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Forest regeneration following land abandonment is driven by historic land use affecting plant diversity and soil carbon stocks (mountainous tropical Asia)

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Abstract

Context

Farmland on steep slopes is increasingly abandoned because it is unsuitable for most forms of modern agriculture. Succession back to forest is often slow or inexistent due to over-exploitation. Observations and measurements in Dong Cao catchment 47.9 ha Vietnam, started under farming and continued after abandonment: 20 years of uninterrupted monitoring of soil, water, land use and vegetation were integrated in this study.

Objective

Our aim is to identify the specific combination of soil features and agricultural practices that are responsible for fast, slow or blocked succession. We differentiate between the recovery of forest structure, relatively easy, and recovery of the original species composition, more difficult.

Methods

Multivariate analysis of vegetation data produced plant communities in a gradient of complexity. Using classic statistics, we sought relationships between environmental variables, land use and vegetation.

Results

Forest recovery failed the first 10 years, then part of the catchment developed forest. Land use explained best the distribution of plant communities over the catchment, slope and soil features were less related. Cassava cropping seriously slowed down the succession to closed forest. During abandonment soil carbon stocks (0–15 cm depth) increased with about 3% per year.

Conclusion

Starting from weedy thickets (2002) we distinguished two successional pathways: a positive pathway towards increased resemblance with the original Lowland forest via broken forest to closed deciduous to closed evergreen forest; a negative pathway away from the original forest species composition to degraded shrub land and low grass. Livestock was related to the negative pathway.

Introduction

Farmland on steep slopes is unsuitable for most forms of mechanisation, has poor access and often shallow soils. Worldwide, agriculture tends to intensify on the more fertile soils, while abandonment of farming is more common in areas with poor soils, on high altitudes, and steep slopes (Chazdon 2003; Vu Kim Chi et al. 2013; Queiroz et al. 2014). In tropical Asia, landform is a decisive factor regarding abandonment of farmland. A clear differentiation is made between farming under hydromorphic conditions in *lowlands* (paddy rice) and farming under rain-fed conditions in *uplands*. In the rather flat plains of the *lowlands* the modernisation of agriculture takes place with its possibility of irrigation and easy transport. Farmland in the *lowlands*, even on marginal soils, is never abandoned because such sites compete with infrastructure, urbanisation and industry. The *uplands* on the contrary, often hilly with poor access make all work extremely time-consuming. Hence, the abandon of farmland in South-east Asia concerns the *uplands* exclusively. Farmland is also abandoned because inappropriate use had produced excessive erosion making traditional farming no longer worthwhile (Thai Phien et al. 1998). Besides, the steady outmigration of young rural people to the cities, does not leave enough population to sustain the cultivation of the slopes. Most often, abandoned farmland is simply colonised by spontaneous regrowth (Arroyo-Rodriquez et al. 2017) or converted to fodder/livestock exploitation (Valentin et al. 2008). In general, land abandonment is considered as an important part of land degradation process (ipbes 2018). Agriculture in South-east Asia is unique for its high number of smallholders and their practice of poly-culture, often involving crop-livestock relations. These farmers subsist on paddy rice grown in *lowlands* and produce a surplus using the *uplands* thus providing the urban population with food and the industries with raw materials e.g. pulpwood, rubber, sugar.

Where the natural vegetation is forest, the land no longer cultivated will eventually revert to forest through secondary succession. Abandoned agricultural land is under no management regime; in contrast, fallows are not abandoned land. Crop-fallow systems aim to re-use the land once the development of the post-harvest vegetation has sufficiently restored the soil and suppressed the weeds. Yet abandoned land and fallows alike could contribute to ecological improvement through carbon storage, biodiversity conservation (Dwyer et al. 2009) and better soil-water relationships (Valentin et al. 2008). In crop-fallow systems fast fallow development is stimulated through specific farming practices (de Rouw 1995) and at the same time these farmers recognize that a succession blocked in an early stage is likely to compromise the productivity of the land, making it useless. While there are agricultural practices that stimulate forest succession leading to the re-use of the land, so there should be practices that slow down succession, leading to abandonment (this study).

Recovery of forest structure, soil nutrient stocks and species richness is far more rapid than recovery of the original species composition (Chazdon 2003), which can take centuries to come back (Rozendaal et al. 2019). Hence true succession is not limited to increase in biomass and species turnover but is the improvement in plant diversity towards the original forest. This makes species composition the key tool to measure true succession (this study). The diversity of the original forest is contained in the standing biomass, the soil seed bank and the bank of vegetative regeneration i.e. stumps, rootstocks, buds or other organs (resprouter bank). Seed bank and resprouter bank are then “residuals” of the original forest in case the standing biomass suffers. Residuals assure the rapid and complete return of the original forest if enough time is allowed. When residuals are destroyed together with the above-ground biomass, then the ready and complete return of the initial species richness is compromised or may be impossible. Agriculture, forestry and husbandry practiced on land originally covered by forest, cause not only the disappearance of the above-ground forest biomass, but affect the forest residuals, too. This relationship seems evident but is sustained by very few field observations. In South-east Asia many hotspots of biodiversity can be found, most of them under direct threat of disappearance. In order to preserve this diversity, it is important to study how the original forest composition comes back or does not come back as a result of specific land use practices. To our knowledge there are no studies that determine by field observations the direct links between cultivation practices, forest residuals, and forest succession.

Large scale and intense disturbance can produce a slow succession or no succession at all (Arroyo-Rodriquez et al. 2017). Scientists, mainly ecologists, are then looking for the dominant factors that shape succession with the aim of predicting the successional pathways (Bellemare et al. 2002; Chazdon 2003; Benjamin et al. 2005; Queiroz et al. 2014; Rozendaal et al. 2019). Most often the factor *land use* before abandonment, is described in very general terms, i.e. logging, cultivation, grazing. The authors agree with the all importance of land use on succession yet state that it is difficult to study because, commonly, an overlay of different land uses occurs. It is then impossible to identify the particular vegetation response to a sequence of human interventions (Chazdon 2003). This approach assumes that about every combination of land use will produce its proper successional stage or pathway; it suggests that the number of possible stages or pathways is endless or high. We question this argument. Our approach is to work the other way round: to survey plots with similar vegetation and then reconstruct for each plot the history of management. We suspect that an accumulation of severe, or complex or frequent disturbance produces a miserable regeneration which is represented by few successional vegetation types. In the opposite situation, following a single event, the number of successional vegetation types will be higher and more varied.

The object of this study is to describe the succession process in a tropical catchment where annual cropping stopped about 20 years ago. Our aim is to identify the specific practices responsible for the blocked, slow or fast succession using detailed records of historical land use, complete floristic inventories, and spatial context. In contrast to most studies that use synchronous data sets, i.e. comparing plots of different ages representing a chronosequence, this study investigates diachronic data sets, i.e. the same site was observed and monitored over a long period, in our case starting before the abandon of farmland.

Methods

Study area

Dong Cao is a cultivated catchment (20°57'N, 105°29'E) of 49.7 ha, located 60 km south of Hanoi in Hoa Binh Province, Vietnam. Farmers, all smallholders, share their work time between the *lowlands* where they cultivate paddy rice for subsistence, and the *uplands* where they cultivate a variety of crops to increase their revenue in association with some husbandry, buffalo, cattle and pigs. This system, coined “Composite farming” (Ziegler et al. 2007) is widespread and well-described (Nguyen Van De et al. 2008; Nguyen Van Dung et al. 2008; Affholder et al. 2010; Vu Kim Chi et al. 2013; Van Trinh Mai et al. 2013; Slaets et al. 2016). Farming in the uplands of Dong Cao was progressively abandoned from 1995 onwards and stopped completely in 2002, leaving the spontaneous vegetation to invade.

