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

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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 inside forest. However, trade-offs between shade and crop yields are common across many agroforestry crops, driving shade-tree loss in forest-derived agroforests and hindering tree rehabilitation in open-land-derived agroforests. To investigate whether this common dynamic plays a role in vanilla agroforests, we studied 209 vanilla agroforests along an 88-year chronosequence in Madagascar and used remotely-sensed canopy cover data to investigate tree rehabilitation 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 open-land-derived vanilla agroforests gained 32.6% canopy cover over 60 years, whereas forest-derived agroforests only gained 14.2%. Canopy cover increased also at the landscape scale: Areas in the agricultural landscape with medium initial canopy cover gained 6.4% canopy cover from 2000 to 2010, but areas with high initial canopy cover lost canopy cover. These opposing trends suggest tree rehabilitation across areas covered by vanilla agroforests, whereas remnant forest fragments in the agricultural landscape were transformed or degraded. Overall, forest-dependent ecosystem functions may thus suffer while functions provided by areas with medium canopy cover may benefit. Our results suggest that yield-neutral tree rehabilitation through agroforestry could, if coupled with effective forest protection, provide a win-win situation for ecosystem functions and agricultural production in smallholder-dominated agricultural landscapes.

Justification statement

Agroforestry is promoted as a way to restore trees in historically forested open landscapes, but trade-offs between shade tree cover and yields are common across many tropical agroforestry crops like coffee or cacao. Using data from an 88-year chronosequence with 209 agroforests, we show that such trade-offs do not exist for vanilla, an important cash crop in the biodiversity hotspot Madagascar. This offers an opportunity for win-win situations between ecosystem functions and biodiversity on the one hand, and farmers income on the other. Furthermore, we show that vanilla agroforests gain canopy cover over time as trees rehabilitate on land formerly used for shifting cultivation. Local-scale gains may also translate to landscape-scale, where canopy cover increased within the agricultural landscape. This finding highlights opportunities for tree rehabilitation on farmland that may increase connectivity between increasingly fragmented Malagasy forests. Yield-neutral tree rehabilitation in vanilla agroforests has thus the potential to restore ecosystem functions and services on the plot- and landscape-scale while offering an economically viable option for smallholder farmers.

Introduction

Rehabilitation of historically forested open land is widely advocated to re-establish connectivity and ecosystem functions in tropical rainforest landscapes (Bastin et al., 2019; Chazdon, 2003). To date, governments and institutions have made pledges to restore 140 million hectares of land in the tropics (Brancalion et al., 2019). However, realizing those pledges could compete with food security, questioning how feasible (Eitelberg et al., 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 et al., 2016; FAO, 2017). Particularly agroforests that are established on historically forested open-land hold a large potential, because open-land-derived agroforests rehabilitate open land (Martin, Osen, et al., 2020). Thereby, the focus lies on the rehabilitation of ecosystem functions, without necessarily restoring ecological integrity (Chazdon et al., 2016). Agroforests that are established inside forests, on the other hand, typically contribute to forest degradation, thus hampering ecosystem functioning (Martin, Osen, et al., 2020).

Nonetheless, trade-offs between shade cover and yields are common across many key agroforestry crops (Tscharntke et al., 2011), limiting their potential to contribute to tree rehabilitation in tropical rainforest landscapes. Such shade-yield trade-offs are exemplified in coffee and cacao agroforests (Blaser et al., 2018; Steffan-Dewenter et al., 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 or subsidies (Tscharntke et al., 2014). In their absence, a decrease in canopy cover and tree height over time commonly occurs (Tscharntke et al., 2011), but time series or chronosequences, which are necessary to identify trends, are rare (see Nijmeijer et al. (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 vanilla. When farmed in agroforestry systems, the vanilla orchid *(Vanilla planifolia)* is typically hung up on 'tutor 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 over recent years, triggering the expansion of vanilla farming (Hänke et al. 2018; Llopis et al. 2019, Supplementary Material Figure 1).

