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Inter-community and on-farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape

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Abstract

Soil fertility in agricultural landscapes is driven by complex interactions between natural and anthropogenic processes, with organic matter (OM) inputs playing a critical role. Asymmetric allocation patterns of these resources among communities and within individual farms can lead to soil fertility gradients. However, the drivers and consequences of such patterns in different socioecological contexts remains poorly documented and understood. The objective of this study was to address this gap by assessing asymmetric OM allocation patterns and the associated consequences for soil fertility management in three indigenous communities located in the Central Ecuadorian Andes. We found that both distance from homestead and perception of fertility were associated with asymmetric OM allocation patterns to fields as well as with soil fertility gradients within farms. For example, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), and exchangeable potassium (K) all decreased with distance from the homestead, while SOC, total N, and available P were positively correlated with a farmer's perception of soil fertility. We note that these fertility gradients remained even in the case of increased farm-level OM inputs. Overall OM allocation patterns differed significantly among communities and were associated with significant differences in soil fertility, with the highest levels of available P and exchangeable K found in the community with the highest OM inputs. The results of this study indicate the importance of asymmetric OM allocation patterns encountered at different scales, both within farms and among neighboring communities, in rural Andean landscapes and their significant interactions with soil fertility gradients.

KEYWORDS
Ecuador, landscape gradients, natural resource management, organic inputs, soil organic carbon

1 | INTRODUCTION

The management of organic matter (OM) plays an important role in the productivity and sustainability of soils, both in terms of providing nutrients for crops as well as the maintenance of soil physical qualities and essential biological processes (Palm, Gachengo, Delve, Cadisch, & Giller, 2001; Wood & Bradford, 2018). Soil organic matter (SOM) is essential for promoting a range of ecosystem functions such as improved soil physical structure (Jensen et al., 2019; Sarker et al., 2018), water capture and storage (álvarez, Carral, Hernández, & Almendros, 2013; Buchmann & Schaumann, 2018), carbon (C) sequestration (Takimoto, Nair, & Nair, 2008), and the maintenance of soil biodiversity and activity (Walmsley & Cerdà, 2017).

The recycling of crop residues, manure inputs, and other on-farm OM resources represent important flows of nutrients in smallholder farming systems that can help address negative nutrient and C balances. This is especially relevant in smallholder contexts where severely constrained financial resources limit the purchase of externally based inputs, such as commercial composts or mineral fertilizers (Fonte et al., 2012; Palm et al., 2001). Waste streams from agro-food industry, such as poultry farming, however, can provide promising sources of C and nutrients for intensive peri-urban farms that commonly generate nutrient deficits (Agbede, Adekiya, & Eifediyi, 2017). While low cost OM sources are promising in such situations, it is important to recognize that OM inputs vary in terms of overall quality and their effects on different soil fertility parameters (Risberg, Cederlund, Pell, Arthurson, & Schnürer, 2017). The chemical composition of OM inputs is particularly important determining rates of nutrient release and availability for crop uptake (Xu, Chen, Ding, & Fan, 2017). Generally speaking, a high quality source of OM inputs for agricultural production requires OM that is easily mineralized, characterized by a low C:N ratio (less than 20:1) and low levels of lignin (<15%) and phenols (<4%; Palm et al., 2001). Variations in macronutrient content of different OM input sources are also common. For example, poultry manure is usually higher in available P in relation to other sources of animal manure or common OM inputs (e.g., crop residues). At the same time, cow and sheep manure tend to have higher proportions of exchangeable K (Moore Jr, Daniel, Sharpley, & Wood, 1995). While soil properties vary naturally within a landscape due to varying climate, topography, and the underlying geology, land and farm management also are important drivers of soil fertility (Van Apeldoorn, Kempen, Sonneveld, & Kok, 2013; Vanwalleghem et al., 2017). In rural farming areas, patterns of OM resource allocation can create management-induced soil fertility gradients, both within and among farms (Tittonell et al., 2013), contributing to either soil degradation or aggradation (Van Apeldoorn, Sonneveld, & Kok, 2011).

Agronomic studies have identified that a number of socioeconomic factors can influence the use of agricultural inputs (Berkhout, Schipper, Van Keulen, & Coulibaly, 2011; Chikowo, Zingore, Snapp, & Johnston, 2014; Tittonell et al., 2013). Household wealth, in particular, can influence the quantity of organic and inorganic nutrient inputs. In a meta-analysis of 57 nutrient balance studies in East Africa, Cobo, Dercon, and Cadisch (2010), found that the fields of wealthier producers typically presented higher N and P balances than those of poorer farmers.

In addition to wealth, different financial, natural, social, and human resources have also been shown to influence the application of nutrient inputs. For example, in a study in the central highlands of Ethiopia, organic nutrient inputs to fields were directly related to the number of livestock holdings and hence the availability of manure (Haileslassie, Priess, Veldkamp, & Lesschen, 2007). In another study in Uganda, it was found that larger farm operations with greater off-farm income displayed the most positive nutrient balances (Ebanyat et al., 2010). Access to labor has also long been considered a major constraint to improved soil conservation and natural resource management (Barrett, Place, & Aboud, 2002; Marenya & Barrett, 2007; Zimmerer, 1993).

In addition to farm-level socioeconomic drivers of resource allocation, within farm factors can determine farm resource allocation at the field level (Chikowo et al., 2014). For example, studies have found that 'home' or near-fields of farms receive greater inputs and as a consequence are more fertile compared to remote fields (Kamanga, Waddington, Robertson, & Giller, 2010; Zingore, Murwira, Delve, & Giller, 2007). Although it is noteworthy that the reverse has also been found in a case-study from Zimbabwe, where due to the more recent conversion of this land from forest to agricultural land-use, improved fertility was observed in remote fields (Masvaya et al., 2010). Studies have found that perception of a field's fertility is also associated with farmer resource allocation patterns, with those fields perceived as more productive (and fertile) often receiving greater inputs than fields perceived as less productive (Mtambanengwe & Mapfumo, 2005; Tittonell, Vanlauwe, Leffelaar, Rowe, & Giller, 2005). In the Andes, Vanek and Drinkwater (2013) demonstrated similar within farm fertility gradients, while noting fewer between farm differences in nutrient management than in African cases. Their study, from a single remote Bolivian community, offers important insight into nutrient management dynamics in the highland Andes, but limited data from this region suggests the need for further examination of Andean systems, including the important aspect of variation between sites (e.g., community-to-community variation).

