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Title: **Shade-tree rehabilitation in vanilla agroforests is yield neutral and may translate into landscape-scale canopy cover gains**

Short title: Tree rehabilitation in vanilla agroforests

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Manuscript highlights:

- Shade-trees in agroforests are commonly cut due to trade-offs between shade and yields
- Across a chronosequence with 209 vanilla agroforests, we do not find such trade-offs
- The lack of this trade-off offers an opportunity for yield-neutral tree rehabilitation

Keywords: agroecology, agroforestry, canopy cover, ecosystem services, land-use history, Madagascar, rehabilitation, restoration, vanilla, yield

Abstract

Agroforestry can contribute to an increase in tree cover in historically forested tropical landscapes with associated gains in biodiversity and ecosystem functioning, but only if established on open land instead of underneath a forest canopy. However, declines in yields with increasing shade are common across agroforestry crops, driving shade-tree removal in forest-derived agroforests and hindering tree regrowth in open-land-derived agroforests. To understand trajectories of change in tree cover in forest- and open-land-derived agroforests and the impacts of tree cover on vanilla yields, we studied 209 vanilla agroforests along an 88-year chronosequence in Madagascar. Additionally, we used remotely-sensed canopy cover data to investigate tree cover change in the agricultural landscape. We found yields to vary widely but independently of canopy cover and land-use history (forest- vs. open-land-derived), averaging at 154.6 kg ha^{-1} yr^{-1} (*SD* = 186.9). Furthermore, we found that forest- and open-land-derived vanilla agroforests gained canopy cover over time, but that only open-land-derived agroforests gained canopy height. Canopy cover increased also at the landscape scale: areas in the agricultural landscape with medium initial canopy cover gained 6.4% canopy cover over 10 years, but canopy cover decreased in areas with high initial canopy cover. These opposing trends suggest tree cover rehabilitation across areas covered by vanilla agroforests, whereas remnant forest fragments in the agricultural landscape were transformed or degraded. Our results indicate that yield-neutral tree rehabilitation through open-land-derived agroforestry could, if coupled with effective forest protection, provide mutually beneficial outcomes for ecosystem functions and agricultural production in a smallholder-dominated agricultural landscape.

Introduction

Rehabilitation of historically forested open land is widely advocated to re-establish connectivity and increase ecosystem functions in tropical rainforest landscapes (Bastin and others, 2019; Chazdon, 2003). To date, governments and institutions have pledged to restore 140 million hectares of land in the tropics (Brancalion and others, 2019). However, realizing those pledges could jeopardize food security if tree cover restoration replaces cropland, questioning how feasible (Eitelberg and others, 2016) and indeed desirable (Holl & Brancalion, 2020) their fulfilment is. In this light, agroforests may provide an opportunity to combine trees with agricultural production on the same land (De Beenhouwer and others, 2016; FAO, 2017). Agroforests that are established on historically forested open-land hold a particularly large potential, because open-land-derived agroforests rehabilitate selected ecosystem functions like erosion control or carbon storage on open land (Martin, Osen, and others, 2020). To describe this process, we specifically use the word ‘tree rehabilitation’ based on Chazdon and others (2016), as the focus lies on the rehabilitation of ecosystem functions, without necessarily restoring ecological integrity. In contrast to this, agroforests planted under the canopy of existing forests typically contribute to forest degradation (Martin, Osen, and others, 2020), thus hampering ecosystem functioning and ecological integrity (Coe and others, 2013; McDowell and others, 2020).

Nonetheless, trade-offs between shade cover and yields are common across many key agroforestry crops (Tscharntke and others, 2011), limiting the potential of these agroforestry systems to contribute to tree rehabilitation in tropical rainforest landscapes. Such shade-yield trade-offs are exemplified in coffee and cacao agroforests (Blaser and others, 2018; Steffan-Dewenter and others, 2007), where felling trees is typically beneficial to farmers aiming at optimizing yields. Finding a balance between ecosystem services, biodiversity and profitability thus requires targeted incentives (Tscharntke and others, 2014). In their absence, a decrease in canopy cover and tree height over time commonly occurs (Tscharntke and others, 2011), but time series or chronosequences, which are necessary to identify trends, are rare (see Nijmeijer and others (2019) for an exception). Finding farming techniques or crops where such trade-offs do not inherently occur would, on the other hand, offers an opportunity to profitably farm crops in high-shade agroforestry systems without the need for further incentives.

One candidate crop where shade-yield trade-offs are currently unknown is the spice vanilla. When farmed in agroforestry systems, the vanilla orchid *(Vanilla planifolia)* is typically hung up on support trees which give support to the non-woody vine (Correll, 1953). Vanilla flowers are then hand pollinated and green pods are harvested nine months later. The green pods are subsequently cured, thereby developing their distinct flavour and black colouration while losing roughly 80% of their weight (Havkin-Frenkel & Belanger, 2018). The resulting black vanilla has strongly increased in price from 2012 to 2019, triggering the expansion of vanilla farming in Madagascar (Hänke and others 2018; Llopis and others 2019, Supplementary Material Figure 1).

In north-eastern Madagascar, vanilla is the main cash crop for smallholder farmers (Hänke and others, 2018) who farm the bulk of Madagascar’s 40% share on the world market (FAO, 2020). Here, vanilla is almost exclusively produced in rather extensively managed agroforestry systems without the application of fertilizers, herbicides and pesticides. This is partly in contrast to other production areas, such as La Réunion or Mexico, where artificial shade houses are common (Havkin-Frenkel & Belanger, 2018). These extensively managed vanilla agroforests also have value for biodiversity: various endemic lemur species live in diverse agroforests (Hending and others, 2018). Vanilla agroforests also have a more diverse avifauna than open land uses (Martin, Andriafanomezantsoa, and others, 2020). Other prominent land uses in the Malagasy vanilla region include remnant forest fragments, irrigated rice paddies and hill rice fields with the associated herbaceous and woody fallows, that form part of the shifting cultivation cycle, locally known as *tavy* (Martin, Andriafanomezantsoa, and others, 2020; Styger and others, 2007). The first cycle of shifting cultivation, where fire is used to convert forest into hill rice fields, is the main reason for forest loss in the region (Schüßler and others, 2020; Zaehringer and others, 2015). This dynamic is consistent with trends across most of Africa, but contrasts with trends in the remaining tropics (Curtis and others, 2018; van Vliet and others, 2012).