In north-eastern Madagascar, vanilla is the main cash crop for smallholder farmers (Hänke et al., 2018) who produce 40% of the world's vanilla (FAO, 2020). Here, vanilla is almost exclusively produced in rather extensively managed agroforestry systems, partly in contrast to other production areas such as La Réunion or Mexico, where shade houses are common (Havkin-Frenkel & Belanger, 2018). 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 fallow, that form part of the shifting cultivation cycle locally known as *tavy* (Martin, Andriafanomezantsoa, et al., 2020; Styger et al., 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 et al., 2020; Zaehringer et al., 2015). This dynamic is consistent with trends across most of Africa, but contrasts with trends in the remaining tropics (Curtis et al., 2018; van Vliet et al., 2012).

Vanilla agroforests may be established inside forest fragments or on open fallow land, thereby differing in land-use history (Martin, Osen, et al., 2020). Forest-derived vanilla agroforests degrade the forest they are established in but will typically be superior to shifting cultivation (Martin, Osen, et al., 2020), i.e. the replacement of forest with hill rice cultivation, for ecosystem function and biodiversity. Open-land-derived agroforests may instead rehabilitate land formerly under hill rice cultivation, as their establishment stops the re-occurring fires which characterize the shifting hill rice cultivation system (Holloway, 2004; Styger et al., 2007). In north-eastern Madagascar, 30% of vanilla agroforests are forest-derived while 70% are open-land-derived (Hänke et al., 2018), further underlining the rehabilitation opportunity offered by open-land-derived agroforestry. The potential of Madagascar to contribute to tree rehabilitation is also recognized in the recent study by Brancalion et al. (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 a biodiversity hotspot (Myers et al., 2000), exacerbating the need for both effective biodiversity conservation within the existing protected areas as well as restoration within the agricultural landscape.