While farm management is an important driver of soil fertility patterns in rural landscapes, the underlying biophysical context also can be critical (Pennock & Veldkamp, 2006). The strength of influence of farm management on the soil patterns of a rural landscape compared to the underlying biophysical conditions appears to differ depending on the soil parameter of interest. For example, while it appears that farm management can induce important fertility gradients for P and K (Tittonell, Vanlauwe, Leffelaar, Shepherd, & Giller, 2005; Zingore et al., 2007), it is not always the case for soil organic carbon (SOC) due to the influence of longer-term, biophysical factors such as soil texture, climate, and hydrology (van Apeldoorn et al., 2014). By enhancing our understanding of landscape patterns of soil fertility management we can begin to integrate an additional scale of understanding that may be critical, especially in mountainous contexts, in exploring pathways to more sustainable land and agricultural management.

In accordance with crop productivity differences reported by farmers in the landscapes considered in this research, fertility gradients were conspicuous. Farmers in each of the communities were keen to further understand these patterns in order to inform broader discussions as to how to better manage this heterogeneity. The objective of this study was therefore to develop a better understanding of the factors that influence landscape-level patterns of soil fertility management, specifically by means of OM amendment. For this purpose, we worked with rural families in three Andean villages to examine socioeconomic, cultural, and farm management factors associated with the use of OM inputs and resulting soil fertility gradients.

Based on the earlier mentioned research, we hypothesized that community and farm-level variables as well as within farm differences such as distance from homestead and farmer perception of fertility would significantly influence OM inputs. We anticipated that asymmetric allocations of OM inputs would be associated with soil fertility gradients both between communities and within farms and that these patterns would also be related to the underlying biophysical context of each of the three communities.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was carried out between February and April 2016, in three Kichwa-speaking communities located in the Central Highlands of the Ecuadorian Andes, Chimborazo Province. Two communities are located in the Parish of Flores, Basquitay (1°82′08.59′S, 78°66′90.15′W) and Naubug (1°51′24.0′S, 78°39′15.6′W). The other community, Tzimbuto (1°80′11.41′S, 78°61′85.80′W), is located in the Parish of Licto. While located nearby to one another, these communities differ significantly in terms of elevation ranges, linkages to local markets, farming strategies, and access to resources (Figure 1 and Table 1). The climate enables nearly year-long production with average temperatures ranging between 10 and 18°C. Average annual precipitation ranges from 250 to 500 mm in the Parish of Licto and 400–500 mm in the Parish of Flores, with greater rainfall at higher elevations and most rain falling between December and May and a drier, windier period from May to November (GAD Parroquial Rural de Flores, 2015; GAD Parroquial Rural de Licto, 2014).

The different elevation ranges mean that the biophysical conditions of the communities developed under ecosystems dominated by distinct vegetation types. The native vegetation of Basquitay, as the highest community (3,400–3,650 ma.s.l.), is characterized as páramo grassland with some significant patches of native vegetation still remaining in the community. Tzimbuto (2,800–3,250 m.a.s.l.) on-the-other-hand likely developed in sub-páramo and Andean forest conditions, while Naubug, with the greatest range in elevations (2,800–3,600 ma.s.l.), likely developed under the three different ecosystems. At the time of this study, remnants of these ‘natural’ ecosystems no longer exist in either Naubug or Tzimbuto. Soils in the study area are generally classified as Andosols, developed on deep volcanic ash parent material. Where management has been historically less