Vanilla agroforests may be established inside forest fragments or on open fallow land, thereby differing in land-use history (Martin, Osen, and others, 2020). Forest-derived vanilla agroforests degrade the forest they are established in but will typically outperform shifting cultivation, i.e. the replacement of forest with hill rice cultivation, for ecosystem functions and biodiversity (Martin, Osen, and others, 2020). Open-land-derived agroforests may instead restore land formerly under hill rice cultivation by rehabilitating tree cover and preventing the re-occurring fires which characterize the shifting hill rice cultivation system (Holloway, 2004; Styger and others, 2007). In north-eastern Madagascar, 30% of vanilla agroforests are forest-derived while 70% are open-land-derived (Hänke and others, 2018), further underlining the rehabilitation opportunity offered by open-land-derived agroforestry. The high potential for tree rehabilitation and habitat restoration in Madagascar is also recognized in a recent study by Brancalion and others (2019), who attribute the 4th largest restoration opportunity area (in terms of benefits and feasibility) of lowland tropical rainforest to Madagascar. Simultaneously, the country is characterized by high levels of endemism (Goodman & Benstead, 2005) and high deforestation rates (Vieilledent and others, 2018) and qualifies as a biodiversity hotspot (Myers and others, 2000). This exacerbates the need for both effective biodiversity conservation within the existing protected areas as well as restoration within the agricultural landscape.

Tropical forest fragment

Forest-derived vanilla agroforest

Open land (Woody fallow)

Open-land-derived vanilla agroforest

Vanilla *pied* (unit of vanilla vine and support tree), flower and green pods

Agricultural landscape in north-eastern Madagascar

Figure 1: *Top row: Forest-derived vanilla agroforests are directly established inside forest. Middle row: Open-land-derived vanilla agroforest are established on open land, typically*

woody fallow. Bottom row: Vanilla pied (unit of vanilla vine and support tree) and agricultural landscape in north-eastern Madagascar where the study took place. Colour labels indicate contrasting land-use history of vanilla agroforests and are used throughout the manuscript. All photos by the authors.

In this study, we 1) examined how land-use history, canopy cover, agroforest age, planting density and precipitation influence vanilla yields, 2) assessed tree rehabilitation dynamics across vanilla agroforests of different age and of contrasting land-use history, and 3) investigated how tree rehabilitation within vanilla agroforests may transform the landscape as a whole. To this end, we assessed vanilla yields, canopy cover and canopy height in 209 vanilla agroforests of contrasting land-use history and of different age (0 – 88 years), thus representing an 88-year chronosequence. Subsequently, we used remotely sensed canopy cover data to study canopy cover change from 2000-2010 on the landscape-scale. Based on previous studies from cocoa and coffee agroforests (Blaser and others, 2018; Jezeer and others, 2017; Perfecto and others, 2005), we expected vanilla yields to decline with increasing canopy cover. We further anticipated canopy cover and canopy height to decline with increasing age of forest-derived agroforests, but expected both variables to increase with age in open-land-derived agroforests, in line with the predictions by Martin, Osen, and others (2020). At the landscape-scale, we presumed that the ongoing transformation of open fallow land into open-land-derived agroforests may positively influence canopy cover around the villages.

Methods

Study region

The SAVA region (25 518 km^2 / Latitude: 14° 16′ S, Longitude: 50° 10′ E) of north-eastern Madagascar is the historic (Correll, 1953) and current (Hänke and others, 2018) center of global vanilla production and a biodiversity hotspot (Myers and others, 2000). Mean annual temperature is 23.7 °C and annual rainfall averages at 2238 mm (Mean across 209 focal agroforests; data from CHELSA climatologies (Karger and others, 2017)). In the southern part of the SAVA region, where we collected the data (SM Figure 2), the natural vegetation is tropical rainforest (Vieilledent and others, 2018), but only 35% forest cover remains across the SAVA region (Ferreira Arruda, 2018).

Selection of vanilla agroforests

We first selected 60 villages in a stratified-random way for a previous study (Hänke and others, 2018). From those 60, we selected 10 villages in a nested stratified-random way that controlled for village size. Specifically, we randomly selected two villages per village size category (0-1000 people, 1001-2000 people, 2001-3000 people, 3000-4000 people, > 4000 people). Within each village, we chose 14 households randomly from the 30 households included in Hänke and others (2018); however, 20 households opted out, leaving us with 120 households.

We then visited accessible (< 4h walking return) vanilla agroforests; 33 households did not own any accessible vanilla agroforests and 27 had more than one agroforest, resulting in a sample of 123 agroforests owned by 87 households. After collecting data from those agroforests, but before doing any data analysis, we checked the number of forest- respectively open-land-derived agroforests in the sample and realised that the number was uneven (36 vs. 87).

We thus decided to include four additional villages from the stratified random sample of 60 villages. For those villages, we knew based on Hänke and others (2018) that their proportion of forest-derived vanilla agroforests would be high, resulting in roughly even numbers of forest- and open-land-derived agroforests in the final sample. In those four villages, we visited 65 households included in Hänke and others (2018). Those households owned 86 additional accessible agroforests (7 open-land-derived, 79 forest-derived). This led to a total sample of 115 forest-derived and 94 open-land-derived agroforests (209 in total) owned by 152 households across 14 villages. SM Figure 2 shows all 14 villages with field data and the 60 villages from the initial sample.

Data collection in agroforests

We collected field data between July and October 2018 after the 2018 vanilla harvest. During visits to the agroforest, we asked vanilla agroforest owners in Malagasy about 1) the realized yield of green vanilla in 2017 and 2018 [kg agroforest^{-1}], 2) estimated green vanilla theft from the agroforest before harvest in 2017 and 2018 [kg agroforest^{-1}], 3) the number of *pieds* (combination of vanilla vine and support tree; **Figure 1**) in the agroforest, 4) the year in which the agroforest was established, and 5) whether the agroforest was forest- or open-land-derived (sensu Martin and others 2020). Vanilla yields are commonly reported as the weight of green rather than black pods, since green pod weight is independent of the curing technique (Havkin-Frenkel & Belanger, 2018). We subsequently added estimated theft to the realized yields as we were interested in the productivity of the agroforests rather than the farmers' income. We measured agroforest size during perimeter walks using handheld GPS devices and applied a slope correction (based on the digital surface model 'ALOS World 3D' (Japan Aerospace Exploration Agency, 2018)) to account for different steepness of the terrain. By combining yield data and the slope-corrected agroforest size, we calculated mean green vanilla yield per hectare [kg ha^{-1} year^{-1}] across the two years for further analysis. Based on slope-corrected agroforest size and number of *pieds*, we calculated planting density [*pieds* ha^{-1}].