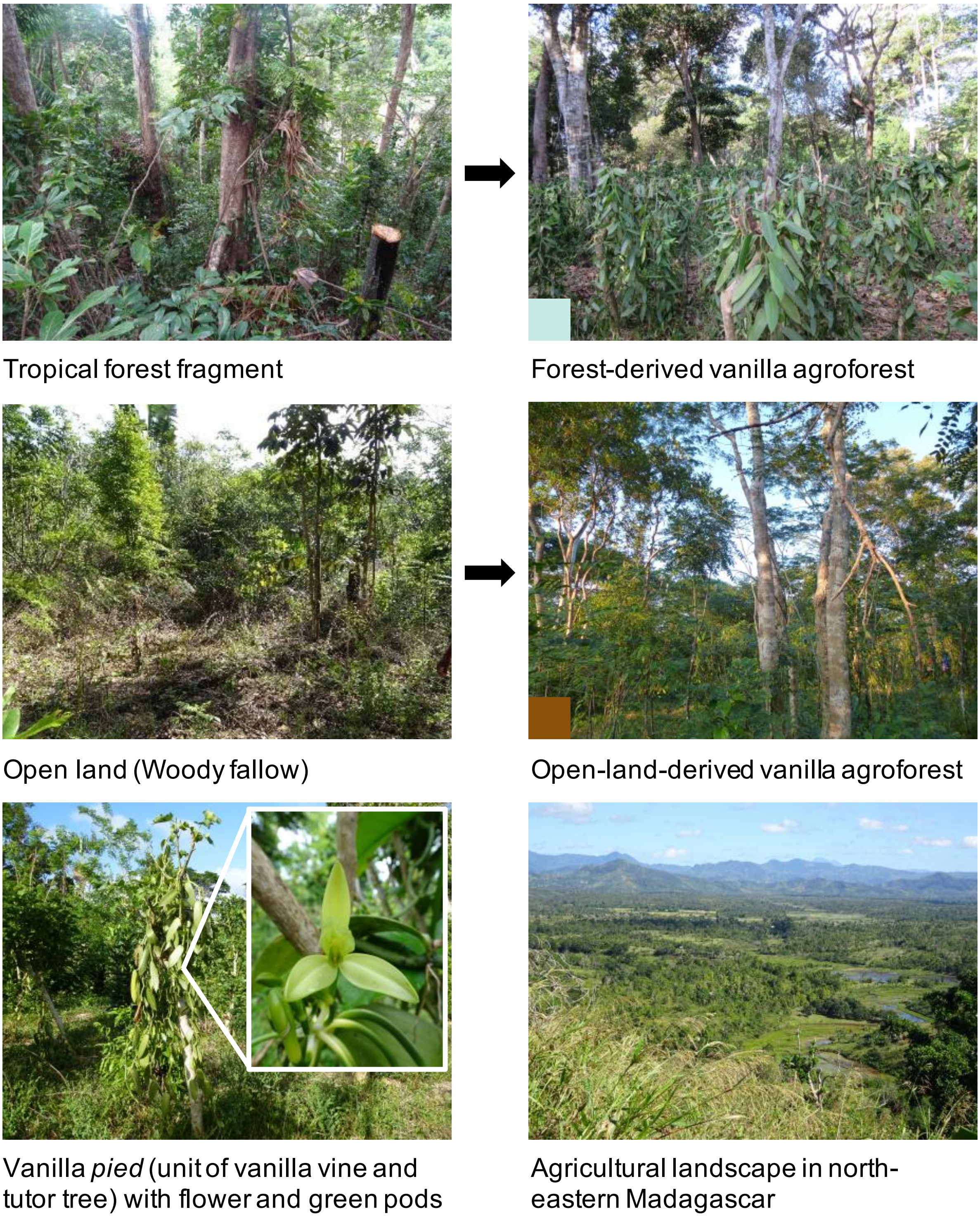

Figure 1: Top row: Forest-derived vanilla agroforests are directly established inside forest. Middle row: Open-land-derived vanilla agroforest are established on open land, typically woody fallow. Bottom row: Vanilla pied and agricultural landscape in north-eastern Madagascar where the study took place. 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 aim to 1) understand how land-use history, canopy cover, agroforest age, planting density and precipitation influence vanilla yields, 2) assess tree rehabilitation dynamics across vanilla agroforests of different age and of contrasting land-use history, and 3) investigate 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 on the landscape-scale.

Methods

Study region

The SAVA region of north-eastern Madagascar is the historic (Correll, 1953) and current (Hänke et al., 2018) center of global vanilla production and a biodiversity hotspot (Brown et al., 2016; Myers et al., 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 et al., 2017)). The potential natural vegetation is tropical rainforest (Vieilledent et al., 2018), but only 35% forest cover remains in the SAVA region (Ferreira Arruda, 2018).

Data collection in agroforests

We conducted our field studies in a total of 115 forest-derived and 94 open-land-derived agroforests (209 in total) owned by 152 households across 14 villages (see Supplementary Materials for village and agroforest selection). 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 native 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 tutor 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, Osen, et al. 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. 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 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 et al., 2017). Observers held a 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* respectively the year of establishment of their agroforest, leading to missing data for planting density and agroforest age in 8 respectively 3 cases (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 (Karger et al., 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 et al., 2018).

Analysis of vanilla yields, canopy cover and canopy height

We used 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. 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 et al., 2013). Due to the highly right-skewed nature of the age and planting density data, we square root transformed these two variables.

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.

In all models, 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. In the yield model, none of the interactions were significant, prompting us to present a 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. In the canopy cover model, none of the interactions were significant but we kept the interaction between land-use history and age despite a p-value of 0.109 because we aimed at comparable and similarly complex models for canopy height and canopy cover. All models are presented in full and reduced (i.e. final) form in the Supplementary Materials (Supplementary Materials Table 1-3).

