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Annual biomass increment of Xerophytic thickets and sustainability of woody charcoal production in southwestern Madagascar

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ABSTRACT

The sustainability of woody charcoal production activity is analysed in xerophytic thickets in southwestern Madagascar. The above ground biomass productivity of xerophytic thickets and the biomass corresponding to woody charcoal production in the Soalara-Sud commune were estimated and compared. All individuals >3 cm diameter in 40 4×4 m^2 plots were harvested for above ground biomass measurements. Four treatments, defined by soil type (lixisol and calcisol) and distance from villages (near $\leq$ 4 km; far > 4 km), were tested. The growth rings, assumed to be annual, of the shrub trunk with the largest diameter, presumed to be the oldest specimen on each 4×4 m^2 plot, were counted to estimate the duration of biomass production on the plot. Above ground biomass productivity was estimated by the ratio between above ground biomass and growth rings number. The mean above ground biomass productivity varied between 0.38 and 0.99 t ha^{-1} year^{-1} of dry mass according to the four treatments. It did not vary significantly with soil type and increased with distance from villages on lixisol where woody charcoal is produced. The total above ground biomass of xerophytic thickets used for woody charcoal production on the current woody charcoal production site is around 862.55 t year^{-1} of fresh matter, equivalent to 107.82 t of woody charcoal. However, the effective woody charcoal production on the study site in 2013 was equal to 600.90 t, which is higher than the woody charcoal production allowed by the xerophytic thickets above ground biomass productivity. Consequently, woody charcoal production activity in the study site is unsustainable and will result in the disappearance of mature individuals belonging to species used for woody charcoal production in less than 15 years. Once this occurs, woody charcoal production will be moved to other xerophytic thickets on calcisol.

1. Introduction

Dry forests in western Madagascar are characterised by their high flora and fauna endemicity (Moat and Smith, 2007). Furthermore, they have high socio-economic value through the goods and services that they provide: (i) timber for building houses and pirogues, (ii) medicinal plants, (iii) food (tubers, honey and meat from hunted animals), (iv) fuelwood and woody charcoal and (v) land for agricultural use (slash-and-burn agriculture) or goat pastures. Woody charcoal (WC) is used exclusively to cook daily meals in the absence of alternative energy sources. Demand for charcoal is increasing with the growth of towns on the west coast (Girard, 2002; Minten et al., 2013; Gardner et al., 2015). The removal of wood to produce woody charcoal is the second most important cause of dry forest degradation in western Madagascar (Casse et al., 2004; Masezamana et al., 2013; Minten et al., 2013) after slash-and-burn agriculture (Blanc-Pamard et al. 2005; Raharimalala et al., 2010). WC production negatively impacts the structure of Malagasy dry forests, especially above ground biomass, tree/shub density and plant height (Randriamalala et al., 2016, 2017). However, it does not affect either dry forest regeneration or diversity (Randriamalala et al., 2016, 2017).

This study examines socio-environmental issues related to the sustainability of forest exploitation by tackling the little known case of xerophytic thickets (XT) in southwestern Madagascar. XT are dry forests located in the coastal zone of southwestern Madagascar, the

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driest part of the island (Randriamalala et al., 2016). WC production degrades these thickets (Raoliarivelo et al., 2010; Masezamana et al., 2013; Randriamalala et al., 2016, 2017), but the activity is an important source of income for the local population (Raoliarivelo et al., 2010; Masezamana et al., 2013). WC consumed by the town of Toliara comes essentially from surrounding XT (Masezamana et al., 2013; Gardner et al., 2015). Two actions were proposed to make WC production in the southwestern forest of Madagascar sustainable (Andrianarivony et al., 2008): (i) the transfer of forest management to local communities forming associations of WC producers, and (ii) the reorganization of the WC production chain. The first action consists of local communities and the regional direction of water and forest coming together and building a spatial forest management plan which defines forest exploitation modes (location and area of WC production sites and definition of the duration of the exploitation cycle). The second action consists mainly in setting production quotas by the WC producer associations and in increasing the efficiency of traditional charcoal kilns. However, the lack of data on annual biomass increment (forest productivity) is limiting the effectiveness of such initiatives. In fact, a condition of sustainable forest exploitation is that the weight of wood removed annually is lower than annual woody biomass increment. The absence of accurate data on forest productivity leads to the delimitation of WC production sites based on unverified assumptions. One, for example, is that a rotation must last 30 years. It is thus essential that forest woody productivity be estimated.