We used tablets to assess canopy cover, as photos from mobile devices have been found to be an adequate, cheap and fast technique to assess canopy cover (Bianchi and others, 2017; Tichý, 2016). Observers held the tablet (Lenovo YT3-850F) above their head (circa 190 cm) and used the built-in camera (Lenovo 5C28C02840) with the standard lens and auto-exposure to take a photo in azimuthal direction. We repeated this procedure at nine locations per plot (see Supplementary Materials), resulting in 1881 photos from 209 agroforests. We then classified all photos into vegetation/sky using the R-Package *caiman* (Diaz and Lencinas 2015; more details on canopy cover classification in Supplementary Materials) and calculated mean canopy cover across all 9 photos to derive one value per agroforest. Additionally, the observer estimated the highest point of vegetation above each camera position, enabling us to calculate the mean canopy height across 9 locations for each agroforest.

Some farmers did not know the number of *pieds* and/or the year of establishment of their agroforest, leading to missing data for planting density and agroforest age in 8 and 3 cases, respectively (out of 209). We imputed this data for the linear mixed effect models using the mean of each respective variable.

Data extraction from raster layers

To investigate how precipitation and temperature influenced vanilla yields, we extracted annual mean temperature and annual precipitation for each agroforest from the CHELSA climatologies with a resolution of 30 arc sec (Karger and others, 2017) using the plot center as a reference point. Due to the strong correlation of annual mean temperature and annual precipitation (-0.76, Pearson correlation coefficient), we only used annual precipitation for further analysis. Analogously, we obtained the elevation of each agroforest from the digital surface model 'ALOS World 3D' (Japan Aerospace Exploration Agency, 2018). Lastly, we extracted the percentage landscape forest cover in a radius of 250 m around plot centres using published binary forest cover data for the year 2017 (Vieilledent and others, 2018).

Analysis of vanilla yields, canopy cover and canopy height

We used three linear mixed-effects models to analyse variation in vanilla yields, canopy cover and canopy height, with 'household' (owner of agroforest, N= 152) and 'village' (N=14) as random effects in all models. We fitted all models using the R-Package *lme4* version 1.1.21 (Bates, 2014) and scaled all explanatory and response variables to zero mean and unit variance, allowing for direct comparison of effect sizes within and across models (Harrison and others, 2018). We used an alpha level of 0.05 and calculated marginal and conditional R^2-values for all models (Nakagawa & Schielzeth, 2013). We used QQ-plots to assess normality of model residuals and tested for variable inflation; none of the models had significant deviations in the QQ-plots or variable inflation values above 1.5.

In a first model, we assessed the variation of green vanilla yield [kg ha^{-1}] in relation to land-use history (forest vs. open-land-derived; coded as 1 vs. 0), canopy cover, age of agroforest, planting density and annual precipitation. To reach normality of model residuals, we applied a Box-Cox transformation to the response variable (Box & Cox, 1964). We determined a lambda of 0.25 to be suitable for the transformation using the *boxcox* function of the R-package *mass* version 7.3.51.4 (Ripley and others, 2013). Due to the highly right-skewed nature of the age and planting density data, we square root transformed these two variables. We additionally included interactions between land-use history and all explanatory variables to test whether responses would differ between forest- and open-land-derived agroforests.

Statistically speaking, the full yield model read: green vanilla yield ~ land-use history + canopy cover + age of agroforest + planting density + annual precipitation + land-use history * canopy cover + land-use history * age of agroforest + land-use history * planting density + land-use history * annual precipitation + (1 | village / household).

In a second and third model, we assessed factors influencing canopy cover (untransformed) and canopy height (Box-Cox-transformed with lambda 0.35), respectively. We used land-use history, age of agroforest, elevation, landscape forest cover and planting density as explanatory variables. Again, we square root transformed the age and planting density data and included interactions between land-use history and all explanatory variables. Statistically speaking, the full canopy cover model read: canopy cover ~ land-use history + age of agroforest + elevation + landscape forest cover + planting density + land-use history * age of agroforest + land-use history * elevation + land-use history * landscape forest cover + land-use history * planting density + (1 | village / household). The full canopy height model was exactly the same, except for the response variable.

In the yield and canopy cover model, none of the interactions were significant, prompting us to present the reduced model without interactions. In the canopy height model, only the interaction between age and land-use history was significant at the $p<0.05$ level. We thus only kept this interaction in the reduced model. All models are presented in full and reduced (i.e. final) form in the Supplementary Materials (SM Tables 1-3).

To visualize the models, we calculated estimated marginal means and their 95% confidence intervals using the R-Package *emmeans* version 1.4.5 (Length and others, 2018). We further back-transformed the estimated marginal means to the original distributions to facilitate the interpretation of model results.

Analysis of canopy cover dynamics in the agricultural landscape

We used remotely sensed canopy cover data to explore how observed tree rehabilitation within agroforests translated to the landscape scale. We obtained canopy cover data for the year 2000 and 2010 from a Landsat-derived product of continuous canopy cover values with 30 m resolution (Hansen and others, 2013). Using the *raster* R-package version 3.0.12 (Hijmans and others, 2019), we subtracted the 2000 layer from the 2010 layer to obtain a new raster layer with tree cover gains and losses, respectively (change of canopy cover between 2000 and 2010 [%]). We restricted both layers to an area of 2 km around the centers of 60 focal villages (excluding any offshore areas), for which we knew that vanilla farming was common and from which we selected the villages for the plot-based part of this study (Village selection described in Hänke and others, 2018). We chose 2 km because agroforests in this range will typically belong to the focal village *(personal observation)*. We then fitted a generalized additive mixed model (GAMM) using the R-package *mgcv* version 1.8-28 (Wood, 2012) to evaluate how the dependent variable ‘initial canopy cover in the year 2000’ determined the independent variable ‘change in canopy cover from 2000 to 2010’. We included ‘village’ as a random effect and also included longitude and latitude of each raster cell as random effects to control for spatial autocorrelation. Therefore, the model read: change in canopy cover ~ initial canopy cover + (1 | village) + (1 | longitude) + (1 | latitude). We further ran the model on the basic dimension k = 8. We checked model assumptions using the *gam.check* function of the *mcgv* R-package which demonstrated k=8 to be adequate and a near-normal distribution of residuals.