Dong Cao catchment is part of a regional network of Critical-zone Observatories (formally MSEC, https://mtropics.obs-mip.fr/). MSEC started in Dong Cao in 1999. The catchment comprises only uplands, ranging from 125 m to 480 m above sea level. The average annual rainfall recorded at the site is highly variable, approximately 1600 mm yr^{-1}, minimum 1048, maximum 2506 mm, of which 80% is concentrated in the rainy season from April to November. The annual potential evapo-transpiration reaches around 960 mm yr^{-1}, hence the air humidity is always high, between 75% and 100% (Meteorological Station in Hoa Binh, cited in Renaud 2003). The mean daily temperature varies from 15°C to 25°C. In winter, cold and humid air masses come in from the north causing minimum temperatures to fall down to 5°C, whereas in summer maximum temperatures over 40°C occur. The average slope angle is 45%, locally exceeding 100% up to a maximum of 120%. The soils are derived from the weathering of volcano-sedimentary schists of Mesozoic age, and are generally over 1 m deep (W.R.B. 1998). Over 90% of soils are Acrisols developed *in situ* or in colluvium, other soils are Leptosols and Cambisols (soil map and slope map 1:5 000 in Online Resource 1). All soils are well-structured due to their relative high clay content over 40% (Podwojewski et al. 2008). The abundance of earthworm and other macro-faunal populations is responsible the stability of aggregates and the remarkable porosity all over the profile (Jouquet et al. 2008).

The original vegetation was Lowland semi-evergreen broadleaf monsoon forest after Whitemore (1988). This formation has a majority of evergreen trees in the canopy, no incidence of fire, and no occurrences of spontaneous bamboo. Considering the local climate with its persistent high air humidity measured at the site, the proportion of evergreen tree species in the original forest should have been much higher.

Land use

Sequence

Historic land use of the period before the start of MSEC in 1999 was obtained from interviews with the inhabitants of Dong Cao. The correctness of their information was confirmed by independent sources (Wezel et al. 2002; Clement and Amezaga 2009). After 1999, MSEC scientists and students supplied an uninterrupted record of farmer's activities in the catchment. The timeline of major events in Dong Cao catchment is presented in Table 1, with details in Table 2.

After the export of timber, the exploitation of the uplands started with burning, piling and re-burning of what was left of the original forest, to gain space and access. For about twenty years the slopes were regularly cultivated with a variety of crops, the fertile sites and lower slopes more frequently than the steep, remote land. In 1986 the government allocated land to individual farmers, as a result cassava cropping took off, responding to the development of pig raising in the region. The demand for pig food was such that for about 15 years the catchment produced nothing else: cassava, modern varieties of maize and arrowroot, all served as pig food. The last fields (cassava) were abandoned in 2002.The opportunities for husbandry accelerated the abandon of farming because the eroded soil produced less than before.

Cassava was cultivated throughout Northern Vietnam, often on very steep slopes, causing flooding and massive erosion with sediment deposits in lowland paddy fields. Subsequently, a national policy of soil conservation measures was applied in the region. For Dong Cao this meant: subsidized tree planting and work on the contour: ditches, and line-planting of bamboo, Vetiver grass and *Vernicia* saplings. The initial plan to reforest the catchment by 80% was not realised. Successful afforestation was limited to weed-free sites, for instance when trees were planted immediately after the last cassava harvest. Planting trees in weedy fields several years after the last harvest, failed. Trees received no or little maintenance after planting and spacing was wide.

Mapping

To verify whether agriculture had an effect on forest succession, details of land use have to be spatial explicit. In our case remote sensing images proved of little use. Firstly, images taken before the abandonment of farming showed insufficient resolution, secondly, the high resolution images of later date suffered from artifacts. For instance, Google Earth images (2014 and later) suggested dense forest on steep slopes which was not the case, and faint, parallel lines appearing in many parts of the catchment suggested the canopies of line-planted trees, or soil conservation work on the contour (ditches, tree planting). Inspection in the field revealed that those parallel lines had no consistent meaning and most of times it was not clear what “produced” the lines. Instead, 161 photographs with panoramic views of the catchment were used, taken by MSEC scientists working in Dong Cao (Fig. 1). Photographs with field checks showed important features: (*i*) not a single tree of the original forest had been spared, (*ii*) the extent and intensity of cassava cropping, (*iii*) areas with successful and failed afforestation, *(iv*) details on species and spacing of the planted trees, (*v*) preferred areas for grazing, passing, resting of the free-roaming livestock. These spatial explicit data could be mapped (see land use map in Online Resource 2).

Land use was associated with topography and landform. In Dong Cao the left and right banks of streams and gullies are not symmetric; right banks have long and moderate slopes, left banks short and steep slopes. Almost all annual crops were grown on the right banks. Bulky products like poles of *Eucalyptus* and wood of *Acacia*, were produced at lower altitudes close to the outlet for easy evacuation, both on left and right bank.

Vegetation surveys

During surveys the catchment was crossed on foot in all major directions. A total of 33 reference samples (relevés) were made following the Braun-Blanquet method (Braun-Blanquet 1964): five in 2002, six in 2004, two in 2010, two in 2011, ten in 2016, and eight in 2017. A sample plot was carefully selected for being representative of a larger area. Plot size was kept small (18m²) to better assure the links between species composition and habitat. Canopy trees not rooted in the plot were included in the species list. A reference sample consisted of a full species list with abundance for each species and additional information on GPS location, slope, land use, soil profile, soil surface features, and soil fauna. All growth forms were taken into account and all age classes. Resprouter status was checked for all woody plants in the plot. The reference samples were used to produce a classification of vegetation types. In addition, many plotless inventories were made of common species and vegetation structure which later assisted in mapping the vegetation types in the catchment. Dried voucher specimens were made of unidentified species occurring in the plots and these were checked in official herbaria (Chiang Mai University, Thailand; Naturalis, the Netherlands). Processing of the floristic data yielded six vegetation types (Communities) and a set of diagnostic species for each Community. The mapping of the communities in Dong Cao catchment was carried out with the help of a key (below).

Key to Communities in 2019 (Community 4 no longer present).

1	The vegetation has no trees, only low grass and shrubs	Community 6
1*	The vegetation has trees	to 2
2	The vegetation has a closed canopy	to 3
2*	The vegetation has a broken canopy	to 4
3	The canopy is composed of wild trees, most are evergreen	Community 1
3*	The canopy is composed wild or planted trees, most are deciduous	Community 2
4	The vegetation consists of patches of forest and shrubs	Community 3
4*	The vegetation consists of patches of herbs and shrubs	Community 5

In 2018 and 2019, frequent returns to the field were made to finalize the mapping of the Communities. The group of indicator (diagnostic) species assisted in the identification of vegetation types in the field. The catchment was crossed on foot with a hand-held GPS to mark off the Community areas, and checks were made in 160 points.

Soil sampling

In 2003 soil samples were collected in 109 sites following 4 transects across the catchment, covering early and late abandoned fields, young tree plantations of *Acacia* and *Vernicia* and adult *Eucalyptus*. Samples were collected in two layers, 0–5 cm and 5–15 cm depth. Local slope and GPS location were also recorded. Bulk densities were determined in three replicates every third site by collecting undisturbed 0–5 cm depth cores with a 100 cm^3 cylinder. These samples were oven-dried until stable weight. All other soil samples were air-dried, sieved to 2 mm to remove debris and stones and grounded to very fine powder using a hand mortar. Determination of total organic carbon was carried out at iEES-Paris by EA-IRMSe by CHN following Huon et al. (2013). In 2016 soil samples were collected in a 50*50 m grid covering the entire catchment. A total of 195 sites were sampled. Soils were sampled in a single layer, 0–15 cm depth and the bulk densities were determined by collecting undisturbed cores with a 100 cm^3 cylinder. At each sample site we recorded the local slope, the number of dung deposits in a radius of 10 m, and the GPS location. Soils were air-dried and sieved to 2 mm to remove debris and stones. Total organic carbon was determined following the method of Walkley and Black. In carbonated soils the Walkley and Black method underestimates soil carbon, but as these soils do not occur in Dong Cao, both analyses can be compared.

