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Exploring social-ecological systems in the transition from war to peace: A scenario-based approach to forecasting the post-conflict landscape in a Colombian region

Abstract

This paper describes the relationship between the landscape and the socio-economic and political characteristics of a highly biodiverse Andean region of Colombia, which is now recovering from the socio-ecological impact of protracted armed conflict. We quantify the current spatial relationship between nature and society, and we include legacy effects from the most recent period of armed conflict and its consequences of forced displacement and land use disruption. The procedure followed provides a quantitative model with a minimum number of socio-economic and political variables that explain variation in land cover. The results represent the relationship between land use intensity and the main socio-economic and political indicators, highlighting a close interaction between landscape configuration, socio-economic structure of local populations, coercive conservation and armed conflict. A simulated post-conflict landscape shows a clear transition gradient towards agrarian expansion and intensification, also in systems where naturalness is a relevant feature. The peace process in Colombia offers opportunities for new schemes of land planning and management, including natural resource governance and policy reforms to improve welfare and resilience of local communities. Our results help define options for future planning given the possible consequences of socio-political legacy effects yet to fully play out across Colombia.

Keywords: land planning; scenario-based approach, peacebuilding process, warfare ecology, post-conflict society

1. Introduction

Historic human settlements have generated cultural landscapes where patterns of land use depend on ecological conditions as well as on cultural, socio-economic and political drivers (Etter and van Wyngaarden, 2000; Wardell et al., 2003). Interactions between society and nature shape cultural landscapes as complex adaptive systems according to the particular biophysical and socio-economic contexts of each place (Berkes and Folke, 1998; Liu et al., 2007; Ostrom, 2009). Thus, natural and socio-economic systems are inextricably coupled, resulting in social-ecological systems that interact at multiple temporal and spatial scales (Folke, 2006; Ostrom, 2009; Ribeiro et al., 2013). Long-term interactions between people and their environment strongly influence landscape configuration and changes in social structures and processes are reflected in the functioning, structure and dynamics of ecosystems at different dimensions (Schmitz et al., 2003; Etter et al., 2006; De Aranzabal et al., 2008; Verburg et al., 2016, Herrero-Jáuregui et al., 2018). These changes have frequently degraded land use mosaics, cultural biodiversity and traditional knowledge, essential for the maintenance of cultural landscapes (Antrop, 2006; Schmitz et al., 2017).

An example is found in Latin America, which over the past century has undergone intense land clearing and deforestation for the establishment of new agriculture (Gibbs et al., 2010, Lerner et al., 2017). In Colombia, since the pre-Columbian era and the Spanish conquest, land conversions have affected large extents of its ecosystems, particularly in the mountainous areas of the Andean region, where marked clearance and conversion of forests and moorlands (*páramos*) has taken place (Etter and van Wyngaarden, 2000; Armenteras et al., 2003; Álvarez-Berríos and Aide, 2015). Inequitable and widespread land conversion and distribution since Colombia became independent, in the 19th century, was a major factor triggering recent conflict (Richani, 1997). In turn, during the last five decades, armed strife has been an important driver of landscape transformation in Colombia.

Conflict has resulted in piecemeal land abandonment as well as excessive exploitation and deforestation (Salas-Salazar, 2016). On the one hand, land abandonment has stimulated the regeneration of the forest in some localities traditionally dedicated to agricultural land uses (Sánchez-Cuervo and Aide, 2013a; Suarez et al., 2018a), a process known as “gunpoint conservation” (Dávalos, 2001; McNeely, 2003; Chaves-Agudelo et al., 2015, Ordway, 2015, Armenteras et al., 2019). Elsewhere, excessive exploitation of natural resources by the armed protagonists resulted in deforestation (Álvarez, 2001, 2003; Dávalos, 2001, Etter et al., 2006). In parallel, this land use change dynamic has had social-economic impacts (Álvarez, 2003; Marull et al., 2018). Rural communities have been forcibly displaced and land acquired illegally even in formally protected areas (World Commission on Protected Areas, 2003; Raleigh, 2011; Castro-Nuñez et al., 2017). Moreover, the armed conflict has also taken place in areas of rich biodiversity, as is typical of many conflict zones over the last century (Fjeldså et al., 2005; Hanson et al., 2011; Baumann and Kummerle, 2016). Therefore, civil war has involved significant threats to both conservation and management of natural resources, and for the socio-economic standards of the local population (Dávalos, 2001; Stevens et al., 2011).

The peace agreement between the Colombian government and the Revolutionary Armed Forces of Colombia (FARC by its Spanish acronym) was, signed in 2016 after many obstacles from the beginning of the negotiations in 1980. It ended more than half a century of war in Colombia, although it is far from being a peaceful country (Vargas, 2012; Sánchez-Cuervo and Aide, 2013b; Rehm 2015, Karl, 2017; Stevenson, 2017). Since the signing of the peace agreement, the recidivism of ex-combatants has been diverted towards organized criminal violence, generally unrelated to political ends (Kaplan and Nussio, 2018).

The end of the war generates many uncertainties about the possible environmental and socio-economic consequences derived from the new socio-political conditions prevailing in Colombia. Several authors point out that complex social-ecological transformations linked to the acceleration of the deforestation process could be triggered (Boron et al., 2016; Baptiste et al., 2017; Castro-Nunez et al., 2017; Armenteras et al., 2019; Salazar et al., 2018, Grima and Singh, 2019). Indeed, after the resolution of long conflicts, countries tend to prioritize social and economic factors, and environmental considerations are often disregarded (Salazar et al., 2018). However, the consequences of war and peace processes on natural resources and biodiversity conservation have been scarcely studied, often because post-conflict data on land use land cover (LULC) are sparse or absent. Most studies on this subject have focused on patterns of land change, rates and drivers of deforestation on the macro-level, but much less is known about the dynamics associated with the interactions between land uses, local socio-economic characteristics and armed conflict (Vargas, 2012). Thus, little is known about the complex relationship between the land use transitions underway in Colombia and the underlying biophysical and human processes, as well as about future prospects for social-ecological change (Etter and Wyngaarden, 2000; Dávalos, 2001; Fjeldså et al., 2005; Stevenson et al., 2010; Boron et al., 2016). One way to understand social-ecological systems and forecast their evolution is the use of scenario studies, in which possible future trajectories due to social and ecological changes are modelled (Carpenter et al. 2006).

This paper presents a quantitative description of the relationship between landscape typology and socio-economic and political structures in Tolima, a Colombian department located in the Andean region, historically affected by the armed conflict, and currently undergoing socio-economic changes associated with the ending of hostilities. Thus, the objectives of this study are: i) to understand the relationship between the landscape structure of the Tolima region and the underlying socio-economy of the local population, ii) to identify the main socio-ecological indicators of this complex interaction system, some of them linked to Colombia's civil war; iii) to establish possible future configurations of land cover by means of a scenario-based approach linked to the socio-economic and political drivers derived from the peace-building process, iv) to describe the environmental implications of the possible land use patterns identified through the scenario analysis.

2. Study area

The department of Tolima (23,325 km^2) is located in the Trans-Andean region of Colombia (Figure 1). In this region, altitude constitutes a major ecological factor, as it ranges from 200 m .a.s.l. in the Magdalena river valley to 5,200 m at the summit of the volcano Nevado del Tolima, on the eastern flank of the Central Range of the Colombian Andes (IGAC, 2004). This marked altitudinal variation favours the presence of a wide range of thermal belts with different vegetation formations ranging from tropical dry forest to *páramos*. *Páramos* are exceptional isolated and desolate systems, endemic in elevated regions of the tropics. They play a key role in regulating regional water supply, and support very high biological, cultural and landscape diversity (Buytaert et al., 2006; Rodríguez et al., 2015). Although they are a priority for conservation (Dávalos, 2001; Fjeldså et al., 2005), *páramos* have become one of the most threatened ecosystems in Colombia (Ruiz et al., 2008).