We analysed all data in R version 3.6.0 (R Core Team, 2019). The underlying data and R-code are publicly available (see data availability statement).

Results

Determinants of vanilla yields

Green vanilla yield per *pied* varied strongly and ranged from 0 – 860 g $pied^{-1}$ $year^{-1}$ with an average of 69.9 g $pied^{-1}$ $year^{-1}$ (*SD* = 112.3; N = 209 agroforests; mean from 2017 and 2018). Note that this estimate includes *pieds* without any yield as it is calculated by dividing the total yield by the number of *pieds* in each agroforest. Similarly, green vanilla yields differed strongly across agroforests, ranging from 0 - 932.7 kg ha^{-1} $year^{-1}$ with an average of 154.6 kg ha^{-1} $year^{-1}$ (*SD* = 186.9; N= 209 agroforests; mean of 2017 and 2018). Using farmgate vanilla prices for the year 2017 (Hänke and others, 2018), this average yield translates into gross earnings of 4684 € ha^{-1}. However, a household in this dataset only farmed 0.46 ha (*SD* = 0.42; N=152) of accessible vanilla agroforests in average. The difference in green vanilla yield per ha between the two years was small (2017: 158.8 kg ha^{-1} (*SD* = 200.1); 2018: 150.2 kg ha^{-1} (*SD* = 202.6)) and a Wilcoxon rank sum test revealed no significant differences between years (W = 21267, p = 0.642, N = 209 agroforests). Farmers reported green vanilla theft in 26 agroforests (12.4%) for 2017 and in 25 agroforests (12.0%) for 2018. Farmers who reported theft, stated that they lost on average 9.15 kg (*SD* = 15.3) green vanilla per agroforest in 2017 and 8.72 kg (*SD* = 8.7) per agroforest in 2018.

Our yield model (**Figure 2**, SM Table 1) revealed that vanilla yields varied independently of land-use history, i.e. whether an agroforest was forest- or open-land-derived. Yields were furthermore not significantly related to canopy cover and annual precipitation. Yields rose with increasing agroforest age and planting density. Overall, the marginal R^2-value of the model was 0.216 while the conditional R^2-value was 0.450. The difference between the two values was mainly driven by the random intercept variance for the random effect ‘household’

(τ_{00} = 0.26); the random intercept variance for the random effect 'village' was negligible (τ_{00} = 0.03)