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 et al., 2018). We 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. To visualize the models, we calculated estimated marginal means and their 95% confidence intervals using the R-Package *emmeans* version 1.4.5 (Length et al., 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 et al., 2013). Using the *raster* R-package version 3.0.12 (Hijmans et al., 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 then excluded areas that fell in the sea and restricted both layers to an area of 2 km around the centres of 60 focal villages 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 et al., 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 initial canopy cover int the year 2000 determined the 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.

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 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 et al., 2018), this average yield translates into gross earnings of 4684 € ha^{-1}. 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; N = 209; p = 0.6423). 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 correlated to canopy cover and annual precipitation. Yields were positively correlated with 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)

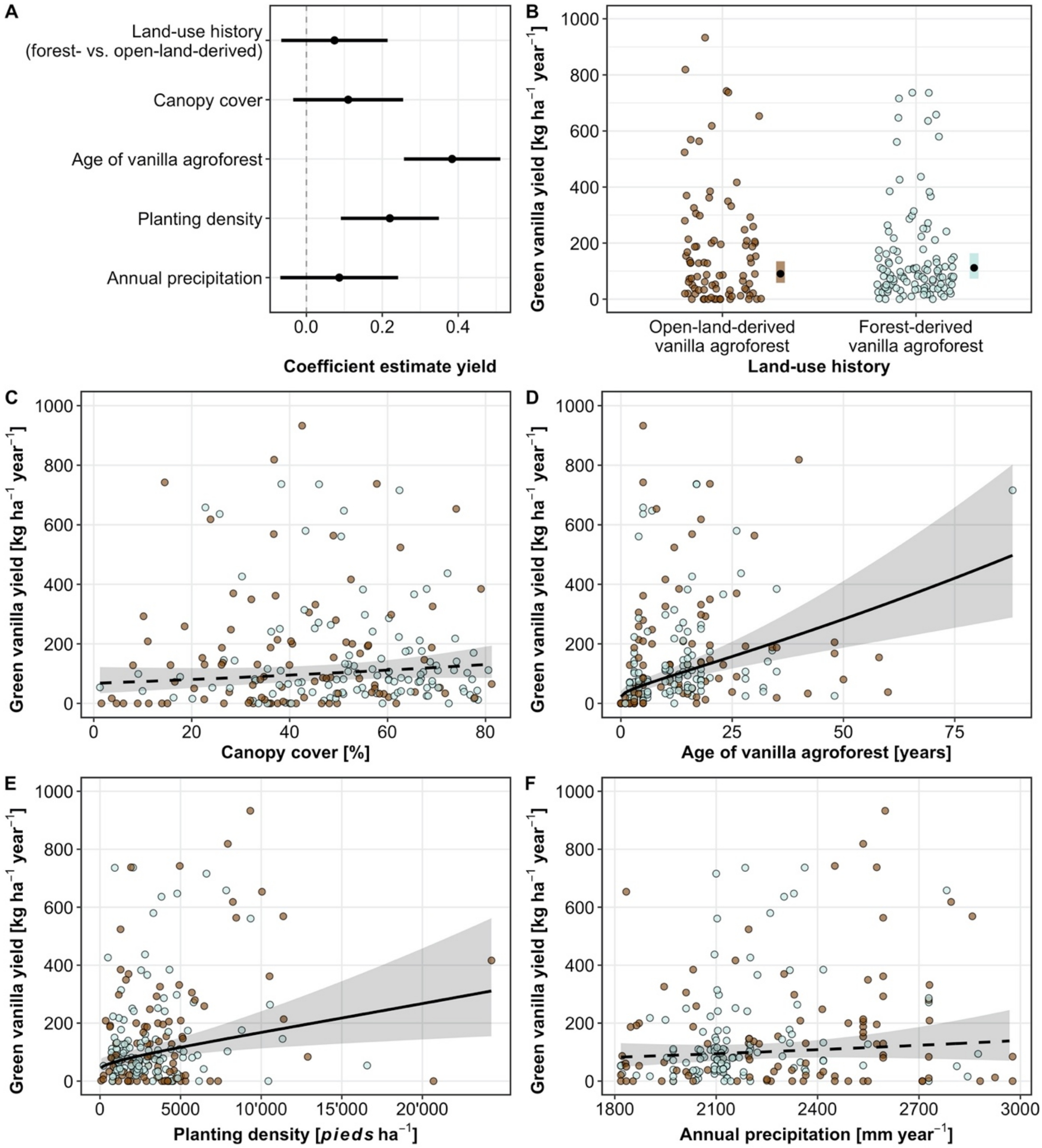

Figure 2: Results of a linear mixed effect model explaining green vanilla yield [kg ha^{-1}] across 209 agroforests. A: Scaled effect plot of the reduced yield model for all five predictors. B-F: Green vanilla yields as a function of land-use history (B), canopy cover [%] (C), age of vanilla agroforest [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 respectively black dots 