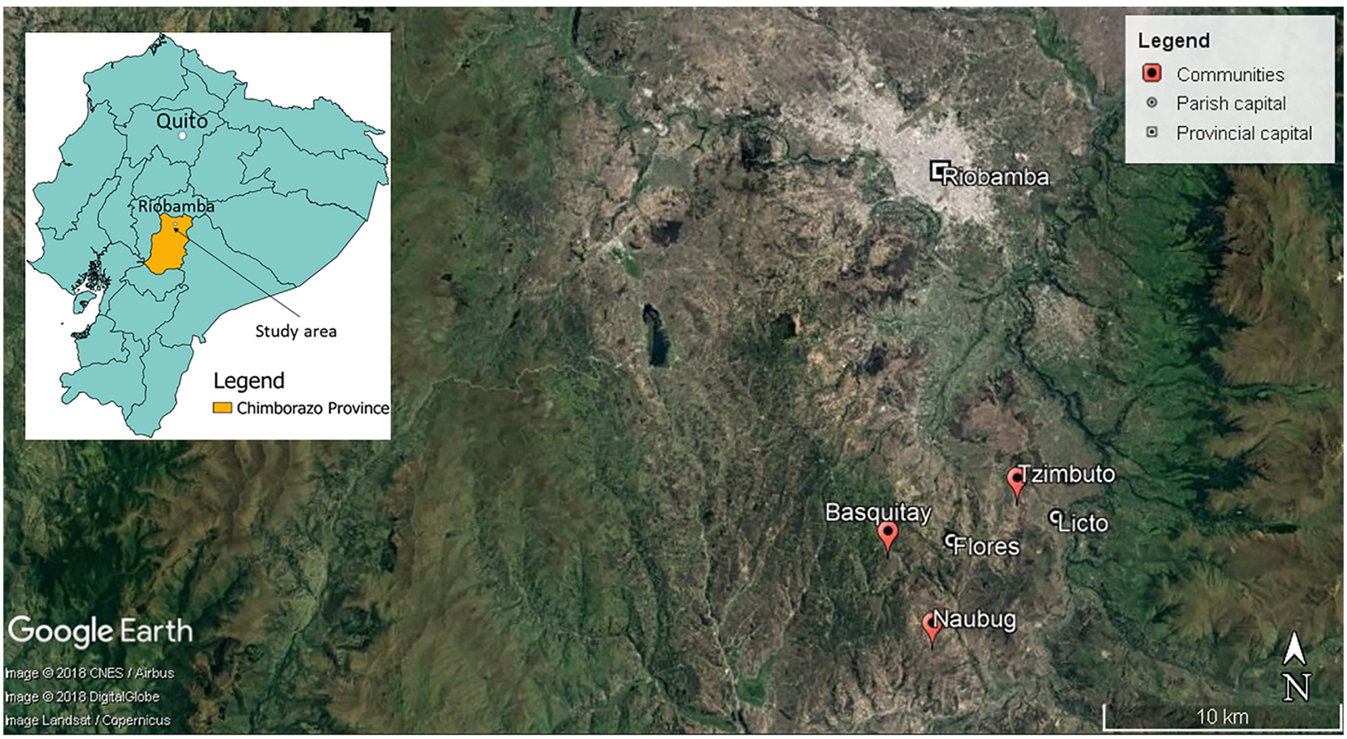

FIGURE 1 Location of the three communities studied in relation to provincial and parish capitals. Inset: map of Ecuador, the Province of Chimborazo, and the location of the communities of study, Basquitay, Naubug, and Tzimbuto [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Socioeconomic and farming characteristics of Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador

Community characteristics	Basquitay	Naubug	Tzimbuto
Population (persons)	120	641	415
Area (km^2)	3.73	8.11	3.73
Population density (persons km^2)	32.17	79.04	111.26
Elevation range (ma.s.l.)	3,400–3,650	2,800–3,600	2,800–3,250
Maximum walking distance of fields from homestead (min.)	60	90	60
Average number of fields per household	4.5	8.7	14.3
Average number of livestock (excluding small animals, such as chickens and guinea pigs)	15.1 (se: 1.86)	5.2 (se: 0.80)	11.1 (se: 1.90)
Main crops cultivated	Forage, tubers	Forage, cereals (for human consumption), tubers	Forage, cereals, vegetables, tubers
Import of manure from outside community	Rare	Rare	Regular
Import of cut forage from outside community	Rare	Regular	Regular
Access to irrigation	No	No	Yes
Market orientation	Livestock, milk production	Few or no products sold	Agricultural products, vegetables, milk, and livestock
Main source(s) of income	Government support payments, livestock (milk and animals), and off-farm income	Government support payments and off-farm income	Government support payments, livestock (milk and animals), sale of agricultural produce, and off-farm income
Diversified sources of income[a]	4/10	3/10	10/10
Income generated from livestock[b]	8/10	4/10	7/10
Income generated[b] from sale of agricultural production	1/10	4/10	10/10

Abbreviation: se, standard error.
[a]Number of farmers out of 10 interviewed gaining income from at least 2 significant income sources (sale of agricultural production; sale of livestock or livestock products; off-farm income).
[b]Number of farmers out of 10 interviewed gaining regular income from the sale of agricultural production or the sale of livestock or livestock products.

FIGURE 2 Photos of the varying landscapes of Basquitay (a), Naubug (b), and Tzimbuto (c), Province of Chimborazo, Ecuador [Colour figure can be viewed at wileyonlinelibrary.com]

intense, surface soil horizons are deep and high in SOM, while intensive management in other areas has denuded the A-horizon, revealing subsoils characterized by relatively low-SOM and composed of hardened volcanic ash, known locally as*cangahua* (classified as inceptisols or entisols under the USDA soil taxonomy). Cangahua soils are especially prevalent in the communities of Naubug and Tzimbuto (Figure 2).

Major crops grown in the communities include potato (*Solanum tuberosum L.*) and other Andean tubers (e.g., oca [*Oxalis tuberosa*], mashua [*Tropaeolum tuberosum*], and ulluco [*Ullucus tuberosus*]), cereals such as maize (*Zea mays*), quinoa (*Chenopodium quinoa*), barley (*Hordeum vulgare L.*), and oats (*Avena sativa*). Families cultivate cereals both for human consumption and cut forage. Alfalfa (*Medicago sativa*) and vetch (*Vicia*) are also grown for forage. More market-oriented farms, mainly in Tzimbuto (which has irrigation access), grow high-value vegetables. At higher elevations (above 3,400 m.a.s.l.) forage crops, quinoa and faba bean (*Vicia faba*) are most common. At lower elevations, cereals dominate along with high-value cash crops (where irrigation was available). Farmers at all elevations rotate other crops with potato as a primary crop, which typically receives the greatest amount of OM inputs. Farming families usually have at least a pair of cattle (for animal traction and milk) as well as pigs, sheep, and smaller animals such as chickens and guinea pigs. Some farms gain income from selling milk and livestock, though both herd composition and the market role of livestock varied in each of the three communities (Table 1). Farmer-owned livestock supply most of the OM inputs in these communities, although Tzimbuto imports significant amounts of chicken manure from commercial chicken farms in the region.

2.2 | Farm and livelihood analysis

Workshops were held in the communities with 10 volunteer farming households from each community. Participants were selected with the aid of local rural development extension agents in order to represent a diverse range of farming households in each community, based on factors such as farm size, number of livestock, market orientation, access to financial and social resources, and family composition. A farming systems survey based on ImpactLite (Rufino et al., 2013) and adapted for the Andean context was then conducted individually with the main laborer of each farming family to provide household data on family composition, market orientation and income.

Due to the high variability in monthly and yearly income from crop and livestock sales, these variables were expressed as categorical variables. When the farmers were able to sell crops or livestock on a regular basis, this was classified as 'regular' income; while 'irregular' income was applied when farmers only sporadically engaged in opportunistic sales of their crops or livestock in times of surplus. The 'diversified income sources' variable was considered 'diversified' when the household received income from at least two significant income sources (sale of agricultural production; sale of livestock or livestock products; or off-farm income).

The survey was supplemented by working individually with farmers to develop a farming resource-flow diagram for each household, which depicted the main resource flows to and from each field, as well as the main characteristics of these fields.