Data analysis

Vegetation

To summarize the plant data we applied multivariate ordination in which similar species and samples appear close together and dissimilar entities far apart (Gauch 1986). The floristic data were drawn up in a two-way sample-by-species data matrix. The samples (relevés) were displayed in columns and the species in rows. Species scores were expressed as cover: 1 = < 1%, 2 = 1–5%, 3 = 5–25%, 4 = 25–50%, 5 = 50–75%, 6 = > 75%. The table arrangement was obtained from ordination (TWINSPAN) followed by refinement by hand. Species recorded both in high and low but not in medium densities, were split into pseudo-species, one corresponding to high cover (> 50%), the other to low cover (< 5%). This procedure is common in automated table arrangement and is needed to check whether the ecological role of the species in the vegetation is different in high and low abundance. Pseudo-species concerned four species: *Bidens pilosa*, *Stachytarpheta jamaicensis*, *Panicum amoenum*, and *Paspalum conjugatum*. The table arrangement yielded a classification of samples into vegetation types (communities) and species into species groups, including the indicator species for communities.

We used ranked reciprocal averaging (DECORNA) to identify a gradual shift of large groups of species along gradients. The programme calculates scores according to four axes, both for species and for samples, the latter being weighted mean species scores. We used only the first axis (eigenvalue 0.71) to explore whether the shift in species abundance calculated by ordination corresponded to a pattern in other data sets.

To describe the vegetation (Kent and Coker 1992) we used Richness, being the total number of species found, and Species/area curves, being species accumulation with increasing sample area. Such curves allow to compare the species richness of communities with each other and to estimate how much of the total richness of a community was actually captured by the (limited number of) samples of that community. Using the relative abundance data for each species in a sample plot we computed Dominance/diversity curves. Species scores are then ranked in ascending order of abundance and plotted on a $\log_{10}$ scale against the species cover. In order to compare communities with each other, the relative abundance was averaged over all the samples belonging to that community. Such curves show difference in evenness and dominance among communities.

The sample-by-species matrix contains no environmental or land use data, hence a vegetation map with plant communities shows purely variations in species composition. In a separate step we compared floristic data with other data. The vegetation map was digitalized and linked through a Geographical Information System to other thematic maps of the catchment: slope angle, soil type, land use trajectory, soil conservation measures, tree plantations, and soil carbon stock.

Soil

For each sample site we calculated the carbon stocks in the top 15 cm of the soil:

(kg C m^{-2}) = TOC concentration (gC kg^{-1}) x bulk density (kg m^{-3}) x depth (m).

We calculated the porosity of the top 5 cm of the soil:

P (%) = [1-(bulk density (g cm^{-3}) / 2.65 (g cm^{-3}))] x 100.

For discriminating the difference in soil carbon between plots of different land use, soil types and plant community, we applied the Student test (comparison of means of two independent samples of unequal size).

To investigate changes in soil variables over 13 years we tried to match the sample locations of 2003 (n = 109) with the grid locations of 2016 (n = 195), using the geo-locations of the sample sites. Matching sample sites succeeded in 59 locations. Matching greatly improved the quality of the soil data. For comparing carbon stocks and bulk densities in 2003 with 2016 the paired *t*-test was used. For discriminating the difference in soil carbon between plots of different land use and between plots covered by different plant communities, we applied the Student test (comparison of means of two independent samples of unequal size).

To test the effect of the environmental variables (soil carbon, local slope, soil porosity and abundance of dung deposits) on forest succession we applied the Kruskal-Wallis test using the 195 grid points. This test detects differences of location in ranked data grouped by a single classification. In the tests the groups were the plant communities and the test was run four times, each time with a new classification corresponding to the four variables: carbon, slope, porosity and dung deposits.

Results

Vegetation classification

The floristic analysis by table arrangement is a search for typical combinations among the common species. The clustering of species (rows) and samples (columns) resulted in six communities (see Appendix for full table and Fig. 2 for summary). A community is characterised by a distinctive species assemblage. For instance, Community 1 (Fig. 2, above left) should have species, not necessarily all, of group 1 and 2, and at the same time the species of the groups 3 through 10 should be absent. For Community 1 the species group 1 is diagnostic, in the same way the species group 3 is typical for Community 2, and so on. See Online Resource 3 for species groups with details on growth form and ecology.

The order of samples (columns left-right) follows the most important ecological gradient in the data set. In Fig. 2 this is a successional gradient with most advanced communities on the left and least advanced on the right. Likewise, the same gradient is expressed by the order of species groups (rows top-down). Because the reference plots were sampled between 2002 and 2017 one would expect that the successional gradient equals a time-gradient with samples collected at the beginning of the abandonment (2002) on one side, and samples collected 16 years later, on the opposite side. This is not the case. The oldest samples are found somewhat in the middle, forming the Community 4, being the initial old-field vegetation of weeds and thickets. Community 4 covered the catchment for about ten years, afterwards three communities replaced it: Community 3, broken forest, Community 5, tall shrubs and grass, and Community 6, low grass. Fifteen years after abandonment, selected areas of broken forest turned into closed forest, either Community 2, mesic forest with a canopy of deciduous species, or Community 1, moist forest with a canopy of evergreen species. In contrast, no significant development could be seen over the years in the Communities 5, tall shrubs and grass, and 6, low grass. Thus from a single vegetation type in 2002 five distinct vegetation types were identified in 2017. All species identified in Dong Cao with authorities, species groups, growth form and DECORANA axis scores are in Online Resource 4. The axis scores for individual species indicate their position in the successional gradient with high scores for advanced succession and low scores for least advanced vegetation.

The vegetation map (Fig. 3) shows the distribution of the five communities over the catchment in 2019: 77% of the catchment (38 ha) is engaged in forest succession, 23% (11 ha) remains open shrubby grassland. The topographic background of the map indicates more forest development at higher altitudes. On moderate slopes, i.e. right banks of streams, all five communities can be found, but on very steep slopes, left banks of streams, only two, the Communities 3, broken forest, and 5, tall shrubs and grass. The almost flat land on the southern crest is exclusively covered by Community 6, low grass.

Description of the Communities

Community details, i.e. species/area curves, dominance/diversity curves and richness are in Online Resource 5.

Community 1 — closed moist forest with evergreen canopy trees *(1 ha, 2%)*

The community is closed forest with three layers, most species are evergreen. The upper and middle layers together form a continuous canopy, leaving the ground layer in permanent deep shade. The upper layer is approximately 15 m high, the middle layer 8 m and the ground layer 0.4 m. Old trees are absent, maximum tree height is 20 m, maximum diameter of trunks 28 cm (measured at 1.6 m height). The middle layer consists of young trees, palms, wild bananas, vines and woody climbers; the ground layer of herbs, particularly ground ferns and dicots, besides seedlings of trees and shrubs. Some of the original Lowland moist forest species had returned to the site, mostly in the ground layer. Local people removed some wood for fuel, wild banana flowers for food, and medicinal plants without opening the canopy. The community is easily identified by some conspicuous plants like *Begonia* and *Wallichia siamensis*, a fish-tail palm. The average richness per plot (18m²) is 26 species.

Community 2 — closed mesic forest with deciduous canopy trees *(12 ha, 24%)*

The community is closed forest with three layers. The community comprises old trees of *Acacia mangium* and *Vernicia montana*, most of them planted between 1995 and 1999, both are deciduous species. In the canopy these planted trees are progressively replaced by spontaneous trees, equally deciduous. Maximum height of *Acacia*, *Vernicia* and wild trees is 24 m, 14 m and 8 m, respectively. The middle layer varies between 1 and 4 m, and the ground layer is commonly less than 0.5 m high. The middle layer is often a dense mass of shrubs, climbers and treelets. The ground layer consists of forest herbs, including ferns, and tree seedlings. The average richness per plot is 22 species.

Community 3 — broken forest *(26 ha, 52%)*

The community is a mosaic of forest and shrubs. The forest-patch and the shrub-patch do not have species in common. The forest patches are two or three layered and very variables in height, 4–20 m. The ground layer, mostly herbaceous, is about 0.5 m high. A middle layer, when present, consists of woody species and climbing ferns, 3–9 m high. The shrub-patches, 0.5–1.5 m high, are one-layered. Broken forest is dominated by species of a drier environment compared to the closed forest. The species richness in plots averages 20 species.