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 12.9% (estimated marginal means 4.9%) higher in forest-derived vanilla agroforests compared to open-land-derived agroforests (Figure 3). The age of the agroforests differed along the chronosequence between 1 and 88 years in forest-derived vanilla agroforests and between 0 and 60 years in open-land-derived agroforests. Age positively correlated with canopy cover, in both forest- and open-land derived agroforestry: In open-land-derived agroforests, canopy cover increased by 32.6% over 60 years, while canopy cover only increased by 14.2% in forest-derived agroforests over 60 years (17.6% over 88 years). Similarly, canopy height was 8.2 m (estimated marginal means 5.2 m) higher in forest-derived agroforests compared to open-land-derived agroforests. The age of the agroforest positively affected canopy height in open-land-derived agroforests where canopy height increased on average by 8 m over 60 years while canopy height decreased by 1.7 m in forest-derived agroforests over 60 years (2.1 m over 88 years).

Vanilla planting density did not correlate with canopy cover or height. Furthermore, agroforests with more surrounding forest cover had higher trees and higher canopy cover, but confidence intervals overlapped zero for the latter. Elevation was negatively associated with both tree height and canopy cover. The canopy cover model had a marginal R^2-value of 0.34 and a conditional R^2-value of 0.56, while the canopy height 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: τ_{00} = 0.16 / canopy height model: τ_{00} = 0.37); the random intercept variance for the random effect ‘village’ was small (canopy cover model: τ_{00} = 0.07 / canopy height model: τ_{00} = 0.02).

