DIVERSITY FOR SUSTAINABLE AND RESILIENT AGRICULTURE
A METHOD TO STUDY COMPLEX AGROFORESTRY LANDSCAPES: ILLUSTRATION IN MADAGASCAR

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CONTEXT

Tropical forested landscapes have experienced major changes over the last century, some of them driven by the transformation of farming systems in response to global change. Population growth and the development of a global market economy, in particular, led to the expansion of cash crops in the tropics, raising concerns about disruption of ecosystems, degradation of natural resources and impacts on rural populations' livelihoods. Cash crop expansion led to massive deforestation in some regions, leading to a loss of biodiversity and associated ecosystem services previously provided by complex forest ecosystems (Barrios et al., 2018). However, tree plantations and tropical smallholder agriculture are also recognised as ways of reframing the food-biodiversity challenge (Leakey, 2020). Some of these agro-ecological systems, such as agroforestry, present features conferring both social and ecological benefits, such as providing diversity of food and other crops, strengthening human-environment connections and traditional values, and likely ensuring ecological sustainability. These features suggest they can be seen as Win (food)-Win (environment) systems (Fischer et al., 2017).

The east coast of Madagascar experienced massive land use changes and deforestation related to the shifting rice cultivation practice (*tavy*). At the beginning of the 20th century, the colonial government widely imposed the plantation of coffee trees (Dandoy, 1973; Ruf & Blanc-Pamard, 1992). A little later and gradually, driven by the population growth and the development of cash crops, farmers abandoned the *tavy* and began the planting of clove trees (*Syzygium aromaticum*) beginning in the 1940s (Danthu et al., 2014).

Some studies suggest that the way farmers spatially manage crop and associated plant species at different scales, from the plot to the landscape, is especially crucial for coping with environmental heterogeneity at these different scales (Jackson et al., 2010). However, attempts to describe and analyse the spatial organization of these plant species are rare in highly diversified systems such as complex agroforests, and those that exist mainly concern home gardens (Mendez et al., 2001; Abede et al., 2013).

The Vavatenina area on the north-east coast of Madagascar offers an interesting case study as it raises the issue of the restoration of formerly forested landscapes by agriculture, and in particular by agroforestry whose development is underway in the area. Our study applied an original method to meet this challenge by combining a landscape spatial analysis with a participatory mapping of agroforests. First, we described the composition and spatial organization of agroforestry at two scales, from that of agroforests in the landscape to that of species within agroforestry plots. Second, we analysed the effects of topography and exposure on the landscape and agroforests heterogeneity.

METHODS

M1 Object based satellite image analysis

Satellite sensors deliver multispectral images at very high spatial resolution (VHSR), i.e. with pixels covering less than a square meter, in visible and infrared wavebands that allow land surface types discrimination. In this study, we processed Pleiades (© CNES) data acquired in September 2018 over our site of interest, and applied an Object Based Image Analysis (OBIA) to describe the land use and land cover of the study area at the landscape level. The following table describes the data chosen for this study.

Table 1: 2018 Pleiades data specifications

Scene ID	Cloud cover	Spatial resolution (meters)	Spectral coverage (nm)	Processing level	Scene extent
PHR1B-2018-09-MS	< 5%	2	430 - 550 (Blue) 490 - 610 (Green) 600 - 720 (Red) 750 - 950 (Near Infrared)	Orthorectified	9.636 x 8.696 km ($83.8\ km^2$)
PHR1B-2018-09-P		0.5	480 - 830 (Panchromatic)		

The multispectral (MS) and panchromatic (P) bands were used to derive a set of texture metrics using ENVI (®L3HarrisTechnologiesInc.) software. After a resampling of the MS data as well as the resulting texture bands to the same resolution as the panchromatic layer (0.5 m), they have been stacked as a single GeoTiff file for OBIA using eCognition (®Trimble).

OBIA, combining multiscale segmentations, and classifications of segments instead of pixels, in a hierarchical process tree, can take advantages of VHSR data by integrating the spatial configuration of ground elements into the classification process. Therefore, several land covers spectrally similar in the average but differently organized can be discriminated.

Processing in eCognition requires a first step of segmentation. This process partitions the image in objects, formed by a group of contiguous pixels sharing the same spectral and textural properties, while being constrained by shape, scale, and homogeneity criterions defined by the user. Multiple successive segmentation levels might be generated, iteratively, depending on the requirements of the processing, which are themselves conditioned by the complexity of the area to be mapped and/or its nomenclature. For our study, 3 levels of segmentation were retained.