2.3 | Soil and field data collection

Four fields per farm were selected together with farmers to encompass a range of soil and environmental conditions as well as distances to the homestead. Soils were sampled in each field by collecting 20 subsamples (0–20 cm) using a trowel from each field and then combining these to generate one composite sample of around 2 kg per field. Soils were air-dried and transported to a laboratory at the Ecuadorian National Institute for Agricultural Research (INIAP) for analysis. Each soil sample was sieved (2 mm) and analyzed for texture (Bouyoucos, 1962), SOC (Walkley & Black, 1934), total N (Kjeldahl, 1883) as well as available P and exchangeable K (modified Olsen method, pH 8.5; Olsen, Cole, & Watanabe, 1954).

Additional data collected for each field included: elevation (using a GPS), slope (using an inclinometer), distance from homestead (in min. Walking time), estimated field size, current, and historical data on crop rotations (past four crop cycles) and organic fertilizer inputs (according to a short farmer questionnaire). Farmers were also asked to rate their perception of relative soil fertility for each field (categorized as 'very good', 'good', 'average', and 'poor'). This was generally based on recent harvests and the color of the soils, with darker soils usually being judged more fertile. Where appropriate, this information was cross-referenced with the data generated from the farming systems survey and resource-flow diagrams, and any discrepancies were rectified by means of a subsequent consultation workshop with participants that took place a few weeks later. Mean fresh weight of OM inputs (manure and compost) were calculated based on the inputs over the past three cropping cycles (Mg ha^{-1} cropping cycle^{-1}) in order to account for variation of input use across the field crop rotation pattern.

2.4 | Statistical analysis

To evaluate differences among communities in soil chemical and textural parameters, and in the mean farm-level OM inputs (Mg ha^{-1} yr^{-1}), one-way ANOVAs were applied with a post-hoc Tukey's honest significant difference (HSD) test. The assumptions of normal distribution and homoscedasticity were assessed by visually inspecting residuals and homogeneity of variance plots and applying the Shapiro–Wilk and Levene's tests. Where necessary natural log transformations were applied to the data to adhere to these assumptions. In the cases that the natural log did not enable the data to adhere to the assumptions, a nonparametric Kruskal–Wallis test was applied, with a post-hoc Dunn's nonparametric pairwise multiple comparison test.

To further assess the potential effects of more granular, between farm, socioeconomic variables on mean farm-level OM inputs, separate mixed linear regression models for each socioeconomic explanatory variable were fitted for farm-level OM inputs, with community included as a random effect. To validate the models, the assumptions of normal distribution and homoscedasticity were tested by visually inspecting plots for residuals and homogeneity of variance. To satisfy these assumptions it was necessary to transform the mean farm-level OM inputs using the natural log. Presence or absence of: income from livestock, income from crops, off-farm income, and diversified income sources were treated as categorical explanatory variables. Number of family members dedicated to farming and average age of active farm workers were treated as continuous explanatory variables.

To assess the potential effect of within farm variables on OM inputs (per field), mixed linear regression models were fitted for OM inputs against the explanatory variables, with nested random effects for community and farm within community included. The assumptions of normal distribution and homoscedasticity were tested by visually inspecting plots for residuals and homogeneity of variance. To satisfy these assumptions, the data for OM inputs were transformed using the natural log. Distance from homestead was treated as a continuous explanatory variable, while perception of fertility ('very good', 'good', 'average', 'poor') was treated as a categorical explanatory variable.

Finally, to assess the relationships between OM inputs and soil chemical properties, and within farm variables (distance from homestead and perception of fertility) and soil chemical properties, linear mixed models for four soil parameters as dependent variables (SOC, total N, available P, and exchangeable K) were produced in a stepwise process for each explanatory variable (OM inputs, distance from homestead, and perception of fertility). Initially a linear mixed regression model was fitted for each soil parameter against fixed effects for community and the explanatory variable, with an interaction term included between community and the explanatory variable. In addition, because of the structure of the data collection procedure with four fields sampled within a single farm, a random effect was included within this model for 'farm'. Where the interaction term with community was significant ($p = <.05$), separate models were then fitted for each community separately, with a random effect for farm. In the cases that the *p*-value for the interaction term was greater than .05, the interaction term with community was removed, leaving a fixed effect for 'community' and random effect for 'farm'. To validate the models, the assumptions of normal distribution and homoscedasticity were tested for by visually inspecting plots for residuals and homogeneity of variance. To satisfy these assumptions it was necessary to transform the data for OM inputs, SOC, total N, available P, and exchangeable K using the natural log. All analyses were carried out using R version 3.6.1 within the RStudio environment Version 1.2.5033, using ade4, agricolae, emmeans, multcomp, car, lattice, MuMIn, sjmisc, and lme4 packages.

3 | RESULTS

3.1 | Drivers of OM inputs

Significant differences in OM inputs were observed among communities (Table 2), such that farmers in the community of Tzimbuto applied significantly more OM inputs to their fields compared to Basquitay and Naubug (Tukey HSD, $p < .05$; Figure 3a).

Distance from homestead and perception of fertility also displayed significant relationships with OM inputs (Table 2), such that OM inputs decreased with distance from homestead (Figure 3a); and with decreased perceived fertility of fields (Figure 4a). None of the between farm variables displayed a significant effect on OM inputs (Table 2).

TABLE 2 *p*-values and R^2 values for ANOVA and multiple linear regression analyses assessing the relationships between OM inputs and between community, between farm, and within farm explanatory variables in the communities of Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador

Explanatory variable	*p*-value	R^{2a}
Between community		
Community	**.003**	**.29**
Between farm		
Number of family members dedicated to farming	.748	<.01
Average age of active farm workers	.220	.03
Number of livestock heads	.250	.03
Income from livestock	.821	<.01
Income from crops	.143	.07
Off-farm income	.192	.06
Diversified income sources	.250	.03
Within farm		
Walking distance from homestead (per 10 min)	**<.001**	**.22**
Perception of fertility	**<.001**	**.13**

Note: The significance for the bold values in this Table is: $p = < .05$.
Abbreviation: SOC, soil organic carbon.
[a]Pseudo R^2 values are presented for linear regressions with fixed and nested random effects.