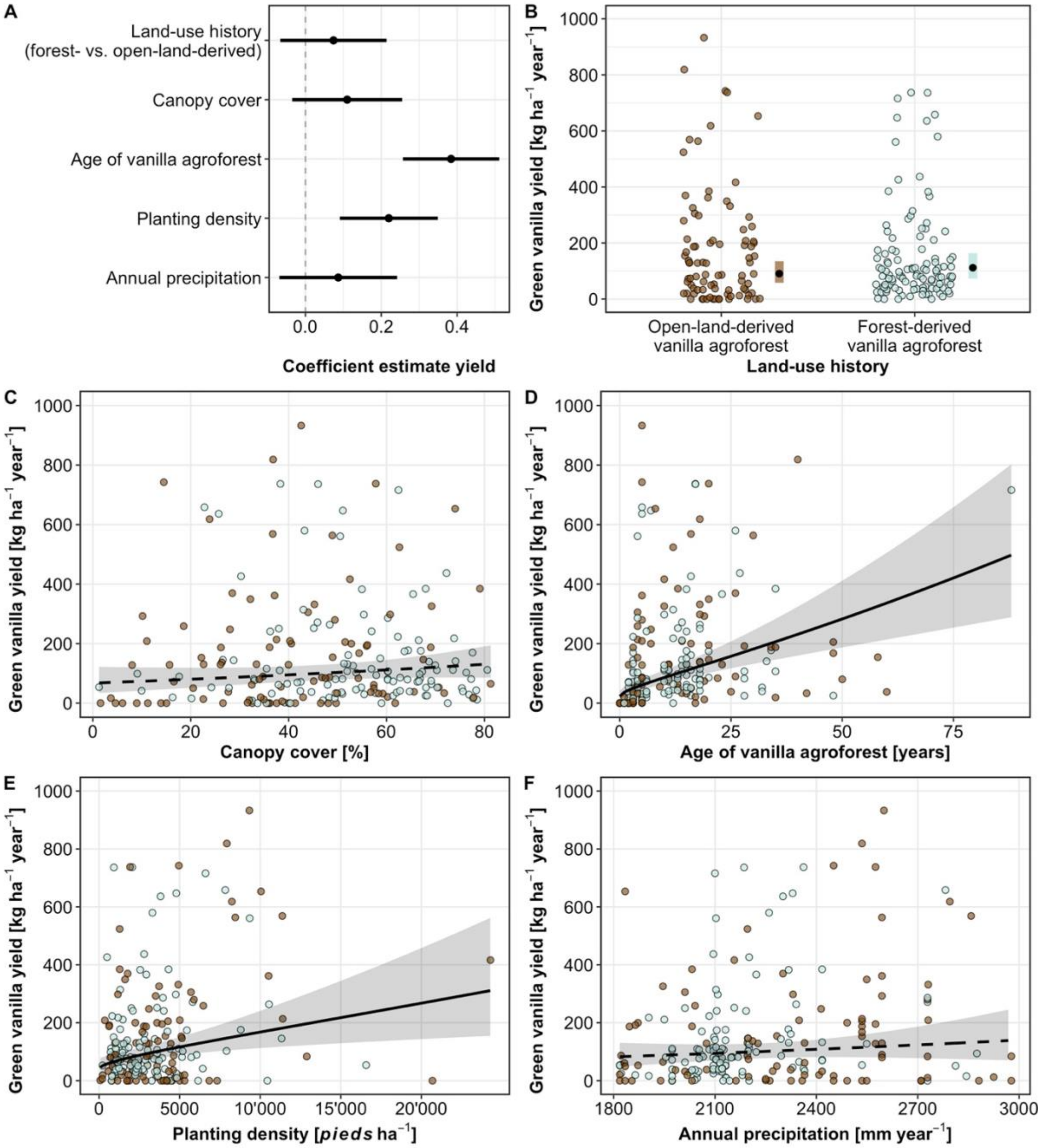


Figure 2: *Results of a linear mixed effect model explaining green vanilla yield [kg ha^{-1} yr^{-1}] across 209 agroforests.* ***A:*** *Scaled effect plot of the reduced yield model for all five predictors.* ***B-F:*** *Green vanilla yields as a function of land-use history (**B**), canopy cover [%] (**C**), age of vanilla agroforest [years] (**D**), planting density [pieds ha^{-1}] (**E**) and annual precipitation [mm year^{-1}] (**F**). Green vanilla yields were independent of land-use history and positively associated with all four continuous variables, but the relationships between canopy cover and yields as well as annual precipitation and yields were not significant. Lines and black dots respectively*

show back-transformed estimated marginal means based on the linear mixed-effect model and shaded areas depict 95% confidence intervals. Points are raw data separated in forest-derived (blue) and open-land-derived (brown) agroforests. A table with model results can be found in the Supplementary Materials (SM Table 1).

Determinants of canopy cover and canopy height

Canopy cover was 12.8% (estimated marginal means 6.3%) higher in forest-derived vanilla agroforests (mean = 52.9%, *SD* = 17.2) compared to open-land-derived agroforests (mean = 40.1%, *SD* = 19.0; Figure 3, SM Table 2). The age of the agroforests differed along the chronosequence between 1 and 88 years in forest-derived agroforests and between 0 and 60 years in open-land-derived agroforests. Age positively related to canopy cover, in both forest- and open-land derived agroforestry: canopy cover increased by 39.5% (CI 34.5 – 44.6%) over 88 years.

Similarly, canopy height was 8.2 m (estimated marginal means 5.2 m) higher in forest-derived agroforests (mean = 14.5 m, *SD* = 7.3) compared to open-land-derived agroforests (mean = 6.3 m, *SD* = 4.6; Figure 4, SM Table 3). The age of the agroforest positively affected canopy height in open-land-derived agroforests where canopy height increased on average by 8 m (CI 6.1 – 10.3 m) over 60 years. Canopy height in forest-derived agroforests was relatively stable (mean decrease of 1.7 m (CI -2.7 – -0.4) over 60 years and a mean decrease of 2.1 m (CI -3.9 – +0.4) over 88 years).

Vanilla planting density did not correlate with canopy cover or height (Figure 3 & 4, SM Table 2 & 3). Furthermore, agroforests with more surrounding forest cover had taller trees and greater canopy cover, but confidence intervals overlapped zero for the latter (Figure 3 A). Elevation was negatively associated with both tree height and canopy cover (Figure 3 A). The canopy cover model (Figure 3, SM Table 2) had a marginal R^2-value of 0.34 and a conditional R^2-value of 0.56, while the canopy height (Figure 4, SM Table 3) model had a marginal R^2-

value of 0.35 and a conditional R^2-value of 0.74. The substantial difference between conditional and marginal R^2-values stemmed from the strong explanatory power of the random effect ‘household’ (canopy cover model: $\tau_{00} = 0.16$ / canopy height model: $\tau_{00} = 0.37$); the random intercept variance for the random effect ‘village’ was small (canopy cover model: $\tau_{00} = 0.07$ / canopy height model: $\tau_{00} = 0.02$).