Tolima has about 1,400,000 inhabitants, distributed in 47 municipalities, which are predominantly rural. In recent years, the total population has increased by 3%, in spite of a 6% decrease in rural areas. According to this, the population growth of Tolima for the 2005-2015 period was one of the lowest nationwide. From the economic point of view, the GDP of the service sector had the strongest participation, whereas agricultural GDP decreased (Renza et al., 2012). Population movement and land use dynamics have been driven strongly by the conflict. These patterns are similar to those observed in the central region of the country: processes of agricultural frontier expansion, redistribution of colonized areas and migration of the rural population to more developed and safer areas, in search of better living standards or fleeing from armed confrontation in the countryside (Ibáñez and Vélez, 2007).

The long-term land transformation processes that have occurred in Tolima, from natural areas, semi-natural landscapes and native agro-ecosystems to intensive and agro-industrial farms, is consistent with the wider landscape pattern of change in the Colombian Andean region (IDEAM, 2015). These changes began with the arrival of the Spanish colonisers and increased after the industrial revolution. Since then, complex land use transitions have been occurring (Boron et al., 2016). Nowadays, this process of change has reached historical levels and transformed landscapes are predominant in the study area (64.2%) (Etter and van Wyngaarden, 2000; Armenteras et al., 2003; Álvarez-Berríos and Aide, 2015; Rubiano et al., 2017).

Colombia has the largest rate in the world of internally displaced people, followed by Syria (UNHCR, 2017; Sierra et al., 2017). The country portrays a complex social-ecological landscape where illegal armed groups, with particular interests in capturing agro-industrial profits, have promoted their own environmental policies and controlled the country's most valuable natural resources (Dávalos, 2001; McNeely, 2003; Chaves-Agudelo et al., 2015). In the Colombian Andean region, the economic and social context has been characterized by violence, lack of governmental institutions, social inequality, uneven development, and widespread (often extreme) poverty. In this context, Tolima, where FARC were born and which has been affected by the armed conflict during more than 50 years, can be considered as a strategic corridor in the armed struggle and one of the epicentres of forced displacement (Sánchez-Padilla et al., 2009; Karl, 2017). Thus, this region, with a long history of armed conflict and socio-political instability, provides an excellent opportunity to develop multivariate models of social-ecological interactions incorporating quantitative descriptors of conflict and violence. The signing of the peace agreement heralds a new but uncertain chapter in the history of Colombia. This agreement contains an "Integral Rural Reform" chapter, which is designed to contribute to the transformation of the rural areas, closing the gap between the countryside and the city and creating conditions for welfare and higher living standards for the rural population (Negotiation Table, 2017). Tolima is one of the 15 departments prioritized for the implementation of this reform. Thus, it is important to develop future scenarios that include all possible dimensions of these social-ecological relationships, in order to build a stronger framework for analysis of future decision-making on landscape change, biodiversity conservation, rural development and human welfare (Ibáñez and Vélez, 2007; Boron et al., 2016).

3. Methods

3.1 Data collection

We assembled quantitative data referring to biophysical, socio-economic and political variables as well as armed conflict information for the 47 municipalities of the study area (Appendix 1). Land cover was derived from the Colombian Ecosystem Mapping 2005-2009 (Corine Land Cover methodology) project at a scale of 1: 100,000 (IDEAM, 2015). Land use/land cover variables (LULC) were reclassified into 17 LULC types. (Appendix 2a). Socio-economic and political data at municipal level were obtained from the official information of the Administrative National Department of Statistics (DANE, 2005). Armed conflict information was obtained from the Conflict and Violence panel of the Center for Studies on Economic Development (CEDE, 2016). Thus, we selected a set of 29 socio-economic and political variables and grouped them into four categories: population descriptors, human life conditions, economic activities and conflict and violence descriptors (Appendix 3).

The spatial reference units were the municipalities because they are the smallest administrative divisions of local management and decision-making and the social and economic information is recorded at this scale. Indeed, several authors encourage the use of municipalities as analysis units in landscape studies (Schmitz et al., 2003; Verburg et al., 2010; Salvati and Serra, 2016; Sarra et al., 2017, among others). They are key units in land planning decisions influenced by both small and large-scale agents and drivers of change and, in addition, municipality data provide a reliable proxy description of the local socio-economic context (De Aranzabal et al., 2008; Salvati and Serra, 2016; Arnaiz-Schmitz et al., 2018).

3.2 Landscape structure analysis

To characterize the landscape structure of the Tolima region we performed a multivariate analysis (Principal Component Analysis, PCA) on the data matrix (17 LULC variables x 47 municipalities) with % cover of each category as the matrix entries. The PCA allowed us to project the municipalities on an ordination plane whose principal axes represent the major axes of landscape variation across the study area (Schmitz et al., 2003; De Aranzabal et al., 2008; Salvati and Serra, 2016).

3.3 Landscape and socio-political relationships

The relationship between landscape and socio-economic and politic structures of the municipalities was analysed through linear models (Schmitz et al., 2003, 2012; De Aranzabal et al., 2008) using two data matrices (*m* x *l*) and (*m* x *s*), which described the 47 municipalities (*m*) through the 17 landscape descriptors (*l*) and 29 socio-economic and political variables (*s*), respectively. The interdependence between land cover variation and the socio-economic and political variables was expressed through multiple regression analyses (Schmitz et al., 2003; De Aranzabal et al., 2008; Ferrara et al., 2015), where the independent variables were the 29 descriptors of the municipalities, and the dependent variables, the coordinates of the municipalities on the land cover ordination plane. The stepwise regressions were performed for each of the first two PCA axes, providing the optimal number of explanatory socio-political-economic variables, as well as their importance and sign as follows:

$$Yl = a + b_1 S_1 + b_2 S_2 + b_3 S_3 + ... + b_k S_k \qquad (1)$$

where *Yl* represents the axis scores for the set of municipalities (coordinates in the first two axes of the PCA), a the intercept, S_k the socio-economic and political variables of greatest significance selected through the regression analysis and b_k their regression coefficients. The set of variables selected by the fitted model characterizes much of the landscape variability, of the landscape and it can be considered as the set of socio-political-economic indicators with the greatest influence on the landscape structure. In order to satisfy the analytical requirements of normality and homoscedasticity, we previously transformed the data by means of log (α +1) (Schmitz et al., 2003; Ferrara et al., 2015).

To verify the regression model we used the following statistics: i) Akaike's information criterion (AIC) was used to select the most parsimonious model (i.e. maximizing the fit model with the least number of predictors). This selection criterion penalizes those models for which adding new explanatory variables do not supply sufficient information to the fit model. Thus, the model which that optimizes this criterion is chosen to be the best model; ii) ANOVA test (F-test) to detect the statistical significance of the model; iii) Durbin–Watson test to verify the random variation and absence of autocorrelation in the residuals; iv) Shapiro-Wilk test on the normality of the residuals; and v) Non-constant Variance Score Test for testing the homoscedasticity of the residuals.

3.4 Post-conflict forecasting of landscape change. A scenario-based modelling

To simulate possible changes of the landscape structure of Tolima under the new Colombian post-conflict scenario, we changed the values of the socio-economic and armed conflict predictors selected in our baseline model to the values recorded in available databases (period 2015-2018) after hostilities ended. These more recent values of the socio-economic and political indicators were retrieved from public censuses (DANE, 2009; CRIT, 2010; CEDE, 2016, Appendix 3). These values represent major post-conflict changes in socio-economic status and indicators of the prevalence of violence. Here we assume that the spatial coupling of ecological state and socio-political explanatory variables can be used to simulate possible meaningful changes in the landscape over time. Our main motivation was to explore the impact of a scenario of socio-political change in these spatial ecological relationships taking into account that, for the first time in the recent history of Colombia, the phenomenon of armed conflict does not act as a restrictive social and economic factor. We therefore assume that these socio-political variables, including conflict indicators, correlate with the societal and economic processes likely to drive subsequent changes in land cover.

The model obtained with the scenario approach provides new coordinates of the municipalities on the PCA plane describing the new possible landscape structure linked to socio-political changes. Due to the lack of current spatial LULC data we validated predictions for agricultural land cover against production in Tolima between 2007 and 2013, specifically for rice and coffee, two of the most significant crops in the region (Marchesi, 2015; Delerce et al., 2016; Andrade et al., 2016; Esquivel et al., 2018). This type of agricultural production variables reflects the dynamic and evolution of primary sector activities through their implicit relationship with land uses (Olschewski et al., 2006, Jha et al., 2014; Tscharntke et al., 2015; Chirindra et al., 2017). Statistical analyses were performed using the XLSTAT software (version 2016.02.23567) and different libraries and several functions implemented in the R statistical software (R core team, 2018).