3.2 | OM inputs, within farm variables and soil chemical properties

Basquitay's soils displayed significantly higher levels of clay, total N, and SOC, and lower levels of sand, available P, and exchangeable K than soils of Naubug and Tzimbuto (Table 3). Basquitay also displayed lower pH levels (6.48) compared to Naubug (7.62) and Basquitay (8.27).

OM inputs were positively related with total N, available P, and exchangeable K. A significant interaction between inputs and communities was observed for SOC, such that the effect of OM inputs on SOC was significant for the communities of Naubug and Tzimbuto, but not for the community of Basquitay (Table 4).

Distance from homestead displayed significant negative relationship with total N. Significant interactions between distance from homestead and communities were observed for SOC, available P, and exchangeable K. SOC only displayed a significant negative relationship with distance from homestead in the communities of Naubug and Tzimbuto. Tzimbuto displayed the strongest negative relationship of distance from homestead for available P between communities, while Basquitay exhibited the strongest negative relationship for exchangeable K (Table 5).

Perception of fertility displayed significant positive relationships with total N and available P, but not for exchangeable K. A significant interaction between communities was observed for SOC, such that perception of fertility was only associated with

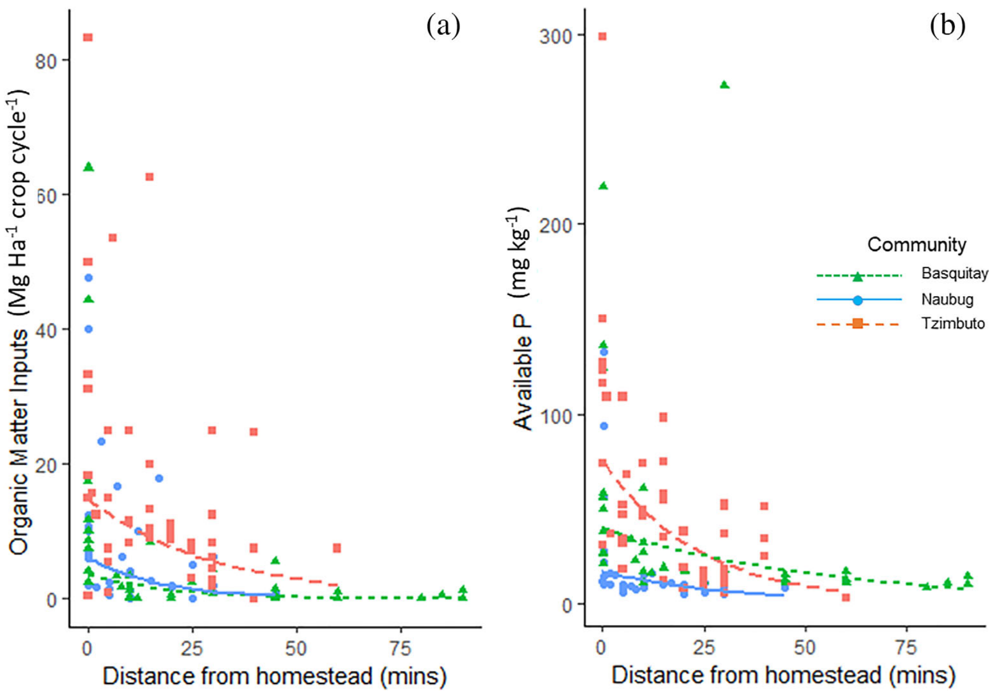

FIGURE 3 Relationship between field walking distance from homestead and organic matter inputs (a) and available P (b) for fields of the communities of Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador [Colour figure can be viewed at wileyonlinelibrary.com]

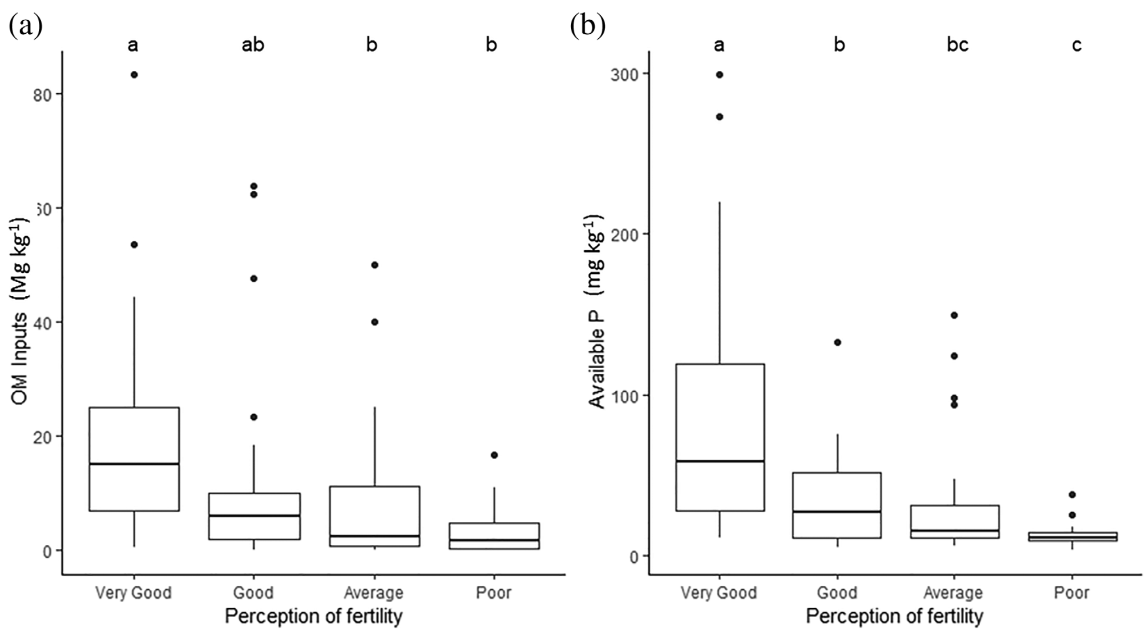

FIGURE 4 Differences in organic matter (OM; a) inputs and available P (b) based on farmers' perception of field fertility in the communities of Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador. Points located outside the 'whiskers' of the boxplots are considered outliers (≥1.5 interquartile range). Tukey's HSD results are presented above each box at the top of the plots, with different letters significantly different at the $p < .05$ level. HSD, honest significant difference

SOC in the communities of Naubug and Tzimbuto. For all soil chemical properties, with the exception of SOC in the community of Basquitay, fields that farmers perceived to be most fertile ('very good' or 'good') displayed the highest levels of the macronutrients measured. Conversely, those fields that were perceived to have 'poor' fertility exhibited the lowest levels of macronutrients (Table 6).