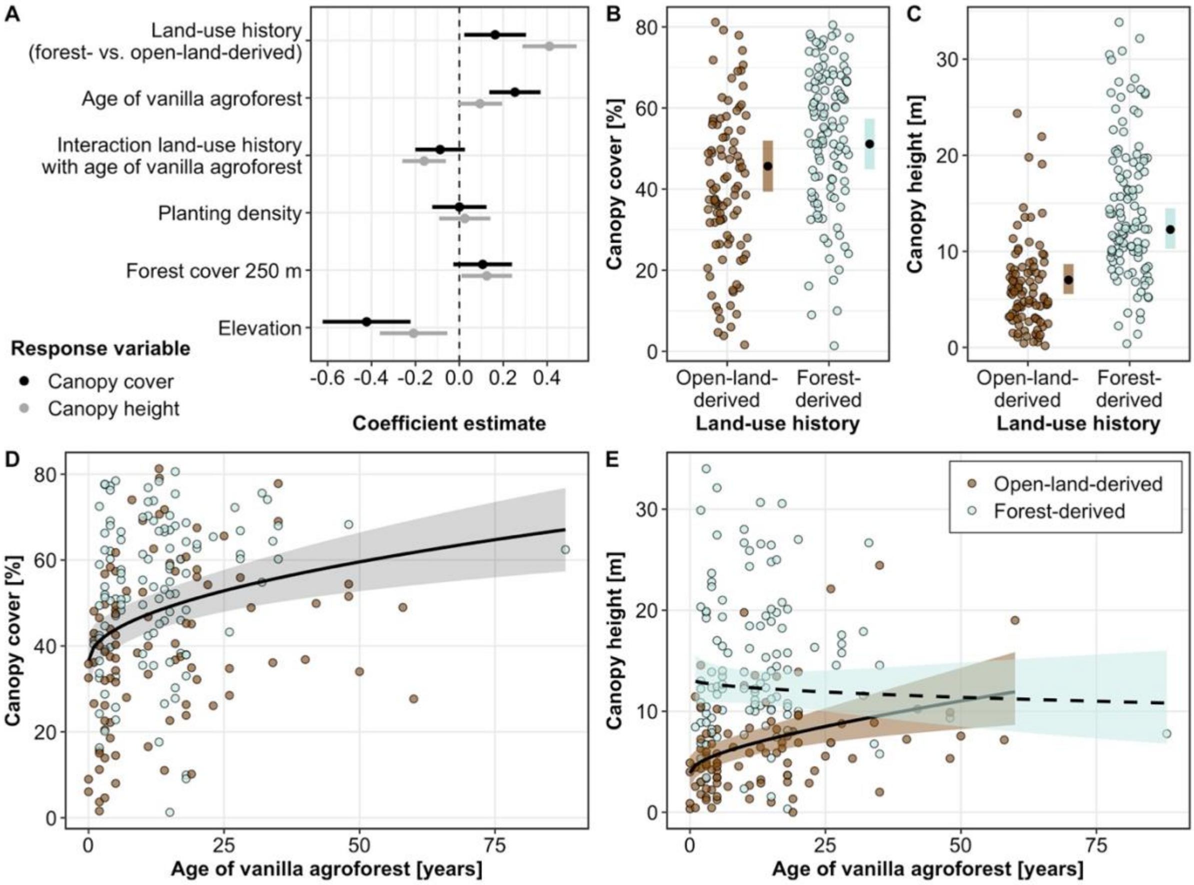
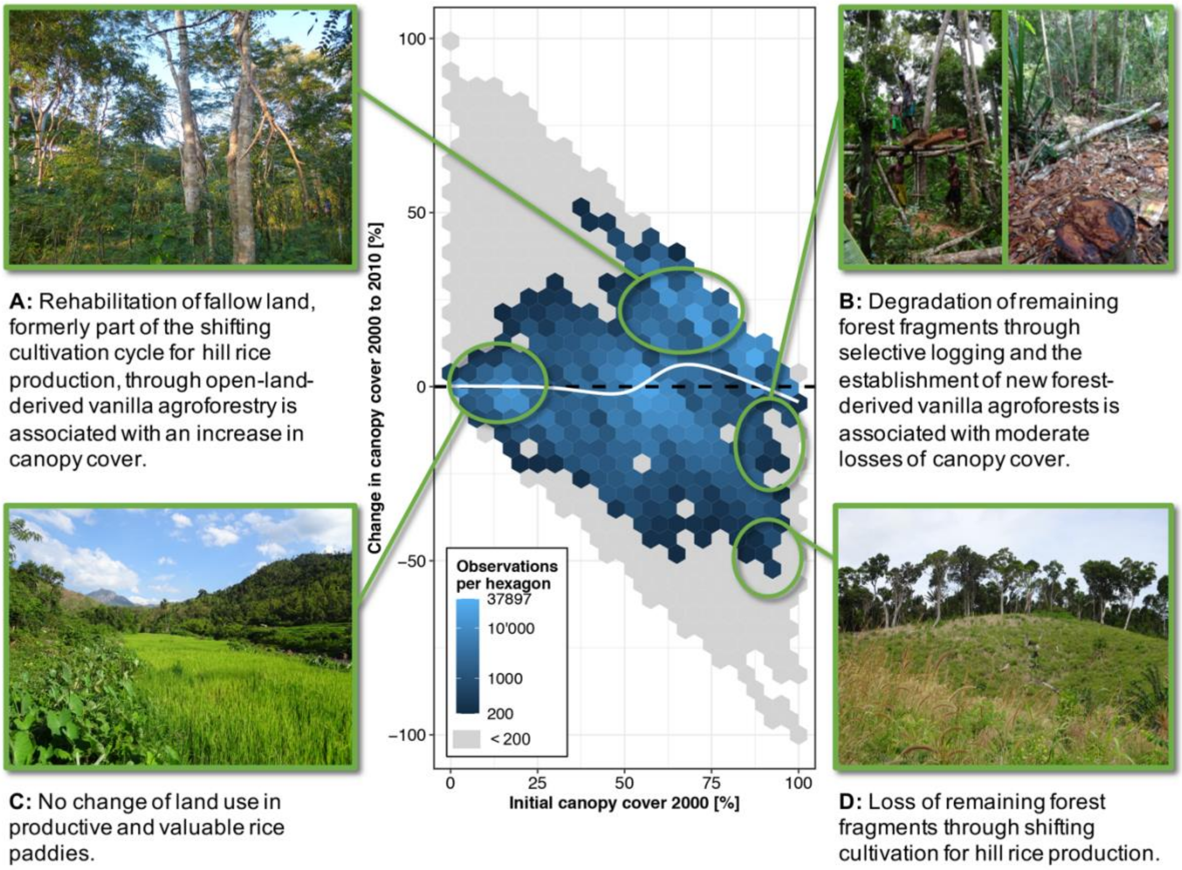


Figure 3: *Results of two linear mixed effect models explaining canopy cover [%] and canopy height [m] across 209 vanilla agroforests.* ***A:*** *Scaled effect plot of the reduced canopy cover model (black) and the reduced canopy height model (grey) for all five predictors, including the interaction between land-use history and age [years] in the canopy height model.* ***B & C:*** *Forest-derived agroforests (blue) had both higher canopy height and higher canopy cover compared to open-land-derived agroforests (brown).* ***D:*** *Older forest- and open-land-derived agroforests had higher canopy cover.* ***E:*** *Older agroforests also had higher canopies, but only if open-land-derived. Lines and black dots respectively show back-transformed estimated marginal means based on linear mixed-effect models and shaded areas depict 95% confidence intervals. Points are raw data separated in forest-derived (blue) and open-land-derived (brown) agroforests. Tables with the results of both models can be found in the supplementary materials (SM Table 2 and 3).*

Canopy cover dynamics in the agricultural landscape

Areas within the agricultural landscape around villages that had low initial canopy cover in the year 2000 experienced little change from 2000 to 2010 (**Figure 4** C, SM Table 4). Areas with medium to high initial canopy cover experienced an increase in canopy cover, reaching the maximum increase of 6.4% at 68.3% initial canopy cover (**Figure 4** A). Areas with very high initial canopy cover lost in average 4.4% of canopy cover (**Figure 4** B & D). Overall, canopy cover increased by 2.7%. The general additive model explained 8.0% of the variation in the data.



A: Rehabilitation of fallow land, formerly part of the shifting cultivation cycle for hill rice production, through open-land-derived vanilla agroforestry is associated with an increase in canopy cover.