4. Results

4.1 Landscape configuration

The ordination plane describes the landscape structure of the Tolima region and shows the distribution of the municipalities according to the loadings of the landscape variables in the two first dimensions (Fig. 2; Appendix 2b). This shows a pronounced gradient of Andean altitudinal variation coupled to land use typology and intensification. The first ordination axis (30.8% of variance absorption) shows a tendency of variation from highly intensive agrarian systems in lowlands (negative end) to traditional agrarian systems in medium altitudes, associated with complex patterns of rural land uses and natural areas (positive end). The second ordination axis (23.51 % of variance absorption) explains the landscape variation from farming systems in lowland and intermediate altitudes, to landscapes of high naturalness of Andean forests and *páramos* ecosystems shaped by traditional mountain agriculture and grazing.

4.2 Socio-politic and ecological relationships

Table 1 shows the characteristics of the linear regression model fitted to identify the relationship between the main landscape tendencies and the political and socio-economic descriptors of human communities. In the applied model, the values of the coefficients of determination and the statistical significance obtained from the two fitted regression functions (R^2= 0.81; P= <0.0001 and R^2= 0.88, P= <0.0001) suggest that most of the landscape variability of the study area can be explained by means of 20 socio-economic and political indicators.

The first regression equation describes the gradient of highly intensive agrarian systems to traditional agrarian systems according to thirteen socio-political indicators (Table 1a). The signs and value of the regression coefficients indicate that intensive agricultural lands, mainly represented by rice fields, are related to income linked to the agricultural sector (agricultural GDP) and to high municipal and land Gini index, kidnapping, and loss of real or personal property. Population density, rurality index, small producer loans, homicides or massacres, torture, land dispossession and population internally displaced and received by displacement, are the main socio-political indicators of agricultural areas at medium altitudes with complex mosaics of land uses.

The second regression equation describes the landscape variation from farming systems in lowlands to naturalness in highlands, in relation to fourteen socio-economic variables (Table 1b). The model highlights a significant association between intensive rice crops and livestock systems with high values of population density, indigenous population, rurality index, income linked both to the primary and service sectors (GDP services), loans for medium and large producers, social integrity and a set of variables linked to violence, such as terrorism, sex crimes, and people received by displacement. Regarding the landscape with a greater degree of naturalness, mainly represented by *páramos* ecosystems and Andean vegetation in highlands, the most influential socio-economic indicator is the land Gini index and the indicators linked to armed struggle and violence are the dispersion in the area of antipersonnel mines and the forced displacement of people.

4.3 Post-conflict forecasting of landscape change.

The post-conflict land cover scenario was driven by current values of socio-economic and political descriptors (Table 1). We observed that, as expected, over the period studied conflict indicators experienced a significant downward trend reaching values close to zero (Fig. 3). Similarly, the municipal Gini index shows a large decrease, indicating a trend towards higher income equity. The socio-economic indicators with the greatest increase are those related to the granting of loans to producers thus conveying an expected lag in their causal influence on land cover change as time is required for the investment of credit to be realised as new agricultural production.

The application of the scenario-based model provides a set of calculated vectors whose elements are the coordinates of the municipalities on the ordination axes describing the new landscape structure (Fig. 4). Landscape changes derived from the post-conflict scenario show a clear transition gradient towards the agrarian expansion and intensification. This can be observed through the displacement of municipalities towards the negative end of the PCA plane, from traditional agrarian systems to highly intensive agrarian systems, along PCA-axis1, and from systems where naturalness is a relevant feature to farming systems, as PCA-axis 2 variation expresses. These processes of change are evident by mapping the simulation outcomes. This allows a spatially explicit landscape simulation linked to the new social, political and economic conditions (Fig. 5).

There is an increase of the areas of coffee and rice production between 2007 and 2013, which validates the trend of agrarian intensification in the simulated post-conflict landscape (Figure 6).

5. Discussion

5.1 Nature, rural landscape and socio-political conflict

It is well known that landscape patterns are fundamentally associated with the socio-economic processes linked to them and that these are major driving forces of the structure and functioning of rural landscapes (Schmitz et al., 2003; Lambin and Meyfroidt, 2010; Verburg et al., 2010, among others). However, to understand social and ecological relationships empirical studies based on high quality data are required (Kininmonth et al., 2015). Such studies are scarce simply because data are often non-existent and explicit and quantitative formalization of the social-ecological relationship is uncommon (Nagendra et al., 2004; Schmitz et al., 2012, 2018; Arnaiz-Schmitz et al., 2018). In this respect our study is unique in the quality and quantity of land cover and socio-political variables that we could access and synthesise. Hence, we provide a new and much needed quantification of the relationships between landscape patterns and social characteristics of the local communities in the Andean region of Colombia that has abruptly transitioned from 40 years of war to peace (Rodríguez et al., 2013; Feola et al., 2014).

In this paper, we have developed an empirical model between landscape structure and social aspects of local population in a Colombian Andean region. The procedure followed has provided a quantitative model of dependence with a limited number of socio-economic and political variables that, by themselves, explain much of the landscape structure variation (De Aranzabal et al., 2008). The analysis of the landscape prior to the peace process (Figure 2), identified three predominant agricultural sectors in the past landscape of the study area: mosaics of integrated crop-livestock systems, cattle ranching and crop intensification, mainly rice production (Tolima is the biggest rice producing region in Colombia; Delgado et al., 2015; Delerce et al., 2016). The main landscape tendencies revealed represent the most common land use dynamics in the Andean region since the 1500s (Rodríguez et al., 2013). In fact, several studies identifying both the good accessibility and the conversion rate of native forest in favour of the agricultural land uses as the main drivers of deforestation patterns (Lambin et al., 2003; Etter et al., 2006). Thus, in the eastern Andes of Colombia transformed ecosystems cover 51% of the total area, while the other 49% corresponded to natural ecosystems, such as *páramos* and Andean and sub Andean forests (Armenteras et al., 2003).

In our study area, the past landscape was closely related to the long-lasting conflict prior to the peace-building process. The variables that significantly explained the state of the landscape under conflict conditions, reveal that landscapes dominated by intensive agricultural land uses (negative end of PCA-axis 1) are related to the more dynamic economic activities, as is evident from the high contribution of agricultural GDP (Table 1a). This situation was the result of several social, political and economic factors, mainly the promotion of agriculture enhanced by the application of new technologies and production systems, better-developed value chains and, an increased processing capacity. The Colombian government has targeted the availability of these resources onto the most productive territories and densely populated villages (Pacheco et al., 2010; Rodríguez et al., 2013; Villaraga et al., 2014). However, our model also illustrates the past influence of violence and social inequality, as indicated by the regression coefficients of those variables that quantify kidnappings, loss of real or personal properties (both corresponding to the search for rent and self-financing of organized criminal violence; González and López, 2007), municipal Gini index and Gini land index. The last two indices reflect unequal distribution of land, resources and income (Table 1a). This social inequality is related to the concentration of land and income in few owners of agricultural industries at the expense of small-scale producers (Royuela and García, 2015; Boron et al., 2016). In Colombia, about 0.4% of landowners monopolize 61.2% of rural properties (Bustamente, 2006; Feola et al., 2014; Guardado, 2018). Unequal land distribution was one of the main reasons for the emergence of subversive groups and eventual armed conflict (Richani, 1997; González and López, 2007; Albertus and Kaplan, 2012).

The maintenance of traditional land uses, represented by integrated crop-livestock systems and remaining natural areas (at the positive end of the PCA-axis 1) largely depends on the municipal rurality index and the ability of small producers to access finance (Table 1a), since this sector are primarily responsible for maintaining the multifunctionality of traditional agricultural systems (Lambin and Meyfroidt, 2010). This type of landscape requires high levels of labour inputs and, therefore, a critical density of rural population. Yet it is these areas, mainly populated by indigenous people, where violence, intimidation and forced displacement have been most common (Table 1a). The process of forced migration was the result of different mechanisms of coercion, threats and violence, indicated in the model by variables such as tortures, homicides and land dispossession, generating an intense dynamic of human displacement in the area (Kälin, 2008; Albertus, 2019).