4 | DISCUSSION

4.1 | Within farm heterogeneity in OM inputs

The results from this study confirm our hypothesis and previous research reporting that agricultural inputs vary significantly due to field-distance from homestead and perception of fertility. Given the

TABLE 3 Average soil texture and chemical characteristics across sampled farms in the communities of Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador

Soil characteristics	Basquitay	Naubug	Tzimbuto	p-Value
Clay (%)[a]	18.06 (0.51)a	12.19 (0.50)b	12.81 (0.47)b	<.001
Silt (%)[b]	46.50 (0.67)a	42.00 (0.67)b	45.00 (0.62)ab	.008
Sand (%)[b]	35.50 (0.65)b	43.00 (0.80)a	42.00 (0.65)a	<.001
SOC (%)[b]	4.04 (0.15)a	1.61 (0.15)b	1.06 (0.14)b	<.001
Total N (%)[b]	0.34 (0.03)a	0.14 (0.01)b	0.11 (0.01)b	<.001
Available P (mg kg^{-1})[b]	10.00 (1.73)b	18.00 (3.36)a	42.00 (5.00)a	<.001
Exchangeable K (cmol kg^{-1})	0.25 (0.04)b	0.57 (0.13)a	0.88 (0.13)a	<.001
pH[a]	6.48 (0.08)c	7.62 (0.09)b	8.27 (0.09)a	<.001

Note: Standard errors are presented in parentheses, while different letters indicate significant differences ($p < .05$) according to the post-hoc Tukey's honest significant difference test or Dunn's nonparametric pairwise multiple comparisons test for non-normal data.
Abbreviation: SOC, soil organic carbon.
[a]Log transformations were applied to the data for one-way ANOVA and the post-hoc Tukey's honest significant difference test to adhere to the assumptions of normality and homoscedasticity.
[b]Kruskal–Wallis tests were applied to variables indicated due to *p*-value = <.05 for the Shapiro–Wilk test for the assumption of normal data. For all nonparametric data, median values are indicated instead of mean values.

TABLE 4 Coefficients, *SE*s (in parentheses), and *p*-values for mixed model linear regression analyses testing the relationship between OM inputs and four different soil chemical properties (SOC, total N, available P, and exchangeable K) in Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador

Soil chemical property	Coefficient[a] (*SE*)	Interaction between inputs and community (*p*-value)	Basquitay[a]	Naubug[a]	Tzimbuto[a]
SOC (%)	–	**.049**	0.015 (0.037)	**0.193 (0.055)****	**0.125 (0.057)***
Total N (%)	**0.10 (0.03)****	.388	–	–	–
Available P (mg kg^{-1})	**0.27 (0.05)*****	.397	–	–	–
Exchangeable K (mmol kg^{-1})	**0.24 (0.06)*****	.240	–	–	–

Note: In the case, where a significant interaction was found between ‘OM inputs’ and ‘community’, the mixed model linear regression analyses were applied separately by community with a random effect included for ‘farm’. Otherwise, the results are presented for the three communities combined (with the interaction term for community removed), but including a fixed effect for ‘community’ and random effect for ‘farm’.
Abbreviation: OM, organic matter; SOC, soil organic carbon.
[a]The predictor variable (OM inputs) and each of the response variables (soil chemical properties) were log-transformed, as such coefficients represent the percent change in the respective soil chemical property for every 1% increase in OM inputs.
**p* < .05.
***p* < .01.
****p* < .001.

TABLE 5 Coefficients, *SE*s (in parentheses), and *p*-values for mixed model linear regression analyses testing the relationship between distance from homestead and four different soil chemical properties (SOC, total N, available P, and exchangeable K) in Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador

Soil chemical property	Coefficient[a] (SE)	Interaction (*p*-value)	Basquitay[a]	Naubug[a]	Tzimbuto[a]
SOC (%)	–	**.031**	0.000 (0.399)	**−0.896 (0.300)***	**−1.980 (0.401)*****
Total N (%)	**−0.499 (0.200)****	.124	–	–	–
Available P (mg kg^{-1})	–	**.010**	**−3.825 (0.904)*****	**−1.784 (0.401)*****	**−4.210 (0.702)*****
Exchangeable K (cmol kg^{-1})	–	**.024**	**−5.446 (1.715)****	**−1.784 (0.501)****	**−1.490 (0.602)***

Note: In the case, where a significant interaction was found between ‘distance from homestead’ and ‘community’, the mixed model linear regression analyses were applied separately by community with a random effect included for ‘farm’. Otherwise, the results are presented for the three communities combined (with the interaction term for community removed), but including a fixed effect for ‘community’ and random effect for ‘farm’.
Abbreviation: SOC, soil organic carbon.
[a]The response variables (soil chemical properties) were log-transformed, as such the results have been back-transformed to present the percent change in the soil chemical property for every 1-min increase in distance from homestead.
**p* < .05.
***p* < .01.
****p* < .001.