Community 4 — weedy fields and thickets

The community is a single continuous ground layer, 1–2 m high. The dense layer is a mix of tall grasses, many of them with C_4 pathway, and weeds, many of them Asteraceae. The community developed after each weeding and fully established post-harvest. Many species are annuals with *Bidens pilosa* dominating every plot. The community occupied the catchment after the abandonment of cropping. The species richness in plots averages 17 species.

Community 5 — tall herbs and shrubs(6 ha, 12%)

The community forms an herbaceous layer about 1.5 m high with isolated shrubs or shrub-like trees up to 6 m high, mostly *Mallotus* species. A characteristic feature is the strong dominance, over 75% of cover, by a single species. The dominant species could be *Bidens* or *Stachytarpheta*, or one of the tall perennial C_4 pathway grasses, *Imperata*, *Panicum*, or *Brachiaria*. The species richness in plots averages 10 species.

Community 6 — low grassland(5 ha, 10%)

The community consists of *Paspalum conjugatum*, a creeping perennial C_4 pathway grass forming loose monospecific mats over extended areas. It grows 5 cm high when not flowering. Grass alternates with the low shrub *Stachytarpheta jamaicensis*, growing up to 0.6 m. Mixed with the shrub, a few other C_4 pathway grasses can be found in low densities. This is a much degraded grassland and extremely species-poor vegetation of only 5 species.

Land use (1975–2019)

For each one of the 33 reference samples (red symbols in Fig. 3) we calculated how many years had been spent in a particular land use. We used the following broad classification: Cultivation (**C**), Tree planting (**T**), Grazing (**G**) and No intervention (**Ab**). Some categories include sub-categories: under “Cultivation” we distinguish between intermittent cultivation of annual crops with short fallow periods (**C-F**), and continuous cropping of cassava (**Cas**), and Ruzi fodder grass planting (**Ru**); under “Tree planting” there is successful (**T**) and failed tree planting (**T-Ab**); Grazing has three levels, heavy grazing (**HeG**), medium intensive grazing (**MeG**) and light grazing in either successful tree plantation (**LiG T**) or failed ones (**LiG T-Ab**). The abbreviations are used in Fig. 4. Some combinations did not occur in Dong Cao, for instance continuous cropping by crops other than cassava and medium grazing in tree plantations. Land uses per sample were chronically ordered and samples covered by the same plant community were clustered, thus associations between historic land use and vegetation recovery become visible (Fig. 4).

Intermittent cultivation over a period of about 20 years was the common history throughout the study area. Sites actually under Community 1, closed evergreen forest, were subsequently abandoned; they have no history of tree planting, grazing or cassava. Community 2, closed deciduous forest, is found on sites where *Acacia* and *Vernicia* trees were planted; here too, no history of continuous cultivation of cassava or grazing. Sites with broken forest, Community 3, experienced extra disturbance after the period of intermittent cultivation, e.g. continuous cassava and light grazing by cattle and buffalos. It is noteworthy that very different actions lead to the same result: broken forest with Community 3. This also accounts for Community 4. Sites covered by tall herbs and shrubs, Community 5, have experienced still more disturbance after the period of intermittent cultivation, i.e. prolonged period of cassava, fodder production, grazing, all produced the same treeless vegetation. The Community 6 is directly linked to livestock. Heavy grazing, probably starting in 1993 (interview data) is the continuous practice. This species-poor grassland had remained unchanged since our first visit to the site in 2000.

Soil carbon

When farmland was abandoned, the soil carbon stocks in the topsoil averaged 34.3 tC ha^{-1} (sdv 5.13, n = 109, 0–15 cm depth). Stocks were unrelated (NS) to soil type, soil depth, and former land use, although there were trends. Late abandoned cassava fields were on average best provided with carbon (37.3 tC ha^{-1}) suggesting that the best soils were latest abandoned. *Eucalyptus* sites had lowest carbon levels (27.0 tC ha^{-1}). Early abandoned plots invaded by weeds (35.4 tC ha^{-1}) and plots planted with *Acacia* trees (34.3 tC ha^{-1}), had similar carbon stocks.

Soil carbon stocks were determined in 2003 (n = 109) and 2016 (n = 195). In 59 sites the locations matched, allowing the calculating of carbon change over 13 years. Figure 5 gives the carbon stocks in the matching locations, showing a positive linear relationship with elevation for both years. These trends can be explained by lower topographic positions being more frequently cultivated and had suffered more soil losses than higher positions. Carbon stocks in the top 15 cm of the soil had increased on average from 34.4 tC ha^{-1} (sdv 8.31, n = 59) to 48.6 tC ha^{-1} (sdv 7.75, n = 59). Over 13 years the average carbon sequestration was thus 14.2 tC ha^{-1}, an increase of 1.09 tC ha^{-1} year^{-1}, a rate of just over 3% per year. A maximum of 2.60 tC ha^{-1} year^{-1} accumulation was recorded and a minimum change of 0.25 tC ha^{-1} year^{-1} loss. The amount of carbon accumulated was unrelated (NS) to previous land use, but again there were trends. Maximum sequestration occurred under spontaneous vegetation without tree planting, more in cases of early abandonment, average 16.9 tC ha^{-1} (n = 25, rate 1.30 tC ha^{-1} year^{-1}) than late abandonment, 14.6 tC ha^{-1} (n = 13, rate 1.12 tC ha^{-1} year^{-1}). Minimum accumulation was measured under tree plantations, more under *Acacia*, 12.8 tC ha^{-1} (n = 10, rate 0.98 tC ha^{-1} $year^{-1}$) than under *Eucalyptus* - *Irvingia* 11.3 tC ha^{-1} (n = 11, rate 0.87 tC ha^{-1} $year^{-1}$). Over the same period the average bulk density increased from 0.95 to 1.02 which equals a loss in soil porosity from 64–61% The change in soil compaction was slight but very significant (t_{59} ***$P < 0.001$).

Mean soil carbon stocks, soil porosity, and slope angle were very significantly different across communities (*** $P < 0.005$, n = 195, Table 3). Following the complexity gradient, carbon levels were found lowest in Closed evergreen forest (41.9 tC ha^{-1}, Community 1) and highest in Low grassland (56.4 tC ha^{-1}, Community 6). Soil porosity was highest in Closed evergreen forest and lowest in Low grassland. Steepness of the terrain averaged 80% in Closed evergreen forest and declined to only 32% in Low grassland. The gradient in soil carbon followed the gradient of dung deposits which followed the complexity gradient of the communities ($0.10 < P < 0.05$ near-significant). The negative impact of livestock on forest succession which was already visible across Communities because it reduced species diversity, is now confirmed by independent environmental data: cattle and buffalos while avoiding the steepest slopes, reduce soil porosity by their trampling and enrich the soil with carbon with their dung.

Discussion

Successional pathways

In Dong Cao the succession back to forest was slow and fragmentary. For about 10 years the slopes were uniformly covered by a thick herbaceous layer with forbs and low shrubs. Our study confirms the observations of Chazdon (2003) that following the abandonment of agricultural land on poor soil with no residual vegetation left and no local sources of seed dispersal available, forest recovery fails to initiate within 5–10 years. In 2019 closed forest covered 25% of the catchment, 52% was broken forest, and the remaining 23% carried no trees or only isolated trees. Successful recovery of the forest structure took place on 25% of the catchment surface but biodiversity recovery, the return of some of the original species of moist lowland forest, had occurred in only 2% of the catchment. The remaining forest contained species of drier environments, for instance deciduous species in the canopy instead of evergreen. Open vegetation was composed of species of broad ecological valance, adapted to a wide range of habitat conditions including still drier environments. Hence, associated with the successional gradient there is a moisture gradient, with sites that have most advanced since the abandon of farming being wettest, less advanced sites are occupied with mesic forest, and least advanced or not advanced at all, are driest (Nikolic et al. 2008, this study). We observed two successional pathways on abandoned farmland. First, positive pathway, called succession, being a progressive resemblance towards the original forest species composition. But vegetation development can go “the wrong way”, a negative path of decreasing similarities with the original forest, called degradation. Instead of progressive colonization by the forest species of more and more humid habitats, sites are occupied by species of drier and disturbed environments.