The second regression explains the secondary landscape gradient (PCA-axis 2; Fig. 2) in terms of several socio-economic and violence indicators (Table 1b), which in the case of the farming systems (negative end of axis 2) are very similar to those linked to agricultural land uses in the previous model (Table 1b). Remote areas, mainly characterised by naturalness (*páramos* ecosystem and Andean vegetation, situated at the positive end of axis 2) have been the focal point of the armed conflict and violence (Salas-Salazar, 2016) giving rise to constant and multiple social deficiencies (Delgado et al., 2015). These included inequitable distribution of land ownership and human displacement in the face of violence and the chronic threat posed by anti-personnel mines. The long history of armed conflict has turned the remote areas of Tolima into insecure and inaccessible places where forced migration in response to violence resulted in abandonment of small-scale low intensity agriculture (Shultz et al., 2014). Thus, our results highlight the remarkable and ironic connection between armed strife and lack of human disturbance, or naturalness, favoured in remote areas where isolation predominates and there are greater guarantees for maintaining natural covers and biodiversity (Cuenca et al., 2016). Several previous studies evidenced these links between civil war and biodiversity in Colombia (Dávalos, 2001; Fjeldså et al., 2005; Sánchez-Cuervo and Aide, 2013b).

In summary, the social-ecological interaction model developed allows to test for correlative/causal relationships among the landscape and social-economic factors including violent conflict, land cover types, land accessibility, naturalness, forest fragmentation, weak state presence, land grabbing, unequal land distribution, forced displacement, social inequality, human vulnerability and poverty (Dávalos, 2001; Rodriguez et al., 2013; Sierra et al., 2017, among others).

5.2 Post-conflict land cover scenarios

The end of hostilities in Colombia heralds a new period of socio-economic stability and new opportunities for investment and development (Boron et al., 2016). However, the current transition period could lead to rapid environmental, socio-economic and political changes whose consequences are still uncertain. After the resolution of long conflicts, countries tend to prioritize social and economic factors, such as peacekeeping, and poverty reduction while environmental considerations are often disregarded (Salazar et al., 2018; Suarez et al., 2018b). Thus, post-conflict changes could imply negative effects on biodiversity conservation. These could arise if political stability and an imperative for growth stimulates rapid ecosystem transformation and land use intensification favouring the enrichment of new landowners, well placed to exploit an intensive agro-industrial model (Morales, 2017; Unda and Etter, 2019) as the simulation foretells. But also, the scenario predictions could trigger positive effects through proactive design of effective governance structures that produce better ecosystem management for a good social and ecological alignment (Kininmonth et al., 2015; Sierra et al., 2017), recovering and improving simultaneously human wellbeing and the resilience of local communities (Ibáñez and Vélez, 2007).

The key challenge for policy and decision makers is to design the best possible adaptive strategies that societies can develop in the face of complex changes (Österblom et al., 2013). The analysis of scenarios is a way to investigate future pathways and the consequences of different policies, and it can be a useful tool for the development of strategies and recommendations (Boron et al., 2016). The development of our scenario-based simulation has been possible due to the unique availability of public data that describe the socio-political profile of the pre and post-conflict regional population (Sánchez-Padilla et al., 2009; Karl, 2017; Suarez et al., 2018a, 2018b; Salazar et al., 2018, Gallego et al., 2019), despite collection and processing having been delayed for political reasons (Vargas, 2012; GMH, 2013). When we use the socio-economic and political relationships that emerged during conflict and adjust these to represent the post-conflict situation we predict a strong process of agricultural expansion and intensification of land uses. Contemporary data on rates of land devoted to agricultural production validate our results. Thus, in the Tolima region there is an evident increase in the area dedicated to the production of rice and coffee (Fig. 6). This regional tendency is consistent with the data of increase of agricultural production at country level (45% of the territory has recently turned to agricultural uses, Unda and Etter, 2019).

Agricultural intensification is a significant tendency worldwide, affecting both biodiversity and ecosystem services supply (IPBES, 2019) and driving a loss of human welfare and wellbeing (Kreidenweis et al., 2018; Harlio et al., 2019). If realised, the projected landscape transformation will impact the conservation of key ecosystems such as Andean forests and many protected areas. Many important natural corridors connecting Andean ecosystems and tropical rainforests may suffer deleterious impacts, even the loss of ecological connectivity and impairment to other ecological processes and the supply of important ecosystem services (Rodríguez et al., 2013).

The phenomenon of overexploitation and deforestation due to agricultural production, even in protected areas, has already been observed in some post-conflict countries (Ijang and Cleto, 2013; Katunga and Muhigwa, 2014). Usually, agricultural intensification results in an agro-business model that leads to large social and economic inequalities (Atallah et al., 2018; Vanderhaegen et al., 2018). This socio-ecological threat could be especially serious in Colombia, which has currently the highest values for income distribution inequality (GINI Index) among the post-conflict countries, and one of the highest rates of natural resources extraction (Suarez et al., 2018a). Conflict cessation, the return of population to rural areas and the recovery of local domestic economies, are very good news for many people displaced and affected by violence. However unregulated increases in the exploitation of natural resources and agricultural intensification constitute a clear and present threat to the conservation of Colombian ecosystems (Dávalos, 2001; WWF-Colombia, 2017; Unda and Etter, 2019).

The Land Restitution Programme, which manages the return of displaced people to their lands (Velez, 2013) has a pivotal social-ecological role in Colombia's peacebuilding process and represents an opportunity to redefine and promote sustainable land uses compatible with nature conservation (Unda and Etter, 2019). In this new period, Colombian decision makers face a challenge to implement proactive and integrated social, economic and environmental planning policy in which land conservation initiatives must be accompanied by adequate policies to ensure natural capital and ecosystem services conservation (Perfecto and Vandermeer, 2010).

Simple models such as ours can be a useful tool to estimate the threats and challenges faced by landscape planning and management from a social-ecological perspective (Tavares et al., 2012; Arnaiz-Schmitz et al., 2018). It is not an objective of this paper to propose or discuss concrete policy options but current global 2030 Agenda and the 17 Sustainable Development Goals, adopted by all United Nations Member States in 2015 after decades of work, provides a shared blueprint for peace and prosperity for people and the planet from now on future (United Nations, 2018). Colombian government signed and adopted SDG agenda, as many other countries around the world, now is time to build.

6. Conclusion

The peace process in Colombia implies an important challenge in land planning for human wellbeing and community resilience. The quantitative model applied portrays the links between different regimes of farming practices and socio-economic indicators such as forced displacement and relocation, mainly of indigenous people, in addition to high social inequality, among other indicators of human welfare losses.

The change from traditional agricultural activities to intensive agriculture can be observed in the increase of the production of rice and coffee, but the change in the number of hectares has not been spatially represented. However, there is a high probability that this tendency of change will become more extensiveas it has been arisen in other countries with similar socio-economic contexts. While such changes may improve the economic conditions of rural inhabitants, it is possible that accelerated and unregulated changes in the landscape might constitute a threat to the conservation of Colombian ecosystems. For this reason, we would encourage inclusion of our model-based analysis in evidence for policy use.

This social-ecological model could be used as an effective and valuable tool for land planning and management, allowing decision makers to forecast new types of landscape, using scenario-based approaches with socio-political and economic indicators as predictors of change, and taking into account intra-regional differences to capture the complexity of these social-ecological systems. With the data currently available in Colombia, this model could be replicated immediately both nationally and regionally, as long as the economic resources needed to update the landscape information are provided. As a result, the specificities of each of the regions of Colombia could be shown in greater detail.

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Figure captions

Figure 1. Location of the study area (Department of Tolima, Colombia).

Figure 2. Landscape structure of the Tolima region. The distribution of the municipalities of the study area on the landscape PCA plane is shown (see municipality codes in Appendix 1). The main landscape indicators (LULC variables with higher loadings) are indicated at the end of the axes.

Figure 3. Post-conflict scenario. The variation values (expressed in percentage) of the socio-economic and political indicators selected by the fitted model are displayed in the design.