Hierarchical classification is a major advantage of OBIA. The classification at a given segmentation level will be inherited by child objects in subsequent segmentation levels. By using this approach, classes of little diversity can be sharply discriminated and discarded from the more complex classes, while particularly diversified classes can be coarsely discriminated at one level and detailed in underlying levels.

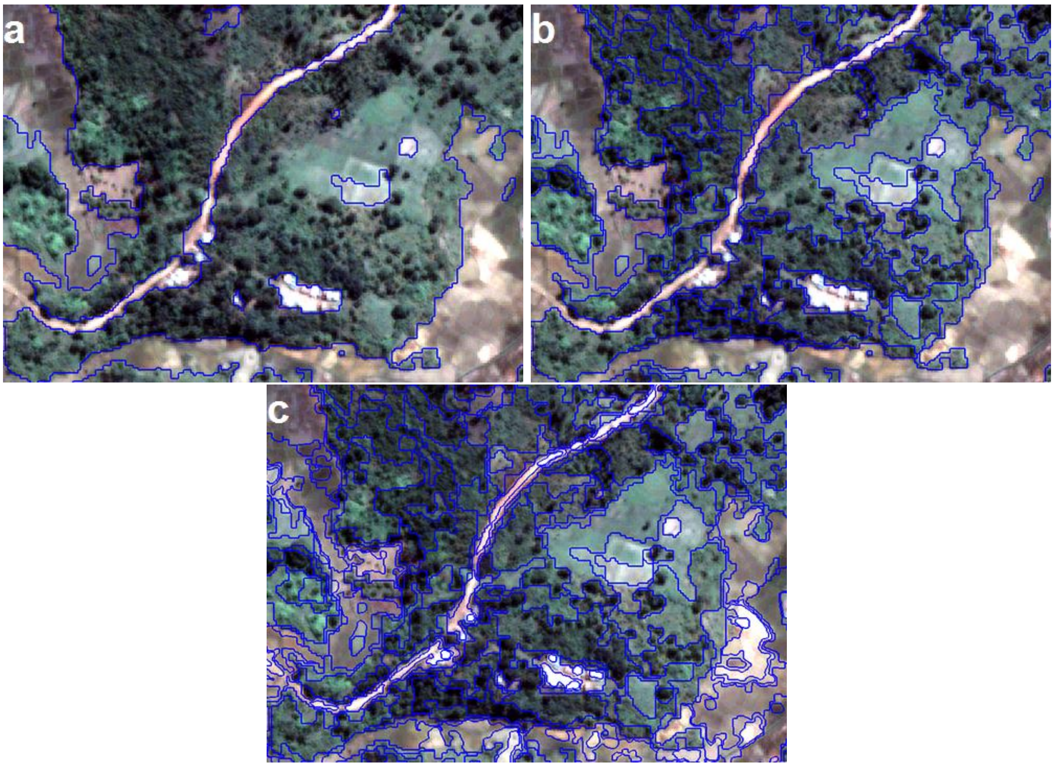

Figure 1: The three retained levels of segmentation

In our study, the process was quite difficult due to the high complexity and variability of the area. The entire processing workflow is presented in the following chart (Figure 2). First, we have discriminated the vegetated areas from the other land covers (built up areas, bare soil, rice fields, and open water) (Figure 1, a) by using the Normalized Difference Vegetation Index (NDVI). Then, based on a second segmentation level applied only to the vegetation class (Figure 1, b), different types were identified based on spatial organizations of the objects' elements (i.e. trees) through textural information, as well as the crop or plant types through spectral information. Finally, thanks to a third segmentation level (Figure 1, c), similar areas that serves the same function were classified and then combined within the same thematic class. At second and third levels, ground-truth reference data were involved to select a set of learning samples for each class. A feature space optimization was then carried out to identify the features (i.e. radiometric and texture metrics) that will benefit to the nearest neighbour classification. Finally, the classification algorithm was trained on the selected samples, and applied on the entire scene. For the other land uses and land covers, we also proceeded with a second segmentation level to discriminate each individual class.

The validation of the classification for the first 2 segmentation levels was carried out visually within the processing software. At the third level, a set of ground truth data collected on the field using a GPS as well as photo-interpreted data were used to compute a confusion matrix and subsequent statistics.