B: Degradation of remaining forest fragments through selective logging and the establishment of new forest-derived vanilla agroforests is associated with moderate losses of canopy cover.

C: No change of land use in productive and valuable rice paddies.

D: Loss of remaining forest fragments through shifting cultivation for hill rice production.

Figure 4: *Canopy cover dynamics in the agricultural landscape in a 2 km circle around centres of 60 focal villages between 2000 and 2010 using canopy cover raster data with 30 m resolution (Hansen and others, 2013). Canopy cover increased overall by 2.7%, driven by canopy cover increase in areas with medium to high initial canopy cover (e.g. vanilla*

*agroforests; **A**). Canopy cover did, however, decrease in areas with very high initial canopy cover (e.g. forest; **B, D**) and was stable in areas with little initial canopy cover (e.g. rice paddies; **C**). The central plot shows hexagon bins of bin-width 5% which are coloured according to the number of 30x30 m raster cells (i.e. observations) within each hexagon bin. Hexagon bins with less than 200 observations are grey. The white line depicts predicted outcomes of a general additive model explaining change in canopy cover (SM Table 4). All photos by the authors.*

Discussion

Across an 88-year chronosequence of 209 agroforests in the SAVA region of north-eastern Madagascar, we found vanilla yields to vary widely and to be positively affected by planting density and agroforest age, while land-use history, canopy cover, and precipitation had no effects on yields. Older vanilla agroforests had higher canopy cover, and, if open-land-derived, also greater canopy height. On the landscape-scale, areas within the agricultural landscape with medium canopy cover gained canopy cover between the years 2000 and 2010.

Determinants of vanilla yields

We found vanilla yields to be hugely variable across agroforests, ranging from 0 - 932.7 kg green vanilla per hectare. This variability was driven by variable yields per *pied* (unit of support tree and vanilla vine) and planting densities. Such variability is typical for smallholder agroforests in tropical countries (Clough and others, 2011) and points towards large yield gaps caused by sub-optimal management practices (Lobell and others, 2009). This also suggests a large intensification potential in existing agroforests and opportunities for sustainable intensification (Tilman and others, 2011). Our mean yield estimate of 154.6 kg ha^{-1} is lower than most other vanilla yield estimates, but published studies cover a large range of rather intensive systems, including plantations with artificial shade (Supplementary Material Table 1), potentially explaining lower yields in rather extensively managed Malagasy agroforests. Our mean yield estimate of 154.6 kg ha^{-1} translates into gross earnings of annually 4684 € ha^{-}

[1], exhibiting the exceptional income opportunity vanilla provides under the high prices of the year 2017 (Hänke and others, 2018). However, an average rural household in the study region only sells 51.6 kg of green vanilla per year (Hänke and others 2018; also including households which did not sell any vanilla) and labour demands for the crop are high (Correll, 1953). Furthermore, high vanilla prices have led to a surge in local living costs, which are estimated at 5751 € per household and year (Hänke & Fairtrade International, 2019), and vanilla theft is commonplace (Neimark and others, 2019), further impairing the situation for farmers.

In contrast to other studies (Havkin-Frenkel & Belanger, 2018; Santosa and others, 2005), we do not see yield declines after a certain plantation age (**Figure 2**, SM Table 1). The explanation for this is twofold: farmers constantly establish new *pieds*, resulting in old agroforests that still contain vanilla vines of young and medium age *(DAM personal observation)*. Furthermore, constant 'looping' of vines on the same *pied* is common: hereby, vanilla vines are guided back down to the soil where new roots establish (Fouché & Jouve, 1999). The originally planted part of the vine may die at some point, but the vanilla plant can survive due to the water and soil access that the additional roots provide. Given that new *pieds* are also propagated by vine-cuttings (Fouché & Jouve, 1999; Havkin-Frenkel & Belanger, 2018), planting of new pieds and looping are comparable processes. In combination with the relatively short time to first produce (circa three years; Havkin-Frenkel and Belanger 2018), the looping of vanilla vines may lead to stable yields over time and could thus avoid boom and bust cycles. Such cycles are a common occurrence in other agroforestry crops like cacao (Clough and others, 2009) and refer to farmers realising short-term increases in yields through shade tree removal at the expense of associated biodiversity and ecosystem functions (Tscharntke and others, 2011). The resulting yield increase may be followed by a decrease, caused by elevated pest pressure and dwindling soil fertility (Clough and others, 2009). Falling yields prompt the abandoning of plantations and further forest conversion to agroforestry elsewhere (Clough and others, 2009). The likely absence of these busts in vanilla agroforests does hence point towards the long-term sustainability of these agroforestry systems.

We also found no link between precipitation and vanilla yields using down-scaled climate data (**Figure 2**, SM Table 1), suggesting that all villages where this data was collected have suitable general growing conditions. Nonetheless, the data is not year- or season-specific and can thus only represent general differences in precipitation between sites, possibly hiding effects caused by exceptionally dry or wet years or seasons.

Increasing vanilla yields without impairing canopy cover

We show that vanilla yields vary independently of canopy cover suggesting that no trade-offs exist between yields and maintaining or restoring trees (**Figure 2**, SM Table 1), much in contrast to comparable crops, where yields typically decline above 40% canopy cover, for example in cacao (Blaser and others, 2018; Clough and others, 2011) or coffee (Jezeer and others, 2017; Perfecto and others, 2005). The here-shown independence of yields and canopy cover enables farmers to maintain remnant forest trees, which are highly beneficial for ecosystem services and biodiversity (Tscharntke and others, 2011), in forest-derived agroforests, at no direct cost. Furthermore, tree and canopy cover rehabilitation in open-land-derived agroforests is also possible without compromising on yields. The independence of vanilla yields and shade is supported by plant-physiological experiments which show that vanilla performs well under various light regimes (Díez and others, 2017).