Figure 4. Post-conflict landscape simulation. Change of distribution of the municipalities on the plane of the new landscape structure generated by the simulation model based on the peace process scenario. The direction of the arrows indicates the displacement of the municipalities from their coordinates on the ordination plane of the original landscape structure (past landscape, arrow origin) to their location in the simulated post-conflict landscape (end of the arrow).

Figure 5. Mapping of landscape spatial patterns of the Tolima region according to the social-ecological scenarios modelled, from a situation of prevailing armed conflict to the ceasefire agreement and peacebuilding process. Maps show the remarkable tendency towards the agrarian expansion and intensification of the simulated landscape.

Figure 6. Change in production area (ha) from 2007 to 2013 for a) rice crops and b). coffee crops.

Appendices

Appendix 1. Municipalities of Tolima Department of Colombia. Municipal codes used in Figure 2 are indicated.

Municipalities	Code	Municipalities	Code
Alpujarra	M1	Líbano	M25
Alvarado	M2	Mariquita	M26
Ambalema	M3	Melgar	M27
Anzoátegui	M4	Murillo	M28
Armero Guayabal	M5	Natagaima	M29
Ataco	M6	Ortega	M30
Cajamarca	M7	Palocabildo	M31
Carmen Apicalá	M8	Piedras	M32
Casabianca	M9	Planadas	M33
Chaparral	M10	Prado	M34
Coello	M11	Purificación	M35
Coyaima	M12	Rioblanco	M36
Cunday	M13	Roncesvalles	M37
Dolores	M14	Rovira	M38
Espinal	M15	Saldaña	M39
Falan	M16	San Antonio	M40
Flandes	M17	San Luis	M41
Fresno	M18	Santa Isabel	M42
Guamo	M19	Suarez	M43
Herveo	M20	Valle San Juan	M44
Honda	M21	Venadillo	M45
Ibagué	M22	Villahermosa	M46
Icononzo	M23	Villarica	M47
Lérida	M24		

Appendix 2. a) LULC variables used to characterize the landscape structure of the study area. LULC were quantified as % of the municipal area occupied. b) Loadings of the 47 municipalities described through LULC on the first two PCA axes and their percentage of contribution. Variance absorption of the two PCA axes is shown in brackets.

a) LULC	b) PCA-axis 1 (30.99%)		PCA-axis 2 (23.65%)	
	Factor loadings	% Contribution	Factor loadings	% Contribution
Rice crops	-8,35	18,31	-10,81	40,27
Coffee crops	1,95	1,00	-1,00	0,35
Cattle ranching	-7,52	14,86	3,34	3,85
Other crops	-0,21	0,01	-0,28	0,03
Mosaics of crops, pastures and natural areas	14,75	57,19	-7,05	17,15
Pastures and natural areas	-0,77	0,16	2,28	1,79
Subandean vegetation	1,12	0,33	-0,07	0,00
Sub-xerophytic vegetation	-2,63	1,82	0,34	0,04
Open areas with/without vegetation	-0,65	0,11	0,20	0,01
Andean vegetation	2,98	2,34	4,71	7,66
Basal vegetation	-0,88	0,20	-0,07	0,00
Riparian systems	-1,54	0,62	-1,13	0,44
Fragmented forest	0,61	0,10	0,54	0,10
Secondary vegetation	-0,18	0,01	0,60	0,12
Water bodies	-1,44	0,55	-0,27	0,03
Artificialized territory	-0,26	0,02	-0,37	0,05
Páramos ecosystem	3,00	2,37	9,03	28,12

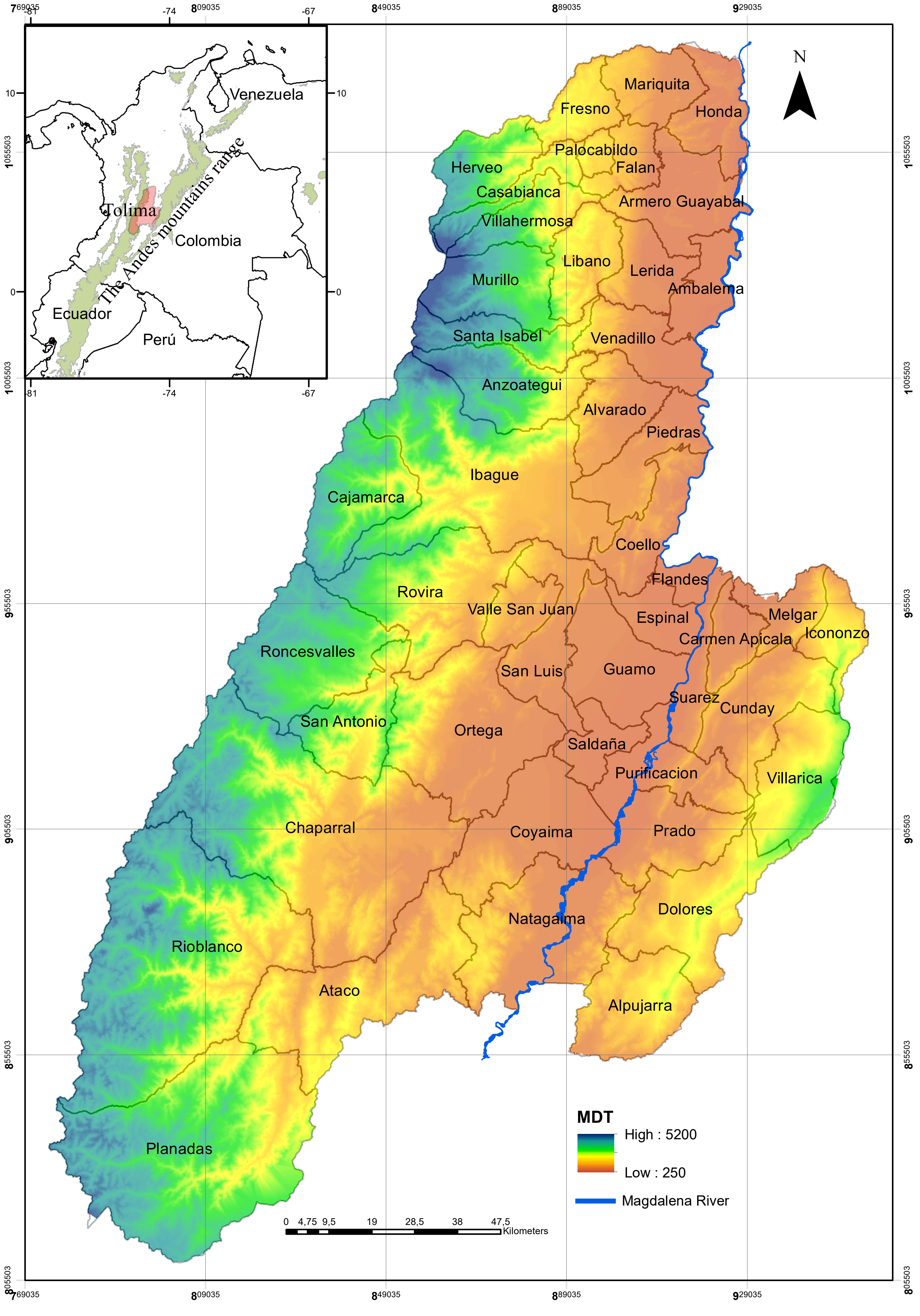
Appendix 3. Socio-economic and political variables used for the characterization of the municipalities of Tolima. The databases and information sources of the socio-economic and political indicators identified used in the design of the post-conflict scenario are shown.