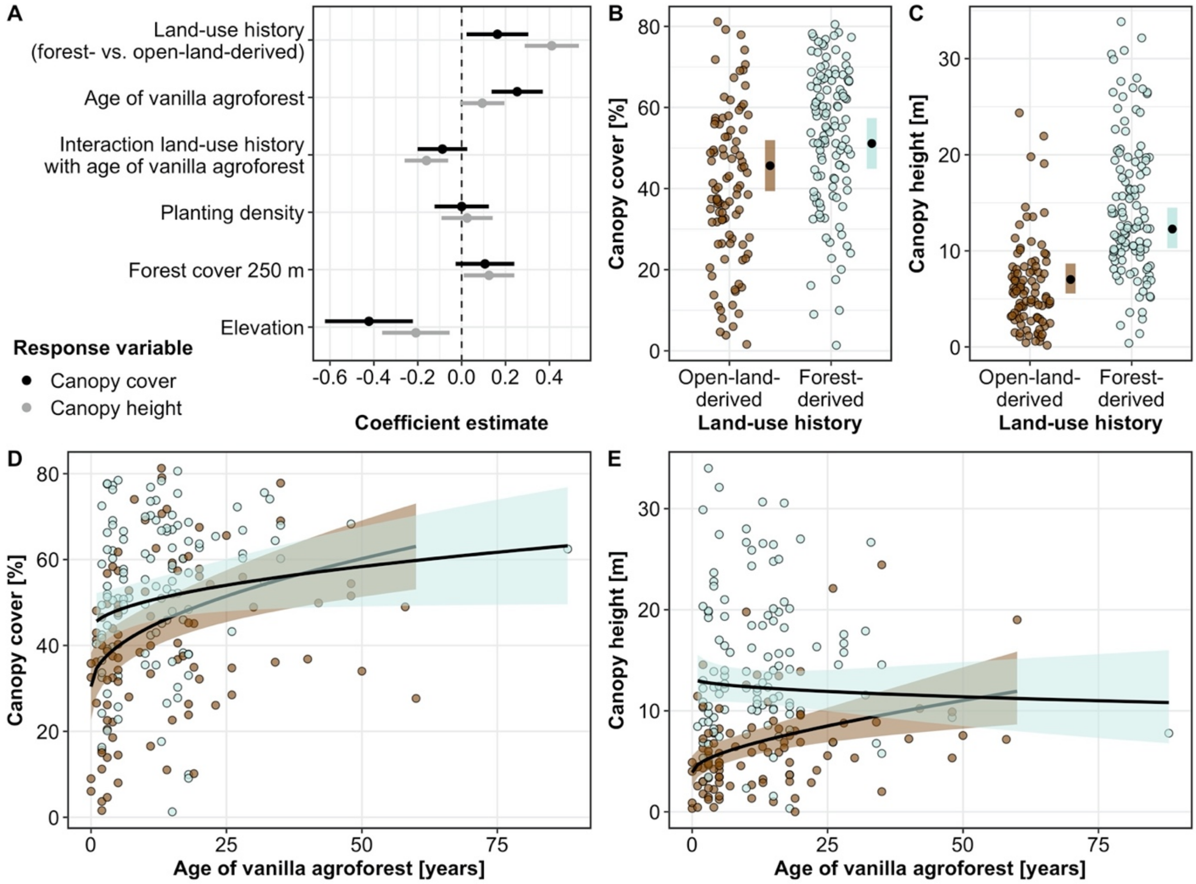

Figure 3: Results of two linear mixed effect models explaining canopy cover [%] and canopy height [m] across 209 vanilla agroforests. A: Scaled effect plot of the reduced canopy cover model (black) and the reduced canopy height model (grey) for all five predictors, including the interaction between land-use history and age [years]. 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, an effect that was stronger in open-land-derived agroforests. E: Older agroforests also had higher canopies, but only if open-land-derived. Lines respectively black dots 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 in the discussion, SM Table 4). Areas with medium to high initial canopy cover experienced an increase in canopy cover of up to 6.4% at 68.3% initial canopy cover (Figure 4 A). Areas with very high initial canopy cover lost 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.

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 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 ha^{-1}. This variability was driven by variable yields per *pied* (unit of tutor tree and vanilla vine) and planting densities. Such variability is typical for smallholder agroforests in tropical countries (Clough et al., 2011) and points towards large yield gaps caused by sub-optimal management practices (Lobell et al., 2009). This also suggests a large intensification potential in existing agroforests and opportunities for sustainable intensification (Tilman et al., 2011). Our yield estimate of 154.6 kg green vanilla per hectare 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. The here-reported 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 et al., 2018). However, an average rural household in the study region only sells 51.6 kg of green vanilla per year (Hänke et al. 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 et al., 2019), further impairing the situation for farmers.

In contrast to other studies (Havkin-Frenkel & Belanger, 2018; Santosa et al., 2005), we do not see yield declines after a certain plantation age. 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 thus die at some point, but the vine survives thanks to the secondary access to water and soil nutrients. 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 3 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 et al., 2009) and refer to farmers realising short-term increases in yields through shade trees removal at the expense of associated biodiversity and ecosystem functions (Tscharntke et al., 2011). The resulting yield increase may be followed by a decrease, caused by elevated pest pressure and dwindling soil fertility (Clough et al., 2009). Falling yields prompt the abandoning of plantations and further forest conversion to agroforestry elsewhere (Clough et al., 2009). The likely absence of these busts in vanilla agroforests does hence point towards the stability of the agroforestry system.