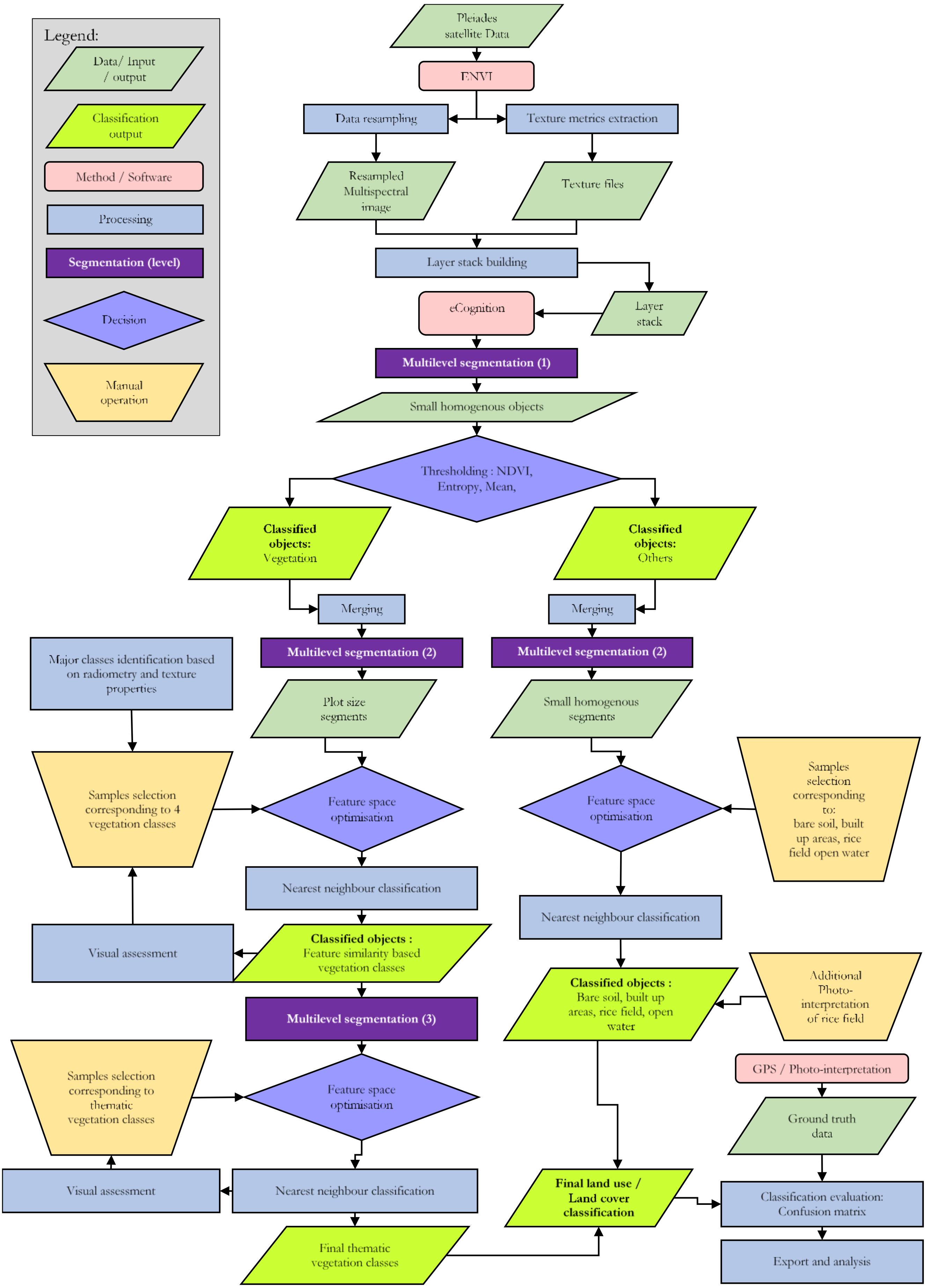

Figure 2: satellite data processing workflow

M2.a Participatory map of agroforestry plot

The spatial organization of plant species in agroforests was studied using a participatory method. First, the farmers were asked to draw on a paper the outline of their agroforest, indicating the direction of the slope and the exposure. The surface area of each agroforest was also measured by GPS. Then, they were asked to list the plant species present in their agroforest and represent them on their map with different coloured letters. In this way, 17 participatory maps were obtained. The list of species thus provided the composition of agroforests according to farmers' perspective, and the participatory map shown how these species were organized in the plot according to the slope.