TABLE 6 Mixed model linear regression results testing the relationship between perception of fertility and four soil chemical properties (SOM, total N, available P, and exchangeable K) in the communities of Basquitay, Naubug, and Tzimbuto, Chimborazo Province, Ecuador

			Fertility perception category			
Soil chemical property	***p*-value**	**Interaction (*p*-value)**	**Very good**	**Good**	**Average**	**Poor**
SOC (%)[a]	**<.001**	**.023**[b]	–	–	–	–
Total N (%)[a]	**<.001**	.255	**0.252 (0.105)a**	**0.160 (0.066)b**	**0.162 (0.067)b**	**0.102 (0.042)c**
Available P (mg kg^{-1})[a]	**<.001**	.275	**46.610 (14.751)a**	**25.782 (7.732)b**	**18.889 (5.664)bc**	**11.306 (3.521)c**
Exchangeable K (cmol kg^{-1})[a]	.251	.738	0.587 (0.247)a	0.598 (0.239)a	0.456 (0.182)a	0.370 (0.153)a

Note: In the case, where a significant interaction was found between 'perception of fertility' and 'community', the mixed model linear regression analyses were applied separately by community with a random effect included for 'farm' (Table S1). Otherwise, the results are presented for the three communities combined (with the interaction term for community removed), but including a fixed effect for 'community' and random effect for 'farm'. Means and *SE*s (in parentheses) of each soil chemical property are presented by perception of fertility. Different letters to the right of the means (a, b, c) signify significant differences at the $p < .05$ level.

Abbreviation: SOC, soil organic carbon; SOM, soil organic matter.

[a]The response variables (soil chemical properties) were log-transformed, as such means and *SE*s have been back-transformed to original units.

[b]Perception of fertility was found to be significantly associated with SOC in the communities of Naubug ($p < .001$) and Tzimbuto ($p < .001$), but not in Basquitay ($p = .894$). Full results of the mixed model linear regression analyses for the relationship between perception of fertility and SOC by community are displayed in Table S1.

positive association between inputs and perception of fertility, we cannot draw firm conclusions as to whether there is a causal relationship between inputs and improved fertility; however, our results do provide evidence that these asymmetric patterns of OM resource allocation may be accentuating existing gradients of soil fertility across the landscape, as found in other studies (Diarisso et al., 2016; Vanek & Drinkwater, 2013; Vanlauwe, Tittonell, & Mukalama, 2006). Furthermore, our findings seem to suggest that the type of manure inputs used by farmers in each community may be influencing these within farm soil spatial patterns.

The effect of distance from homestead was observed to be strongest for exchangeable K in the community of Basquitay, but it was strongest for available P in Tzimbuto (Table 5). Contrary to the other two communities, farmers in Tzimbuto imported considerable amounts of poultry manure (Table 1), which is relatively high in available P in relation to the other sources of animal manure or common OM inputs (e.g., crop residues). On the other hand, cow and sheep manure tend to have higher proportions of exchangeable K (Moore Jr et al., 1995). Such differences in manure nutrient stoichiometry may help explain the contrasting soil fertility gradients, whereby available P accumulates most in near-fields of the community using imported poultry manure and exchangeable K accumulates most in the near-fields of the communities mainly using on-farm generated manure.

Another noteworthy finding is that the fertility gradients are not necessarily prevented or reduced when farmers have higher farm OM inputs, which suggests that these patterns may not be linked to overall access to OM inputs. While Tzimbuto's farmers incorporated nearly twice as much OM inputs into their fields on average compared to the farmers in Basquitay and Naubug (Figure 3a), the effect of distance from homestead on available P was, in fact, stronger than for the other two communities (Table 5 and Figure 3b). This is an important finding, as it contradicts the notion that fertility gradients may be reversed by a simple increase in access to OM inputs. Indeed, it may be that the observed effect of distance from homestead is not only a result of constrained OM resources, but a complex combination of different factors. Indeed, during the resource-flow mapping and consultation workshop, farmers often reported that field accessibility, farming habits, and strategies, access to different agricultural fertilizer types, labor use efficiency, transport, and logistics were also important reasons for the asymmetric distribution of OM inputs.

This finding is consistent with those of Vanek and Drinkwater (2013), which concluded that asymmetric allocation of OM inputs were, at least in part, due to the inaccessibility of far-fields in the mountainous Andean terrain. Access to inorganic fertilizers was also found to be an important factor in asymmetric allocation patterns in a study in the Central Highlands of Ethiopia, where near-fields received greater quantities of OM inputs, while far-fields received greater quantities of inorganic fertilizer, which is generally lighter and easier to transport (Haileslassie et al., 2007). Meanwhile, two other studies undertaken in Zimbabwe presented cases where the fertility gradient was found to be the reverse. In these cases the cropping conditions were either more favorable in the far-fields for the main cash crop suggesting that the asymmetric allocation patterns were strategic or the far-fields were only recently converted into agricultural land (Chuma, Mombeshora, Murwira, & Chikuvire, 2000; Masvaya et al., 2010).

This finding has important implications for agricultural development, as simple intervention strategies, such as the provision of nutrient or OM inputs, will not lead necessarily to the improvement of fertility in the most distant and least fertile fields. Further research is necessary to explore the drivers behind these well-recognized asymmetric resource allocation patterns in agricultural landscapes, so as to develop more contextualized pathways for improving the overall fertility and productivity of farms. For example, if the main constraint on increasing soil fertility of distant fields is one of logistics and labor, rather than access to resources, a better solution for improving productivity may be the promotion of in situ approaches to increasing nutrient and OM inputs, such as through the use of green manures, forage rotations with direct grazing, or alternative cropping systems that reduce nutrient exports (Caulfield et al., 2020). In the event that an asymmetric OM allocation involved broader risk management strategies whereby the fertile infields were used for reliable crop production, while the outfields were used as low investment 'bets', a deeper discussion around risk management and sustainable land management may be more fruitful (Goland, 1993). In particular, attention should be paid to better understanding historical trajectories and the development of feedback loops and vicious cycles of land degradation, where lower inputs are linked with poorer fertility perception, eventually leading to land abandonment. Simple responses to these more complex relationships, such as increasing overall access to OM inputs, are unlikely to be successful.

