems—A co-evolutionary perspective on natural resource management. *Ecol Econ* 63(1):9–21.