The following trends were observed associated with the positive pathway: increase in species number, increase in growth forms, increase in woody cover and height, gradual development to a three-layered closed forest, increase in evergreen species, increase of species of moist habitats and shady places, and the gradual replacement of heliophyle grasses by shade grasses. Ferns were precious indicators of changes in the successional process. The negative pathway was associated with: decrease in growth forms, decrease in height, decrease to extinction of woody cover, appearance of C_4 pathway grasses gaining dominance and replacing the C_3 pathway heliophyle grasses, decrease to extinction of all trees, shrubs, lianas of humid and moist forest and establishment of trees, shrubs, lianas of drier and disturbed environments. The impact of cattle and buffaloes was absent to slight in closed forest, slight to medium in broken forest and medium to strong in open vegetation. The spread of the degraded vegetation matches the pattern of preferential grazing along gentler slopes, while the flattest sites were the longest exploited and the deepest degraded.

Livestock

In Dong Cao, forest development was negatively associated with livestock: the less impact of cattle and buffalo the more rapid the positive succession to moist evergreen forest took place. But past a certain threshold of passing, resting, grazing, trampling, a negative development sets in to seriously degraded grassland. The practice of free-roaming livestock was found to (*i*) slow down succession (Burgers et al. 2005; Fukushima et al. 2008; Wangpakattanawong et al. 2010, this study), (*ii*) decrease the forest-biodiversity (Burgers et al. 2005; Nikolic et al. 2008, this study), and to (*iii*) deviate the process from forest succession to degradation (Nikolic et al. 2008, this study).

The negative path was due to buffalos in Nikolic et al. (2008), northern Vietnam and buffalos and cattle in Dong Cao. In Nikolic et al. (2008) the degradation was worse than in Dong Cao because it led to stable woodland, a kind of dry savannah, very different from the climax “Lower montane rainforest with bamboo”. The human impact on vegetation was greater, too: (*i*) the hill slopes were deforested in the 1960s, about 15 years earlier than in Dong Cao; (*ii*) livestock populations were higher; (*iii*) the farmers over-cultivated the land even more than the farmers of Dong Cao did; and (*iv*) there was no incidence of tree planting. These practices led to a more pronounced degradation and xerophytization of the environment compared to Dong Cao, as can be judged from both species lists. Thereby the climate is cooler with a more pronounced dry season, making it more difficult for lower montane species to establish. In Dong Cao the same process of degradation is less advanced, due to the continuous high humidity, higher average temperatures, lower livestock densities, some planting of trees and, most importantly the cessation of annual cropping for almost 20 years. Farmland in Nikolic et al. (2008) study site was not abandoned but *de facto* has become unsuitable for annual crops. Farmers state that all sites require a long period of rest during which the spontaneous vegetation develops before they can be cultivated again: an estimated 30 years for herbaceous covers resembling our open bush and low grass land (our Community 4), an estimated 20 years for bushy vegetation with sparse wood (our Community 5), and about 10 years for woody shrub land (similar to Community 3).

Did tree planting accelerate the forest succession?

Tree plantations catalyzed the process of forest succession only where a ground cover developed, thus preventing erosion and increasing soil fertility. Under *Eucalyptus* the soil remains bare and when abandoned and the stumps removed, a stable, species-poor community installs of tall herbs, shrubs and an isolated tree, resisting the colonization of trees. The other tree species naturally develop ground cover. When planted in medium densities and a regular pattern, i.e. *Acacia mangium, Vernicia montana* and *Irvingia malayana*, grassy patches are avoided and a closed canopy develops. Little by little native trees join the canopy and replace the planted trees. However, when planted in a wide grid or in irregular patterns, i.e. *Styrax tonkinensis*, *Canarium tramdenum*, and *Chukrasia tabularis*, open spaces are invaded by herbaceous covers. These patches attract livestock, feeding on the herbs and appreciating the shade from the trees. In Dong Cao the observation is that tree planting, even in cases of poor establishment, prevented the massive invasion of C_4 grasses, the development of livestock and hence the negative successional pathway.

Plant diversity

Species of disturbed environments, weeds, forbs, pioneer trees, are widely dispersed, hence the same diagnostic species identified in this study, indicate the same environment elsewhere, for instance the communities of early successional stages in Dong Cao, matched those found elsewhere in Vietnam (see species lists in Ziegler et al. 2004; Nikolic et al. 2008). In contrast, the communities of advanced successional stages, like Community 1 in this study, and the old-growth forest types described by Ziegler et al. (2004) and Nikolic et al. (2008), are all different from each other. Zieglers' site was slightly drier than Dong Cao and Nikolics' site was located at an higher altitude (700 m). As forest succession advances exclusive species belonging to the local climax tend to establish. In the three sites the soil/climate conditions were different, so the species composition of their respective advanced secondary forest was different, too. This illustrates the very high plant diversity in South-east Asia.

Plant diversity does not always increase when farmland is abandoned, for Asia Queiroz et al. (2014) found in 60% of case studies a drop in species richness following abandonment. This could be a question of sampling technique. Few studies include plants of all ages and growth forms (this study), most account only for dominant species, or ignore species with low cover, low height, or life forms other than trees. This greatly limits the recorded richness. In Dong Cao, species richness after abandonment of farming always increased. Community richness in fields and recently abandoned fields was estimated about 40 species. When this vegetation remains open with herbs, shrubs and some isolated trees, the total richness increased to about 60 species. In case a forest with a discontinuous canopy develops, the community richness increased to about 70 species. Though species richness increased, the conservation value of all these very common species is very low. In Dong Cao, only closed forest produced some conservation recovery in the occurrence of the species groups 1 and 2 (Community 1).

Soil carbon sequestration

In good structured clay soils carbon sequestration is high (Bottinelli et al. 2021) and more carbon accumulates in uncultivated soils than in cultivated land (Feller and Beare 1998, this study). After abandonment soil carbon accumulation in Dong Cao was high, an average rate of 1.09 tC ha^{-1} $year^{-1}$ in the top 15 cm soil measured over a thirteen-year interval. Minasny et al. (2017) reports case studies of carbon sequestration in soils after adoption of the best management practices available. Ignoring peat soils, Minasny et al. (2017) reports annual sequestration rates between 0.2 and 0.5 tC ha^{-1} $year^{-1}$ in permanently cultivated tropical uplands. A change from cropland to grassland increased the rates to 0.3–0.6 tC ha^{-1} $year^{-1}$, and tree plantations under favourable management had sequestration rates of 0.26–0.57 tC ha^{-1} $year^{-1}$ (cases from Nigeria, USA, Taiwan, Indonesia). All sequestration rates were well below those measured in Dong Cao. Only one case was found, a forestry site in Sulawesi, Indonesia (Dechert et al. 2004), with a sequestration rate of 1.12 tC ha^{-1} $year^{-1}$, similar to Dong Cao. Sulawesi and Dong Cao have in common the favourable conditions for storage: clay content > 40%, bulk densities close to 0.95 (g m^{-3}), and an initial carbon stock of 45–47 tC ha^{-1}. Thus abandoned farmland undergoing spontaneous forest regeneration accumulates under favourable soil and climate conditions far more carbon in the soil than cultivated fields, even those under the best practices available.

We expect a maximum of carbon stocks under forest and a minimum under low grass for the soil carbon would follow the successional gradient of vegetation complexity and biomass accumulation. Our data, very significantly, indicated the opposite: 56.4 tC ha^{-1} under low grassland and 41.9 tC ha^{-1} under moist closed forest. Increasing carbon stocks in the topsoil matched increasing livestock activity. Livestock prefers gentle slopes where their dung accumulates. The result is a concentration of livestock in the most degraded vegetation where the dung is incorporated in the soil assisted by an abundant macrofauna. Currently, the livestock impact dominates the influence of forest succession, i.e. the constant high dung supply in the most degraded vegetation overrules the effect of the far greater standing biomass and the greater plant diversity in the closed forest plots, where, without livestock, soil carbon stocks should be maximum.