4.2 | Between community differences in OM inputs

When considering between community and between farm heterogeneity in OM inputs, our results revealed large differences in OM inputs among communities located in close proximity to one another, such that farmers from the community of Tzimbuto incorporated more OM inputs than farmers in Naubug or Basquitay (Table 2 and Figure 3a). However, our findings did not find evidence for significant differences in OM inputs between farms based on individual socioeconomic variables (Table 2). This diverges from previous research, undertaken mostly in east Africa, where such socioeconomic factors have been suggested as important drivers of OM inputs and positive nutrient balances (Barrett et al., 2002; Cobo et al., 2010; Haileslassie et al., 2007; Marenya & Barrett, 2007).

Part of the reason for this discrepancy could be that the small sample size considered here may have been insufficient to detect clear OM input patterns based on these more granular socioeconomic factors. However, it may also suggest that the individual socioeconomic factors considered do not provide the whole explanation as to how farmers manage their resources. In this regard, this research agrees with Vanek and Drinkwater (2013) who observed no association between manure application rates and farmer wealth in the Bolivian Andes.

Broadly speaking, our findings agree with others who have suggested that no single variable appears to be sufficient in accounting for the diversity in land and farm management, both within or between communities; instead differences are a result of interactions between the biophysical and socioeconomic and cultural trajectories unique to each individual context (Caldas et al., 2007; de Sherbinin et al., 2008; Tittonell, 2014). In our case-study, these formative interactions may be best encapsulated at the level of the community where the biophysical contexts and socio-economic and cultural differences may be greater between communities than between farmers.

Despite the proximity of the three communities to each other (Figure 1), they represent distinct biophysical contexts (soil, climate, vegetation), and these are likely to have shaped multiple farming systems attributes, including OM inputs (Caulfield et al., 2020). Socioeconomic and cultural differences are also likely to have contributed greatly to the between community differences in OM inputs. For example, Tzimbuto is the only community with widespread access to irrigation, due to construction of an irrigation canal over 20 years ago. Tzimbuto also has stronger links with regional markets since it is located close the parish capital Licto and enjoys better transport links with the provincial capital of Riobamba. It appears that these improved opportunities may have allowed farmers in Tzimbuto to invest more deeply in agricultural production than those in Naubug or Basquitay, hence the observed higher OM inputs observed.

4.3 | Community level OM inputs and soil fertility gradients

It appears that the observed differences between communities in OM inputs may be contributing to greater soil heterogeneity in these agricultural landscapes of the Andes. As mentioned above, the use of different types of organic inputs between communities may be driving different within farm fertility gradients for available P and exchangeable K. Moreover, it is noteworthy that Tzimbuto displayed, on average, the highest levels of available P and exchangeable K compared to the other two communities, despite exhibiting the lowest levels of SOC (Table 3). Macronutrients such as P and K have been suggested to be more responsive than SOC to differences in agricultural inputs (Tittonell, Vanlauwe, Leffelaar, Shepherd, & Giller, 2005; Van Apeldoorn et al., 2013;van Apeldoorn et al., 2014; Zingore et al., 2007). The larger additions of organic resources in Tzimbuto could potentially help explain the greater accumulation (or reduced loss) of these nutrients in this community.

On the other hand, SOC generally reflects longer-term processes related to soil texture, climate, and hydrology and is generally less sensitive to short-term management influences (van Apeldoorn et al., 2014; Zingore et al., 2007). The cooler climate and high moisture levels found at higher elevations supports SOM accumulation through faster accumulation and slower decomposition (Lavoie and Bradley, 2003; Zehetner and Miller, 2006), while higher clay content is also known to stabilize SOM (Chivenge, Murwira, Giller, Mapfumo, & Six, 2007; Six, Conant, Paul, & Paustian, 2002). This is reflected in our finding that Basquitay, the community with the highest SOC, but significantly lower levels of OM inputs than Tzimbuto, was also the community with the highest elevation range and soil clay content (Figure 3a and Table 3). Furthermore, it is noteworthy that Basquitay was the only community where no evidence was found for an association between OM inputs and SOC, distance from homestead and SOC, and perception of fertility and SOC (Tables 4-6). We suspect that the high baseline levels of SOC likely eclipse any influence that farmer OM inputs may have in this community.

This differential response of soils in each community to OM inputs suggests that it is critical to consider biophysical and management context specific intervention strategies. For example, in

Tzimbuto one could argue that continued soil aggradation measures using OM inputs would continue to prove beneficial in the future. On the other hand, in Basquitay, where SOC levels were less responsive to OM inputs, but already exhibited high background levels, soil conservation measures may be more useful. Meanwhile in Naubug, with its greater SOC variability compared to Tzimbuto, but with generally lower SOC levels than Basquitay, may require a more of a hybrid approach conserving the richer soils and aggrading the soils with lower levels of SOC.

5 | CONCLUSIONS

The results of this study call attention to the importance of the diversity in OM inputs that may be encountered within farms and between neighboring communities in rural Andean landscapes, and their potential impacts on and interactions with the unique biophysical contexts found between communities as a result of a steep elevation gradient and associated climatic differences. We found that asymmetric allocation patterns of OM appear to be accentuating existing soil fertility gradients and that greater overall OM inputs did not prevent or reduce the development of commonly observed fertility gradients. We also found that despite the close proximity of the three communities studied, differences in infrastructure and access to markets may be driving differences in the quantity and quality of OM inputs. These differences in OM inputs among communities may be associated with variations in soil fertility, with the highest levels of available P and exchangeable K found in the community with the highest OM inputs. We also suspect that differences in the underlying biophysical context (soil and climate) between communities contributes to the observed variability in soil fertility, with the community located at the highest elevation range, with the highest soil clay content and with the highest baseline levels of SOC, Basquitay, being the only community to display no significant association between OM inputs and SOC. In addition, Basquitay was the only community not to display significant within farm SOC gradients. These findings suggest that intervention strategies to support food security and development in smallholder farming communities need to take into account smaller-scale, within farm variability and the multiple social and ecological factors that shape farmer investment in soil management.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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