Variable categories	Selected descriptors	Description and units of measurement	Sources for the post-conflict scenario
Population indicators	Municipal area	Km^2	
	Population density	Number of inhabitants / km^2	The population density and rurality index indicators are municipal values of projection for the year 2015. https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion.
	Rurality index	Percentage of total rural population by total municipality population	
	Indigenous population density	Number of indigenous people / km^2	Indigenous reservations at the national level: Digital Government Colombia. June 2017. Directorate of Indigenous Affairs, Rom and Minorities - Ministerio del Interior. https://www.datos.gov.co/Ordenamiento-Territorial/Resguardos-ind-genas-a-Nivel-Nacional/d7se-6xhm/data
Human life conditions	Unsatisfied basic needs	Critical deficiencies in the population: inadequate housing, public services, critical overcrowding, lack of school attendance, high economic dependence. Percentage of households that do not cover basic needs and is compared with the national (27.7) and departmental (29.2) levels. Deprivation in 5 of the 15 variables corresponds to the poverty line. The values are compared with the national total (33.3) and departmental level (44.5).	
	Total multidimensional poverty index	Analyses the dimensions of home, childhood and youth, work, health, home public services and housing conditions. It is compared with the national (55.7) and departmental (49.3) levels.	
	Equity (GINI index-municipal)	Degree to which the distribution of household income approaches or moves away from a situation of perfect equality.	Center for Studies on Economic Development. General characteristics panel. 2017.
	Equity (GINI index-land)	Degree to which the distribution of land property approaches or moves away from a situation of perfect equality. It is	

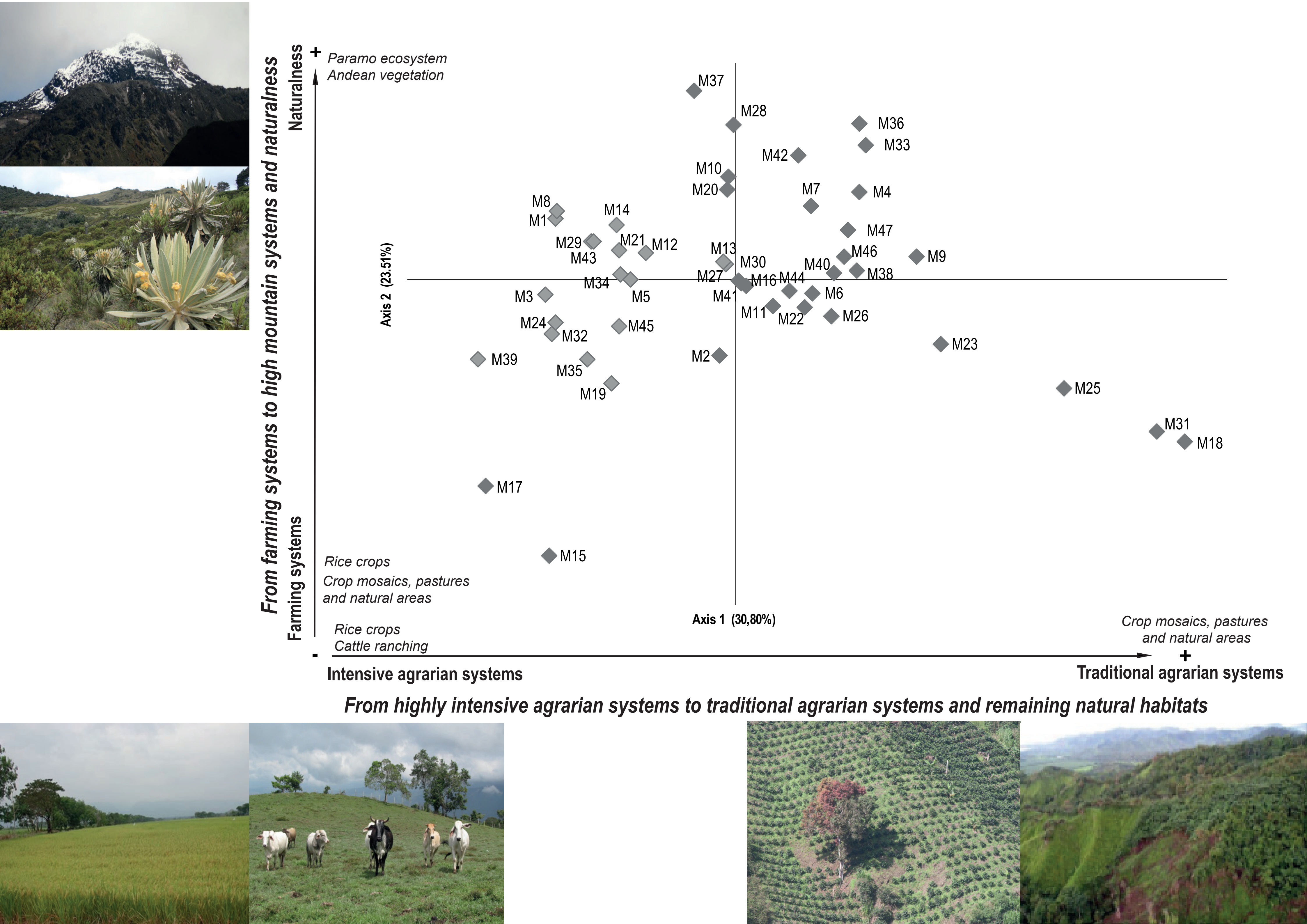
		compared with the national (87.8) and departmental (77) levels.	
Economic activities	Agricultural GDP	Percentage of Gross domestic product	Center for Studies on Economic Development. General characteristics panel. 2017.
	GDP services	Percentage of Gross domestic product	
	Industrial GDP	Percentage of Gross domestic product	
	Small producer loans	Percentage of loans to the small agricultural producer of all loans granted	Center for Studies on Economic Development. Agriculture and land panel. 2017.
	Loans for medium and large producers	Percentage of loans to the medium or big agricultural producer of all loans granted.	
Conflict and violence descriptors*	Armed harassment/ambushes	Number of war action that is carried out under the legitimate task of war. Makes use of licit means and weapons in combat.	Center for Studies on Economic Development. Conflict and violence panel. 2017.
	Antipersonnel mines	Number of antipersonnel mines. Non-lethal dimension of the armed conflict that has equally serious consequences.	
	Enforced disappearance	Number of disappearances. Deprivation of the freedom of a person whose whereabouts are unknown, in which there is no request for something in return and the victimizer denies responsibility for the fact.	
	Homicides/massacres	Number of homicides. Selective assassinations are the type of violence used by the armed actors that have killed the most in the development of the conflict.	
	Kidnapping	Number of kidnapping. Practice for economic purposes and propaganda logic, which made kidnapping a political weapon to negotiate and get social support.	Center for Studies on Economic Development. Conflict and violence panel. 2017.
	Sex crime	Number of sex crimes. Violence against women in the context of armed conflicts or authoritarian regimes.	
	Terrorism	Number of terrorism acts. Any indiscriminate attack perpetrated with explosives against civilian targets in public places, in order to cause a high lethality and devastation on the civilian population.	
	Threats	Number of threats. Practice of constant violence with a high capacity for social and emotional destabilization, which seeks the lasting installation of fear, distrust, the rupture of solidarities and paralysis in the daily lives of the victims and their community expressions.	
	Torture	Number of people tortured. Any act by which a person is intentionally inflicted pain or suffering, whether physical or mental, in order to obtain from her or a third party information or a confession.	Center for Studies on Economic Development. Conflict and violence panel. 2017.
	Attacks on public goods	Number of attacks. Total or partial destruction of goods and environments. This type of attack involved material devastation, but sometimes also caused injuries and deaths of the population.	
	Land dispossession	Number of people who claim to have been dispossessed. Expropriation of material	Center for Studies on Economic Development.

	goods through violent practices used by armed groups using different mechanisms of coercion and violence that forced the peasants to leave the land.	Conflict and violence panel. 2017.
Loss of real or personal property	Number of attacks and declarations of loss of assets. Attacks or sabotage against electrical, energy and road infrastructure or private institutions. Also counted are the houses and goods that are damaged in the attacks to populations by the use of cylinders bomb, the burning of vehicles in the illegal roadblocks and the goods affected by the terrorist attacks.	
Social integrity/freedom	Number of actions. Action against a populated area, where the presence of the public force exists and whose effect reaches both the civil and military establishments, whether in goods or people. The damage to property can be evidenced by the partial and / or total destruction of homes, religious buildings, public buildings, and partial and / or total destruction of police posts. Damage in military and / or civilian personnel refers to crimes such as homicides and / or personal injuries, among others.	Center for Studies on Economic Development. Conflict and violence panel. 2017.
Linking children and adolescents with armed conflict	Number of children linked. It constitutes a crime in which the armed actors recruit civilians under eighteen years of age, forcing them to participate directly or indirectly in hostilities or in armed actions.	
Forcibly displaced people	Percentage of displaced people. Forced displacement - crime against humanity - is a massive, systematic, long-lasting phenomenon that is largely linked to the control of strategic territories.	Center for Studies on Economic Development. Conflict and violence panel. 2017.
People received by displacement	Percentage of people received by displacement per municipality	