Land use

Plots with identical climate/soil conditions can carry very different vegetation types, although the number of years since farming stopped was the same. Historic land use before the abandonment of farmland as logging, erosion, unsustainable agricultural practices, and fires along with uncontrolled grazing are increasingly recognized as the determinant factors in secondary succession (Chazdon 2003; Nikolic et al. 2008; Arroyo-Rodriquez et al. 2017).

The Graphic Abstract (Fig. 6) illustrates the common pattern of human interventions in mountainous South-east Asia. It starts with the destruction of the initial forest and leads to abandonment. Forest has to be cleared for access and any form of production. Burning is the only option for smallholders to get rid of massive debris. The use of fire to combat weed growth and liberate nutrients for crops stops naturally, because after a while there is no biomass left to burn. Clear-felling and removal of all tree, shrub and liana stumps is common practice to increase the planting area and to ease the evacuation of produce.

For cassava and other root crops, taking out all superficial large roots greatly facilitates the harvest of the tubers. Removal of non-woody plant material like the root systems of perennial grasses is needed for the improvement of pastures because low performing local grasses have to be replaced by more productive ones. These interventions have consequences for forest regeneration because, progressively, the residuals of the original forest are lost. Residuals are the individual organisms or their propagules that survive a disturbance event and abundance of residuals is a measure for the disturbance intensity (Turner et al. 1998). They are the key to the recovery process. Depending on the farming practices of the local people, residuals can be completely destroyed (composite farming in Dong Cao) or largely survive. The resprouter bank and most of the soil seed bank remain largely intact after the felling of the forest and a single burning of the dried debris (de Rouw 1993). Rotational shifting cultivation in Laos, practiced on steep slopes under similar soil/climate condition as in Dong Cao, preserves important resprouter banks, (de Rouw et al. 2015). Subsequently, succession to forest is fast and species diversity is high (Sovu et al. 2009; McNamara et al. 2012; McNicol et al. 2015). The resprouter bank is by far the most important source of woody plant diversity including many primary forest species, so it contributes to conservation (Nyerges 1989; Fukushima et al. 2008; Wangpakattanawong et al. 2010). Destruction of the resprouter bank occurs after piling and repeated burning and by stump removal (de Rouw 1993, Fukushima et al. 2008). Loss of the soil seed bank is caused by erosion of the topsoil on steep land. Under shifting cultivation and residual weeding (M-Tropics Laos site), soil erosion was slight, under continuous farming and clean weeding (M-Tropics Vietnam site) soil losses were tremendous (Valentin et al. 2008). Absence of the local seed bank opens opportunities for highly competitive heliophyle ruderals, clonal weeds and fast-growing C_4 pathway species to gain dominance, contributing to slowing down the succession while providing opportunities for livestock.

Declarations

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Contribution

All authors contributed to the general co-production of this work, revised it, and agreed on its content. AR, NB, SH, JM, PP, BS and TNV did field work and treated their own data. AR prepared data base, Tables, Figures, wrote the manuscript. GM was responsible for GIS maps. BS and PW checked plant identification.

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Ethics declarations

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Supplementary Information

Below are the links to the electronic supplementary material:

Online Resource_1 (pdf 784 ko),

Online Resource_2 (pdf 785 ko),

Online Resource_3 (pdf 707),

Online Resource_4 (pdf 722),

Online Resource_5 (pdf 568)

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Tables

Table 1 to 3 are available in the Supplementary Files section.

Figures

Figure 1

Photographs of Dong Cao catchment taken by the authors. **Top left**: very steep slope cultivated with cassava, behindabandoned hill top, background lowland with paddy fields. **Top right**: mosaic of young cassava and abandoned plots, background Vetiver grass strips (yellow) planted on the contour. **Bottom**: drone aerial photo showing the spontaneous development of forest on the abandoned farmland.

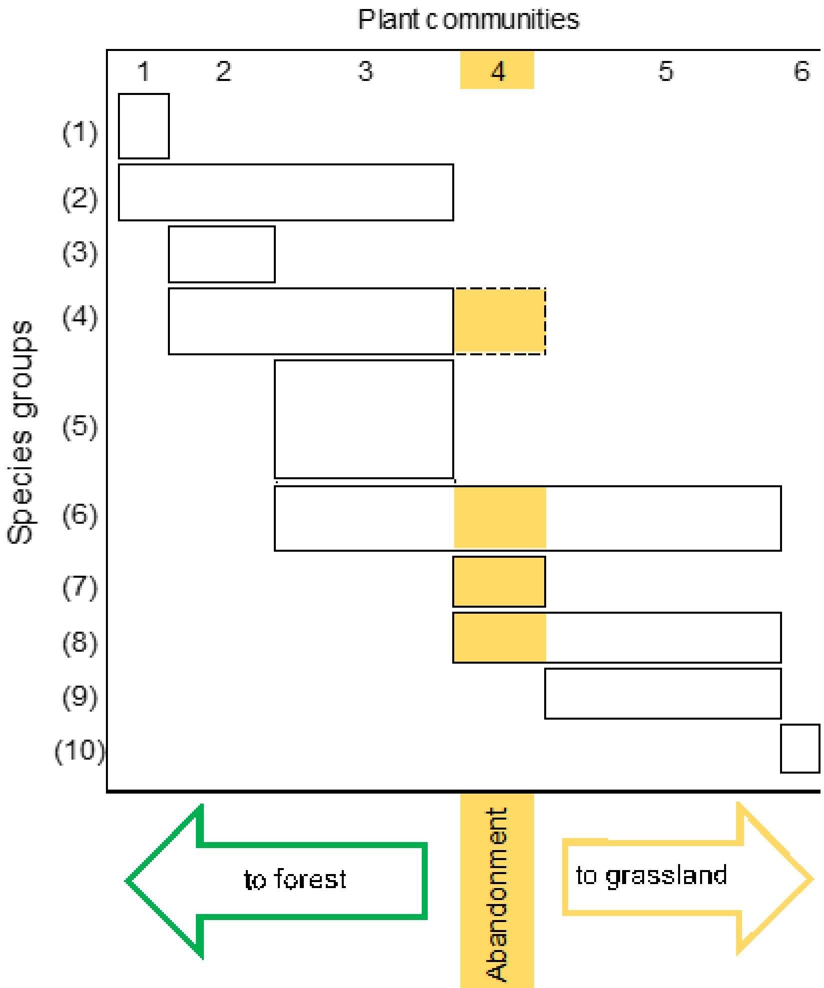

Figure 2

Diagram of six plant communities and ten species groups. The Braun-Blanquet table arrangement concentrates samples with similar species composition into Communities and species occurrences into blocks (species groups). The sample sequence left-right corresponds to a complexity gradient with most advanced communities on the left (Community 1) and least advanced on the right (Community 6). The Community 4 covered the study area after abandonment whereupon either a positive succession to forest or a negative succession to grassland occurred.