M2.b Coding of the participatory maps

The participatory maps were coded to enable comparison of the spatial organization of each species within plot. Two variables were defined to describe it: the position of the species according to the slope (i.e., top, center, bottom) and the way in which each species was spatially distributed compared to the other species over the total area (i.e., random, edge, or aggregated). For each variable, the number of times a species was associated with it was counted. A Fisher's exact test was applied to the occurrence data of each variable to test whether the 14 most frequent species ((frequency > 7) were significantly associated to a given pattern of spatial organization (14 species: clove, lychee, jackfruit, breadfruit, banana, vanilla, coffee, avocado, silky oak, traveler palm, bamboo, guiana chestnut, orange, *Gliricidia sepium).*

RESULTS

R1.a Composition and spatial organization of land uses and agroforestry at landscape scale

We produced a map of the land uses covering all the region of interest, with a nomenclature comprising 14 classes: open water, built up areas, roads and bare areas, rice fields, annual crops (including pasture and low vegetation), and 9 classes of land uses containing woody vegetation (as trees or shrubs) at different densities and various compositions. The global precision of this map is 74%, the lowest intraclass precision being in the woody vegetation land uses such as the diversified parks. We were indeed able to discriminate different types of agroforestry systems based on their vegetal diversity and structure complexity, and to recognize clove crops.

This map was produced at 0.50m/pixel spatial resolution, and can thus be zoomed in to work at very local scale, like a village, for instance, or any other group of stakeholders.

Such map allows to consider the organization of the landscape and the distribution of the different land uses over the region. None of the land use types is dominating the landscape: their respective proportions are quite comparable, and vary from 5 to 18% only. Although, their location is not similar. For instance, annual crops, *Rubus alceifolius* dominated fallows, and shrubby fallows, respectively covering 16%, 18%, and 5% of the total region area, concentrate at the South-West of the area. Besides, agroforestry systems are rather located in the centre of the region, with diversified agroforest covering 14% of the area, and other agroforestry systems only 5 to 6% each. Rice fields, covering only 8% of the area surface, are scattered throughout the area.

We can also cross this digital map with other geographic information to understand how environmental and physical characteristics influence this distribution, or with local farmer surveys to consider the relationships with crop practices.

R1.b+c+d Effects of the topography (altitude, slope and exposure) on the spatial organization of land uses and agroforestry

The produced digital land use map also makes it possible to extract quantitative data on the area covered by each land use according to its place in the topo sequence. Indeed, it can be combined to data such as a Digital Terrain Model, acquired by radar sensors like SRTM on board of the Space Shuttle or any other source. Charts are then displayed to show how these land uses are distributed depending on the altitude, the slope, or the exposure of the land. They are useful to understand the laws that govern the establishment of cropping systems.

For the exposure, we considered the slopes that are highly vulnerable to cyclones (about 38% of the area in our map) and those more protected.

The slopes were also split in two categories: low and high slopes, considering 15° as a common threshold, which separates almost equally the domain covered by the map.

Finally, the effect of altitude was analysed, searching the threshold where the distribution of land uses undergoes a change. It was found that from 80m to 350 this distribution remains quite the same. But when raising more then 350m, there is an inversion between the woody land uses and the fallows. The charts data were then chosen to represent this abrupt transition. It shows that only 10% of the covered area is located higher than 350m. At this altitude, no more rice nor clove are cultivated, parks have disappeared, and woody plantations and diversified agroforests are very rare. Most of the surface higher than 350m is covered by fallows of various density and diversity.

R2. Composition and spatial organization of plant species in agroforests (Mariel et al. 2021)

The plant diversity cited by the farmers over the 17 agroforests consisted of 51 species, grouped in 28 families, the most common being Myrtaceae represented by five species, followed by Fabaceae, Moraceae and Rutaceae, each represented by four species. The plant diversity measured and based on farmers' reports varied between the 17 agroforests: on average, the farmers listed 15 species (± 4; range 8-22). The average size of the agroforests was 0.5 ± 0.3 ha (min = 0.10 ha/max = 0.96 ha) and the average slope of 17.7 ± 8.9° (min = 9°/max = 29°).