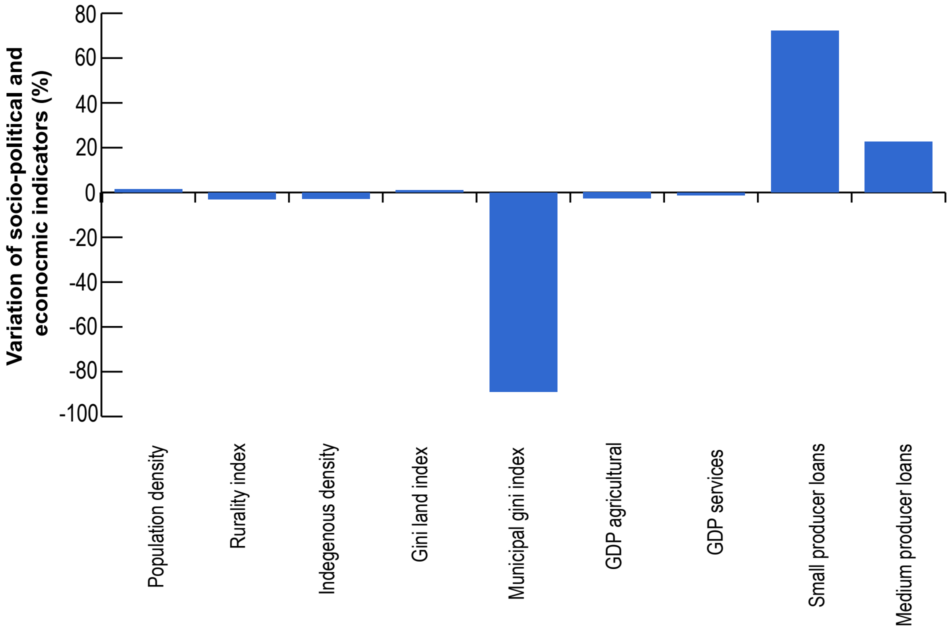
* The conflict and violence variables were relativized, taking the number of actions per 100,000 inhabitants.



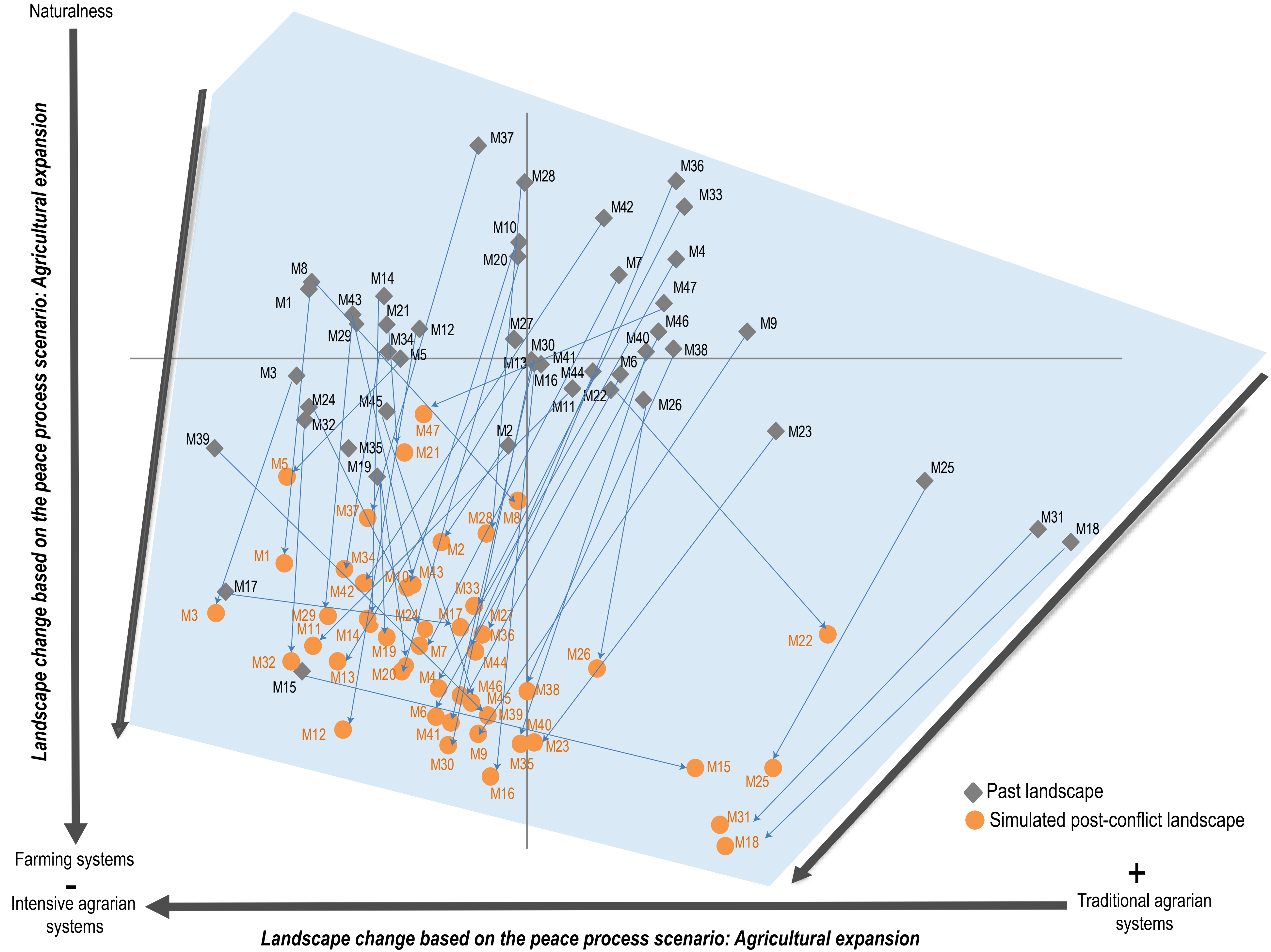
Venezuela
Tolima
The Andes mountains range
Colombia
Ecuador
Perú
N
Mariquita
Fresno
Honda
Palocabildo
Herveo
Falan
Casabianca
Armero Guayabal
Villahermosa
Libano
Lerida
Murillo
Ambalema
Santa Isabel
Venadillo
Anzoategui
Alvarado
Piedras
Ibague
Cajamarca
Coello
Flandes
Rovira
Valle San Juan
Espinal
Melgar
Carmen Apicala
Icononzo
Roncesvalles
San Luis
Guamo
Suarez
Cunday
San Antonio
Ortega
Saldaña
Purificacion
Villarica
Chaparral
Coyaima
Prado
Natagaima
Dolores
Rioblanco
Ataco
Alpujarra
Planadas
MDT
High : 5200
Low : 250
Magdalena River
0 4,75 9,5 19 28,5 38 47,5
Kilometers
769035 809035 849035 889035 929035
1055503 1005503 955503 905503 855503 805503
-81 -74 -67
10 0



From farming systems to high mountain systems and naturalness
Naturalness
+
Paramo ecosystem
Andean vegetation
Farming systems
Rice crops
Crop mosaics, pastures
and natural areas
Axis 2 (23.51%)
Axis 1 (30,80%)
M37
M28
M36
M33
M42
M10
M20
M7
M4
M8
M1
M14
M47
M29
M43
M21
M12
M13
M30
M46
M9
M40
M38
M27
M16
M44
M34
M5
M3
M41
M6
M11
M22
M26
M24
M32
M45
M23
M2
M39
M35
M19
M25
M31
M18
M17
M15
Rice crops
Cattle ranching
-
Intensive agrarian systems
Crop mosaics, pastures
and natural areas
+
Traditional agrarian systems
From highly intensive agrarian systems to traditional agrarian systems and remaining natural habitats