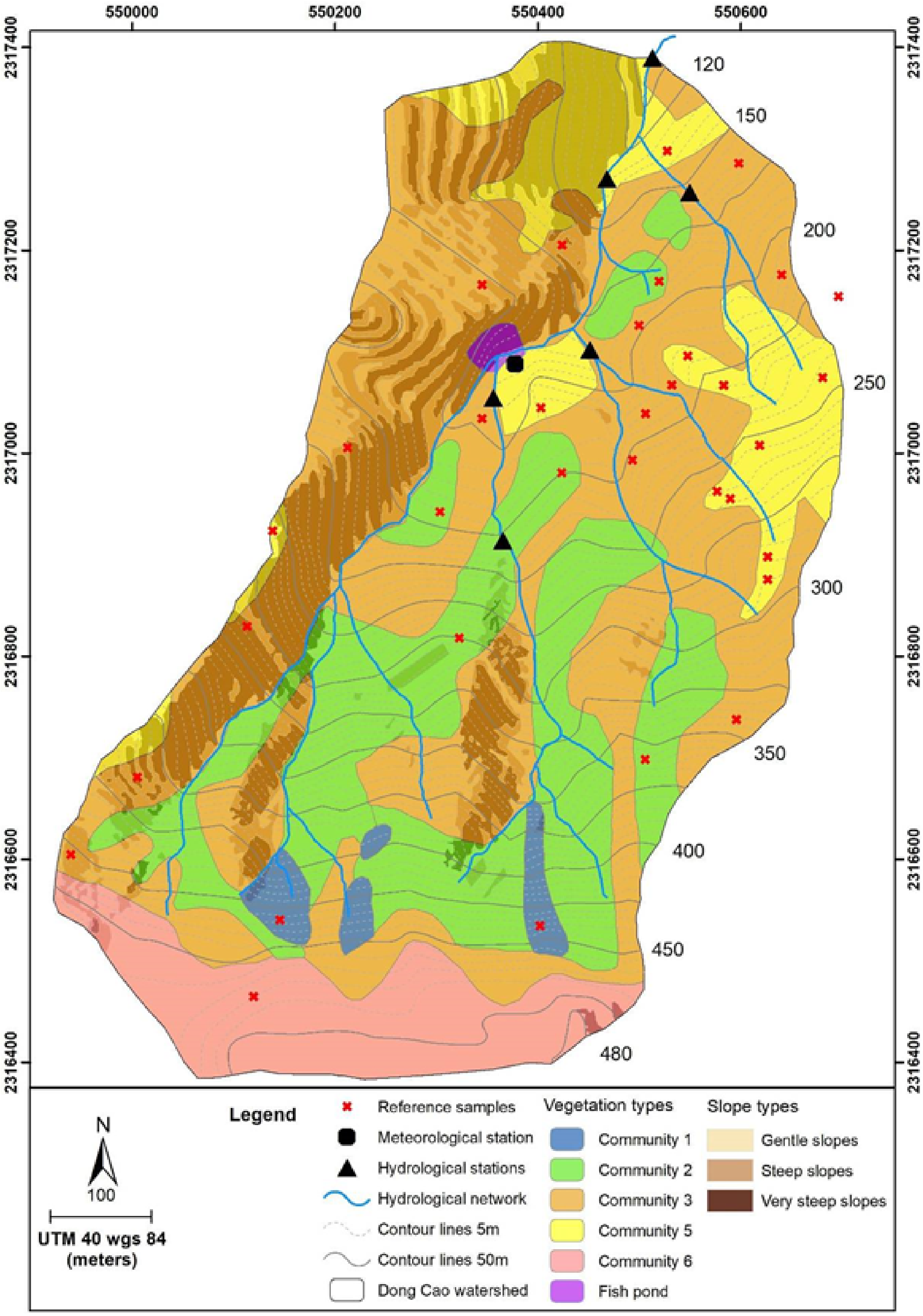

Figure 3

Vegetation map of Dong Cao catchment. In 2019 five communities were present in a sequence of complexity: Community 1 most advanced, Community 6 least advanced. Community 4, no longer present, was the dominant vegetation when farming was abandoned.

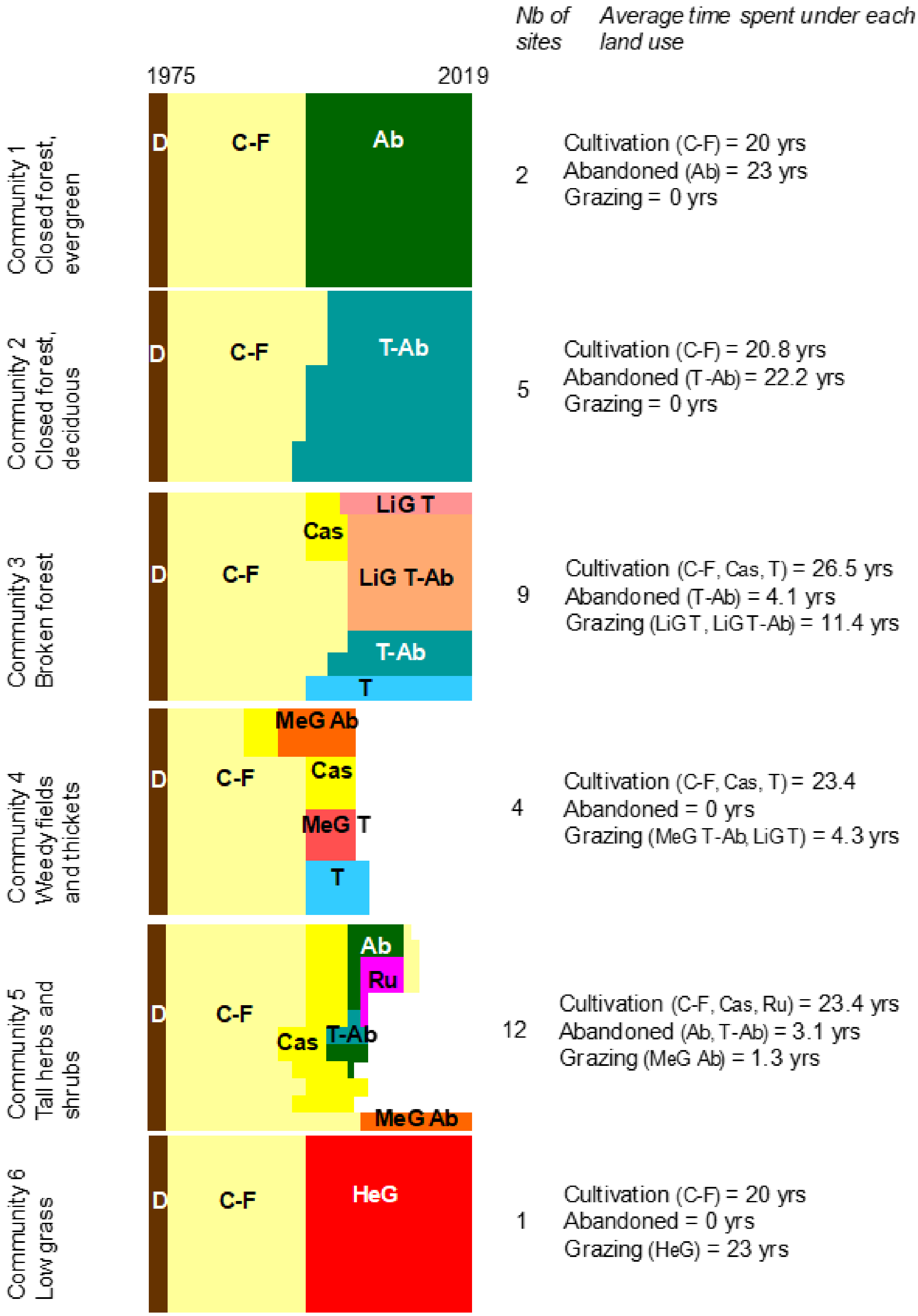

Figure 4

Land use in the 33 sample plots grouped in Communities with time spent (years) under each land use. Communities (top-down) are presented along a gradient from species rich to species poor (abbreviations see above).