The results of the Fisher's exact test indicated significant dependence between the plant species and the two variables describing the spatial organisation: the spatial distribution of species within the plot (p-value < 0.0005) and the location of species according to the topography of the plot (p-value < 0.05). The spatial distribution pattern showed that the farmers tended to distribute clove and silky oak randomly across their agroforest, to plant bamboo and lychee on the border, and to spatially aggregate vanilla, banana, breadfruit and coffee. Concerning the spatial location variable, the farmers tended to prefer planting vanilla, coffee and bamboo at the bottom of their agroforest, and planting silky oak and traveller's palm at the top. The other species were planted equally frequently in the three locations.

DISCUSSION

Composition and spatial organization of land uses and agroforestry at landscape scale

This region is quite diverse in terms of land covers and land uses. Five different tree cropping systems can be distinguished, and also four different fallow types, in addition to rice and other annual crops or pastures. A remote sensing-based mapping can help analysing this composition, in terms of proportions and distribution. The area covered by the different land uses is almost the same for all of them, even though there are more fallows than crop lands.

The crops spatial organization is far from homogeneous: some land uses are concentrated only in some areas while others are scattered all around. The land use map is also a good tool to analyse this distribution, qualitatively, but also quantitatively if using landscape spatial analysis softwares. This will be the next step in this study.

As the first analysis, we show here a strong relationship between the topo sequence and the organization of land uses. For instance, woody crops, and especially clove and other agroforestry systems, are privileged on the opposite side of cyclone influence exposure. Rice fields only set up on shallow slopes, replaced by fallows on steeper slopes. Only fallows remain at higher altitudes. The combination of altitude, slope, and exposure, thus participate to shape the complex landscape of this agroforestry region.

Composition and spatial organization of plant species in agroforests (Mariel et al. 2021)

The plant diversity of agroforest appears to be largely driven by the diversity of functions associated with the different plant species, allowing farmers to fulfil a range of needs (e.g. food production for human or animal self-consumption, income generation, the production of building material and firewood). Thus, the differences in the frequency of occurrence of the plant are partly linked to these contributions, in particular, the diversity of fruit species.

The topographical gradient at the plot scale and its consequences for the environmental characteristics (soil, moisture, exposure to sunlight and to cyclones) appear to structure the spatial organisation of plant species, making it possible to provide growing conditions adapted to the needs of each plant species.

Analysis of the participatory maps of agroforests highlighted common practices that can be explained by farmers' perception of the soil fertility, as reported in many ethno-pedological studies (Barrera-Bassols & Zinck, 2003) and through the catena concept developed by Milne and his colleagues in the 1930s to formalize farmers' perceptions of the spatial distribution of soils along a topographical gradient (Milne, 1947; Borden et al., 2020).

These farmers' perceptions of environmental heterogeneity and its effect on plant species drive the way farmers spatially organize plant species in their agroforest, that contribute to shape complex and heterogenous agroforestry landscapes.

CONCLUSION

While agroforestry systems have expanded relatively recently in Madagascar (Dandoy, 1973; Arimalala et al., 2019), our work has revealed an important ongoing process of land use diversification in the Vavatenina area. The shift in land use from slash-and-burn to agroforestry, initiated and driven by local people, offers promising prospects for restoring formerly forested areas to limit erosion and regulate hydrological flows, and restoring soil fertility, while allowing for the conservation of an array of agrobiodiversity that depends on the maintenance of regulatory ecosystem services (e.g., soil erosion limitation) (Hillbrand et al., 2017).

Our results illustrate the relevance of adopting a multi-scale approach and the combination of different methods (remote sensing and participatory mapping) to better understand what contributes to shaping a complex landscape. This poster presents preliminary studies, that show the strong relationships between the physical environment and the farmers cropping practices. Especially, the topography (altitude, slope, and exposure) clearly shapes both the distribution of land uses at the landscape level and the intraplot structure and diversity. Deeper analysis should now be undertaken to mine all the spatial information that such approach can provide, and explore all the potential of very high-resolution land use maps to extract landscape indices and agronomical patterns.

This study also highlights the holistic vision that farmers have of their environment, which they translate into the way they manage agrobiodiversity and more generally natural resources. In this sense, the restoration of ecosystems in such landscapes must promote the close involvement of farmers and a strong recognition and consideration of their knowledge.

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