Variation of socio-political and economcmic indicators (%)
80
60
40
20
0
-20
-40
-60
-80
-100
Population density
Rurality index
Indegenous density
Gini land index
Municipal gini index
GDP agricultural
GDP services
Small producer loans
Medium producer loans


Naturalness
Landscape change based on the peace process scenario: Agricultural expansion
Farming systems
-
Intensive agrarian systems
+
Traditional agrarian systems
Landscape change based on the peace process scenario: Agricultural expansion
Past landscape
Simulated post-conflict landscape
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12
M13
M14
M15
M16
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M31
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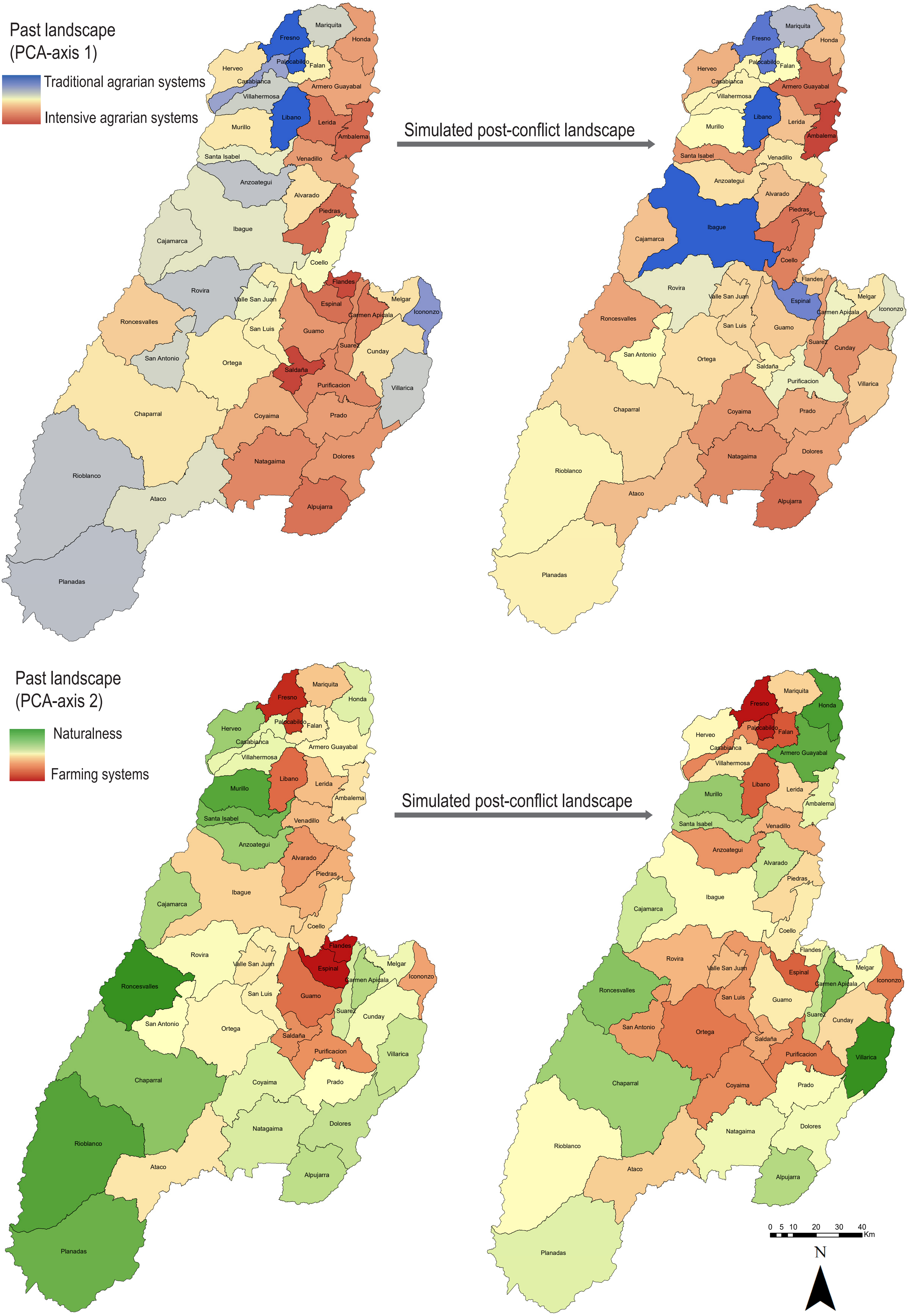
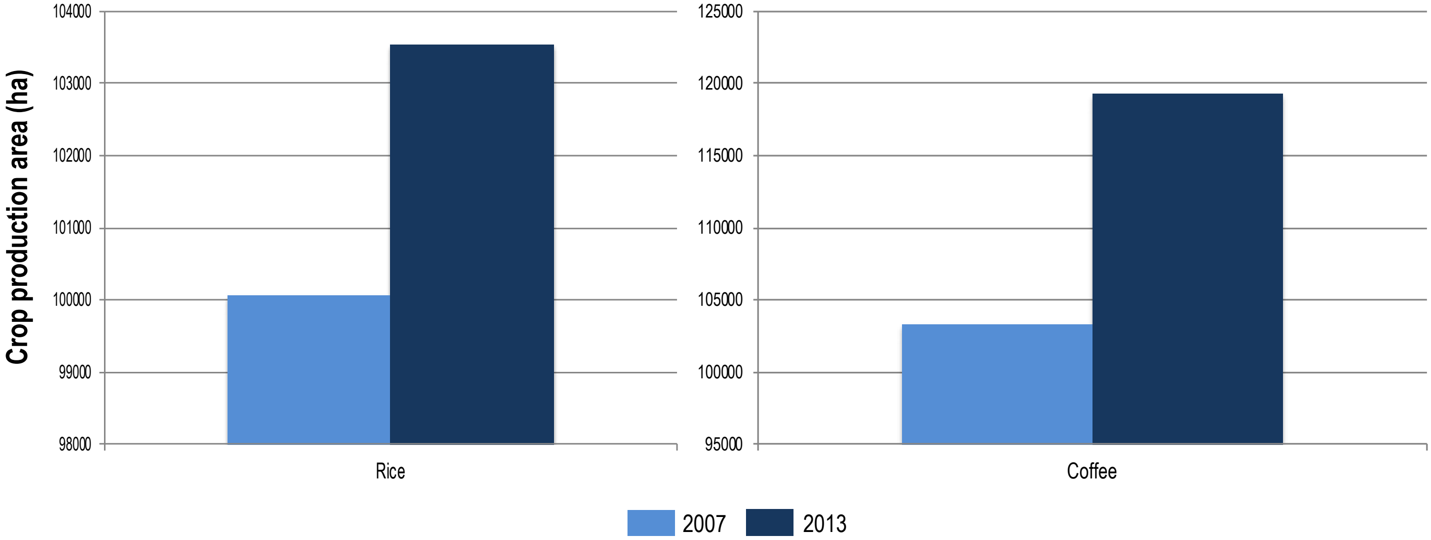
M44
M45
M46
M47


Past landscape
(PCA-axis 1)
Traditional agrarian systems
Intensive agrarian systems
Simulated post-conflict landscape
Past landscape
(PCA-axis 2)
Naturalness
Farming systems
Simulated post-conflict landscape
Mariquita
Fresno
Honda
Herveo
Palocabildo
Falan
Casabianca
Armero Guayabal
Villahermosa
Libano
Lerida
Murillo
Ambalema
Santa Isabel
Venadillo
Anzoategui
Alvarado
Piedras
Ibague
Cajamarca
Coello
Rovira
Flandes
Valle San Juan
Melgar
Espinal
Carmen Apicala
Icononzo
Roncesvalles
San Luis
Guamo
Suarez
Cunday
San Antonio
Ortega
Saldaña
Purificacion
Villarica
Chaparral
Coyaima
Prado
Natagaima
Dolores
Rioblanco
Ataco
Alpujarra
Planadas
0 5 10 20 30 40
Km
N


Crop production area (ha)
104000
103000
102000
101000
100000
99000
98000
Rice
125000
120000
115000
110000
105000
100000
95000
Coffee
2007
2013