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 weight of the random effects. The random effect 'household' might reflect differences in management practices between households (Hänke et al., 2018), while 'village' might represent biotic or abiotic village-level effects, such as different soil properties. We thus call for more research on vanilla yield determinants that may generate more applicable management advice for farmers.

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, much in contrast to comparable crops where yields typically decline above 40% canopy cover, for example in cacao (Blaser et al., 2018; Clough et al., 2011) or coffee (Jezeer et al., 2017). The here-shown independence of yields and canopy cover enables farmers to maintain remnant forest trees in forest-derived agroforests, which are highly beneficial for ecosystem services and biodiversity (Tscharntke et al., 2011), 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 et al., 2017).

Interestingly, vanilla planting density was independent of canopy cover and canopy height. 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. Given the benefits of trees for biodiversity and ecosystem functions and services (Leakey, 2014; Tscharntke et al., 2011), this further strengthens the case for sustainable intensification opportunities in vanilla agroforestry.

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, et al., 2020). Here, open-land derived agroforests may contribute to tree rehabilitation, but empirical chronosequences that document tree recovery in open-land derived agroforests are rare (but see Nijmeijer et al. (2019)). Here we show that canopy cover is higher in older forest- and open-land-derived agroforests than in younger ones. Furthermore, trees were higher in older open-land-derived agroforests, but not in older forest-derived agroforest. 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 et al., 2009) and the restoration of ecosystem services (De Beenhouwer et al., 2013) while providing new habitat for tree-dependent taxa (Clough et al., 2011). The transformation of land under shifting cultivation into cash cropping systems is furthermore in line with regional (Andriatsitohaina et al., 2020) and global trends (van Vliet et al., 2012).

In contrast to open-land-derived agroforests, canopy cover in forest-derived agroforests will likely only recover after an initial drop at time of establishment (Martin, Osen, et al., 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, i.e. farmers today cut more trees at time of establishment than they did in the past, resulting in recently established forest-derived agroforests with low canopy cover in the chronosequence.

Taken together, our results highlight the value of open-land-derived agroforests for tree rehabilitation and shows that forest-derived vanilla agroforests may have relatively stable canopy cover over time.

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. This is to be expected, given the high productivity of irrigated rice and its local importance for food security (Hänke et al., 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).