Interestingly, vanilla planting density was independent of canopy cover and canopy height (**Figure 2**3, SM Table 2). This suggests that closing yield gaps is possible by planting vanilla *pieds* more densely and that doing so does not *per se* impair canopy cover or height within the currently existing planting density range. Maintaining or promoting trees will likely have positive effects on biodiversity and ecosystem functions (Leakey, 2014; Tscharntke and others, 2011). For example, predation rates rise with increasing stem density in vanilla agroforests of north-eastern Madagascar (Schwab and others, 2020), indicating that trees promote pest control. In sum, the possibility to plant vanilla more densely without impairing canopy cover further strengthens the case for sustainable intensification opportunities in vanilla agroforestry.

Limitations of yield data

Despite methodological improvements over, to our knowledge, all previous studies (SM Table 1), this study lacks detail on many potential drivers of vanilla yields. This is highlighted by the strong random intercept variance. The random effect ‘household’ might reflect differences in management practices between households (Hänke and others, 2018), while ‘village’ might represent biotic or abiotic village-level effects, such as different soil properties. We also acknowledge that the estimation of the weight of stolen vanilla pods, which we had to factor in for ~12% of agroforests, brings in additional uncertainty. Lastly, our study cannot draw conclusions beyond the range of the data examined, for example the effects of shade on vanilla yields in highly intensified systems. We thus call for more research on vanilla yield determinants that may generate more applicable management advice for farmers.

Increasing canopy cover and tree height over time

Tree rehabilitation in agroforestry systems is a global priority (FAO, 2017). However, many tropical agroforests of key cash crops like cacao or coffee are forest-derived, thus typically contributing to forest degradation rather than tree rehabilitation (Martin, Osen, and others, 2020). Open-land derived agroforests, on the other hand, may contribute to tree rehabilitation, but empirical chronosequences that document tree recovery in open-land derived agroforests are rare (but see Nijmeijer and others (2019)). Here we show that canopy cover is higher in older forest- and open-land-derived agroforests than in younger ones (**Figure 2**, SM Table 2). Furthermore, trees were taller in older open-land-derived agroforests, but not in older forest-derived agroforest (**Figure 2**, SM Table 3). This suggests that open-land-derived agroforests can play a key role in tree rehabilitation, given that they originate from open fallow land. They could thus contribute to increased carbon storage (Nair and others, 2009) and the restoration of ecosystem services (De Beenhouwer and others, 2013) while providing new habitat for tree-dependent taxa (Clough and others, 2011). To what extent this will be the case also depends on the tree species that farmers allow to regenerate or plant. Here, native trees will be necessary for many biodiversity benefits while introduced fruit and timber trees could provide benefits to farmers (Tscharntke and others, 2011).

In contrast to open-land-derived agroforests, canopy cover in forest-derived agroforests will likely only recover after an initial drop at the time of establishment (Martin, Osen, and others, 2020), which is not covered here as our chronosequence does not include forest fragments. The stable tree height is in line with this interpretation, as the removal of single trees at time of establishment may not reduce mean tree height at the plot level. Alternatively, the resulting chronosequence could also stem from a change of practices over time, resulting in recently established forest-derived agroforests with low canopy cover in the chronosequence.

Taken together, our results show that forest-derived vanilla agroforests may have relatively stable canopy cover over time and highlight the potential of open-land-derived agroforests to restore ecosystem functions in cultivated landscapes. The transformation of land under shifting cultivation into cash cropping systems is furthermore in line with regional (Andriatsitohaina and others, 2020) and global trends (van Vliet and others, 2012).

Canopy cover dynamics in the agricultural landscape

We used remotely sensed canopy cover data to explore how observed plot-scale tree rehabilitation translates to the landscape-scale. Comparing canopy cover changes between 2000 and 2010, we found that areas with lowest initial canopy cover, probably mostly rice paddies, had stable canopy cover (**Figure 2**4, SM Table 4). This is to be expected, given the high productivity of irrigated rice and its local importance for food security (Hänke and others, 2018; Laney & Turner, 2015), which make a conversion of rice paddies to other land uses unlikely. Areas with very high canopy cover, i.e. forest fragments around villages, lost canopy cover over time. Here, small losses may represent forest degradation through selective logging for timber or through the establishment of new forest-derived vanilla agroforests. Some of these areas also showed large losses, likely reflecting shifting cultivation, where forest is cut and burned for hill rice cultivation (**Figure 4**).

Areas with medium to high initial canopy cover showed increases in canopy cover, most likely representing fallows that were transformed to open-land-derived vanilla agroforests. Here, the cessation of repeated burning for shifting cultivation, that comes with the establishment of permanent agroforestry, may have enabled tree rehabilitation on the land, as observed inside the plots.

Overall, theses dynamics resulted in a net increase in canopy cover on the landscape scale, as observed for agricultural landscapes across Madagascar (Zomer and others, 2016). The combination of canopy cover gains and losses may be positive for species and ecosystem services that can be provided by areas with medium canopy cover, such as the provision of fruit or firewood. Forest-dependent species and ecosystem services that depend on high canopy cover, as found in forest, will suffer. Conservation of remaining forests is thus necessary to conserve the large share of Malagasy biodiversity that cannot persist outside forest (Irwin and others, 2010). Furthermore, the forests of north-eastern Madagascar have some of the highest carbon stocks of all Malagasy forest (Vieilledent and others, 2016), underlining the importance of forest conservation also in light of climate change mitigation. Importantly, these findings are limited to the agricultural landscape around 60 focal villages that are predominantly not at the deforestation frontier. Canopy cover dynamics might be different around villages closer to large connecting forest blocks, where an overall increase in canopy cover seems unlikely given the ongoing deforestation trend in north-eastern Madagascar (Vieilledent and others, 2018). Further research elucidating the differences in canopy cover dynamics between villages close and far away from the forest frontier will hence be highly relevant.

Conclusion

Our main finding, that yields and canopy cover in vanilla agroforests of north-eastern Madagascar varied independently, suggests the possibility to combine high vanilla yields with a high tree cover. This has potential benefits for ecosystem services and biodiversity in a globally important biodiversity hotspot. Our finding contrasts with other agroforestry crops for which higher canopy cover typically impairs yields. Furthermore, the higher canopy cover in older compared to younger vanilla agroforests suggests opportunities to rehabilitate landscapes by enhancing tree cover in open-land-derived agroforests. If coupled with effective protection of remaining forests, yield-neutral tree recovery in agroforestry systems could contribute to a multifunctional and biodiversity-friendly agricultural landscape.

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