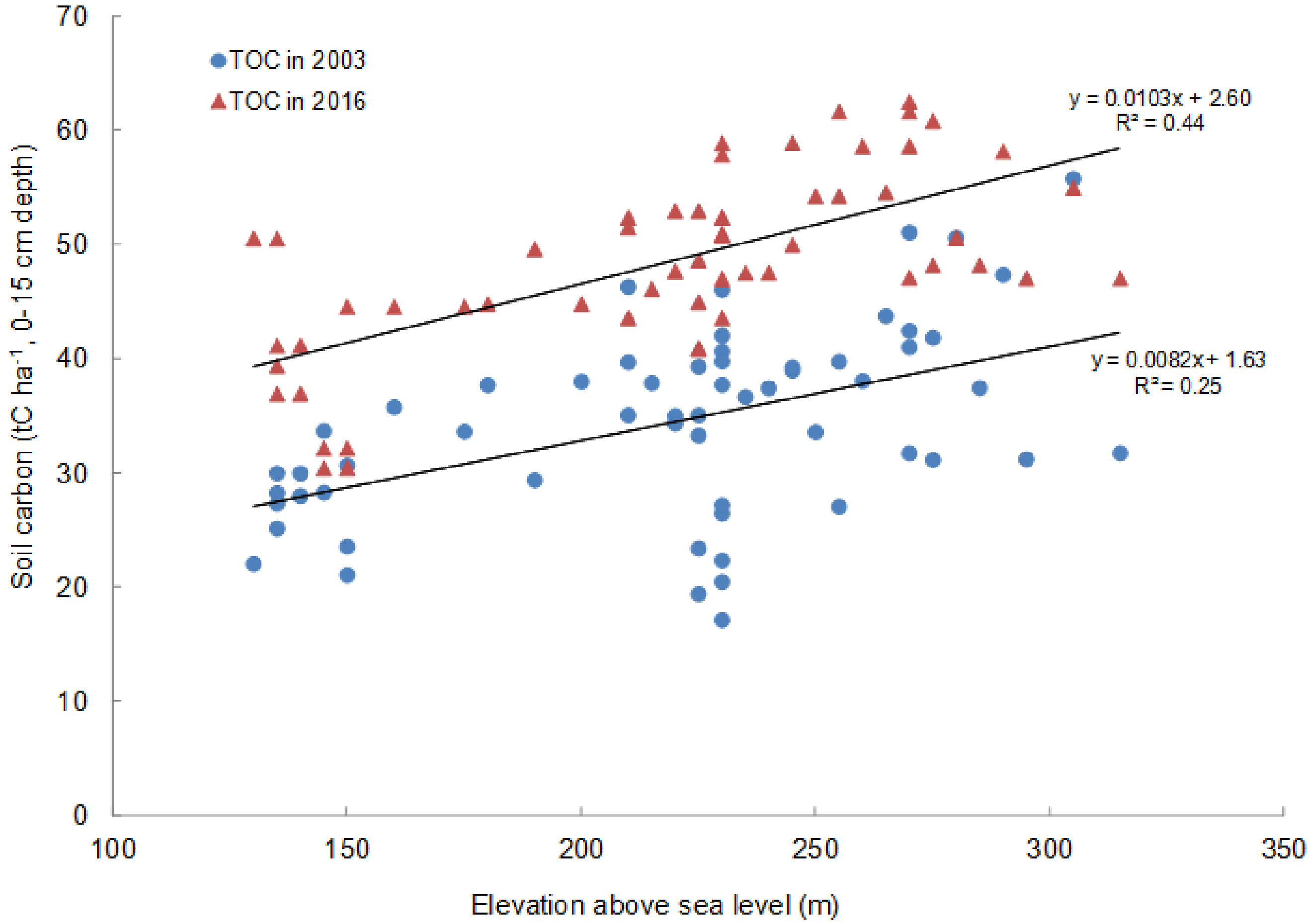

Figure 5

Soil carbon stocks in 2003 and 2016 in 59 matching locations, Dong Cao catchment.

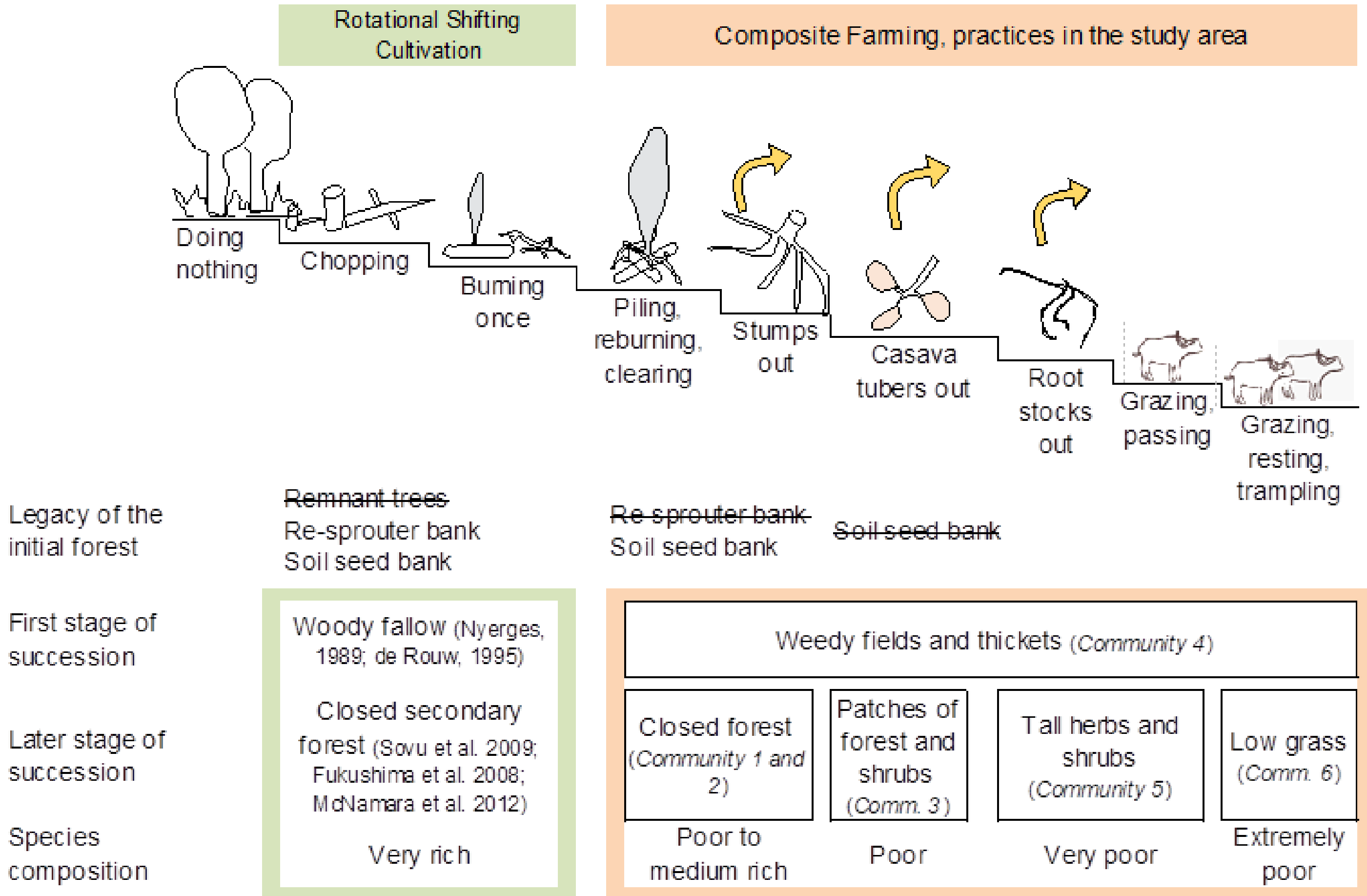

Figure 6

The Graphic abstract summarizes the sequence of human interventions when tropical forest is cleared for cultivation. Only the key practices are represented, those directly responsible for destruction of forest residuals and therefore the major contributors to slowing down the succession process and reducing plant diversity. With each downward step the cumulative disturbance is such that regeneration becomes more and more difficult and plant communities increasingly species-poor. It also shows the resilience of the environment to human damage and its capacity to recover from disturbances. Only long-cycle shifting cultivation with a single burning allows the preservation of most of the primary forest species.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- RealLandscapeDeRouwTable1.xlsx
- RealLandscapeDeRouwTable2.xlsx
- RealLandscapeDeRouwTable3.xlsx
- RealLandscapeDeRouwAppendix.docx
- RealLandscapeDeRouwCaptionsofAppendix.docx