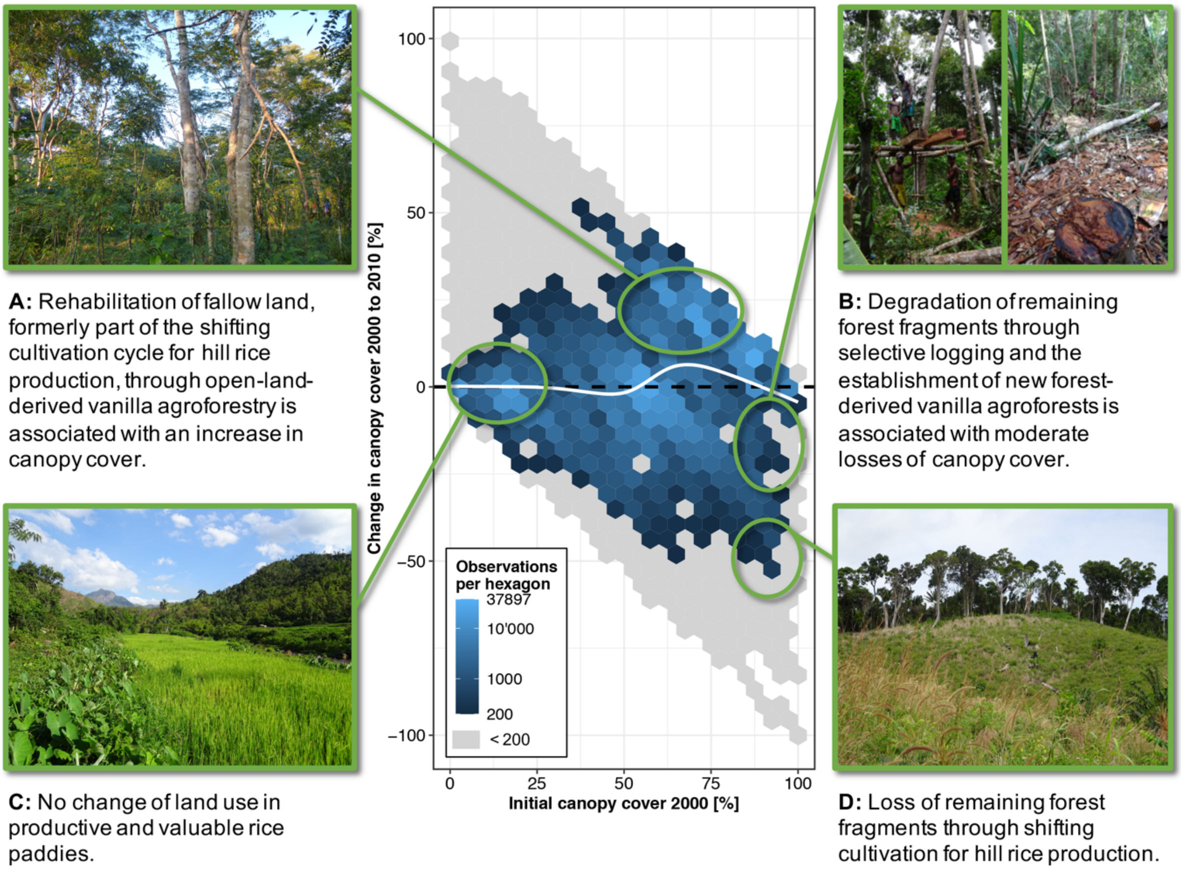

Figure 4: Canopy cover dynamics in the agricultural landscape in a 2 km circle around centres of 60 focal villages between 2000 and 2010 using canopy cover raster data with 30 m resolution (Hansen et al., 2013). Canopy cover increased overall by 2.7%, driven by canopy cover increase in areas with medium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

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 et al., 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 et al., 2010; Martin, Andriafanomezantsoa, et al., 2020). Furthermore, the forests of north-eastern Madagascar have some of the highest carbon stocks of all Malagasy forest (Vieilledent et al., 2016), underlining the importance of forest conservation 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 in villages closer to large connecting forest blocks, where an overall increase in canopy cover seems unlikely given the ongoing deforestation trend in Madagascar (Vieilledent et al., 2018).

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 cover of trees. 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 tree rehabilitation opportunities in open-land-derived agroforests. If coupled with effective protection of remaining forests, yield-neutral tree recovery in agroforestry systems could provide a win-win situation for ecosystem functions, such as carbon storage, and agricultural production in smallholder-dominated agricultural landscapes.

Authors' contributions

All authors conceived ideas and planned data collection and analysis. DAM, AW, and KO coordinated the data collection; TR collected field data; DAM analysed and visualized the data; DAM led the writing of the manuscript. All authors contributed to the writing and gave final approval for publication.

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Data availability statement

Supplementary Materials, Data, and R-Code are available within the Open Science Framework (OSF): Martin, D. A., Wurz, A., Osen, K., Grass, I., Hölscher, D., Rabemanantsoa, T., Tscharntke, T., Kreft, H. (2020). Shade-tree rehabilitation in vanilla agroforests is yield neutral and may translate into landscape-scale canopy cover gains. *OSF*. https://doi.org/10.17605/OSF.IO/J64M8

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