On the international level, assessments of forest productivity are essentially associated with tree plantations (Singh and Toky, 1997; Lodhiyal and Lodhiyal, 1997, 2003), humid forests (Chave et al., 2001, 2008; Hertel et al., 2009; Vasconcelos et al., 2012) and mangroves (Hossain et al., 2008; Komiyama et al., 2008). The methods generally used are diachronic (observing the same plots states at two periods t0 and t1), indirect and based on allometric equations. In contrast, few biomass increment assessments have been made in semi-arid ecosystems, and those which have been conducted generally concern only a few species and not the entire ecosystem (Paton et al., 1998; Mbow et al., 2013). In Madagascar, the woody productivity of dry secondary forests was assessed in the northern region using dendrochronological methods to evaluate their potential as sources of timber and fuelwood (firewood and charcoal; Lopez, 2004). It was shown that an exploitation cycle of 15 years associated with a mean exploitable diameter of 10 cm can be sustainable (Lopez, 2004).

This study aims to assess the sustainability of WC production in XT in southwestern Madagascar by comparing annual woody biomass removal and increment. We address the following question: is the woody charcoal production of XT a sustainable activity? In other words, is the annual removal of woody biomass undertaken in the framework of this activity lower than the annual increment of woody biomass?

2. Method

2.1. Study site

The study site, located on the Mahafaly plateau, Soalara-Sud commune, Toliara II District, in southwestern Madagascar (Fig. 1), was previously described by Randriamalala et al. (2016). The semi-arid climate of the study site is defined by a short rainy season (<500 mm) followed by a ≥9 months dry season (Raoliarivelo et al., 2010).

2.2. Practices of woody charcoal production on the study site

The production of woody charcoal (WC) on the study site was already described by Randriamalala et al. (2016). This activity is an important source of income for the local population. The entire production is exported by pirogue to the town of Toliara (Raoliarivelo et al., 2010; Masezamana et al., 2013; Ramaroson, 2014), about 25 km away by sea (Fig. 1).

Current WC production sites in the study area are located in the eastern part of Soalara commune at a distance of less than 4 km from nearby villages (Randriamalala et al., 2016). WC is only produced on degraded XT growing on lixisol, in an area estimated to be 8399.70 ha (shape file and GIS data of Randriamalala et al., 2015).

Fuelwood, which is used for cooking, is also collected from sites near villages, both on lixisol and cacisol. However, the corresponding woody biomass was not estimated in this study, which focuses only on WC. In fact, as firewood is gathered generally through the selective collection of dead and fallen branches rather than the falling of entire trees, the use of fuelwood rarely threatens sustainable forest management (Casse et al., 2004; Minten et al., 2013).

2.3. Annual woody charcoal (WC) production

Sacks of WC from Soalara-Sud commune unloaded at the Mahavatsy II harbour in Toliara were counted during 10 non-consecutive days in November 2013. This month belongs to a period (September–November) corresponding to a peak in the annual production of WC in Soalara-Sud Commune (Raoliarivelo et al., 2010). An overestimation of the amount of WC production is expected. In fact, all of the WC from the study site is taken to Toliara by pirogue and unloaded at this harbour (Raoliarivelo et al., 2010; Masezamana et al., 2013; Ramaroson, 2014). Six WC sacks were chosen randomly and were weighed to calculate the mean weight of the sacks, which all have the same size. WC production of the Soalara commune in 2013 was estimated by Eq. (1):

$$\mathrm{WCP} = \mathrm{E(NS)} \times \mathrm{E(SW)} \times \mathrm{ND}, \tag{1}$$

where E(NS) is the mean daily number of WC sacks unloaded at the harbour (10 observations), E(SW) is the mean weight of a WC sack (6 observations) and ND is the number of days that WC sacks are unloaded. The ND value is 313 because WC sacks arrive at the harbour every day except Sunday (ND = 365–52 = 313; Pers. Obs.).

2.4. Woody biomass productivity

2.4.1. Above ground biomass measurements

Field work was conducted in March 2012. Twenty $20 \times 20\ \mathrm{m}^2$ plots were randomly sampled along soil type and disturbance gradient characterised by distance from villages (Table 1). An inventory of all shrubs and lianas belonging to overstory vegetation (≥1.3 m height) was drawn up in each plot (Randriamalala et al., 2016). Surveys conducted with local guides enabled the identification of species fit for WC production (Appendix A) and the calculation of the proportion of WC species on each plot. Two $4 \times 4\ \mathrm{m}^2$ plots were randomly sampled on the $20 \times 20\ \mathrm{m}^2$ plot to evaluate above ground biomass (AGB) using the destructive total harvest method. Every plant on each $4 \times 4\ \mathrm{m}^2$ plot was cut at ground level and sorted into two subsets (diameter ≤3 cm and >3 cm) before weighing. Vegetal samples from the two subsets were collected and oven-dried at 85 °C during 72 h to estimate their humidity rate.

2.4.2. Age estimation

To estimate the age of each plot, the trunk with the biggest diameter on each $4 \times 4\ \mathrm{m}^2$ plot was harvested. It was assumed that this trunk belonged to the oldest plant on each plot. As dendrochronology methods can be applied to shrubs (Liang et al., 2012; Xiao et al., 2012; Srur et al., 2013; Zimowski et al., 2014; Oddi and Ghermandi, 2015), the rings of the largest shrub trunk

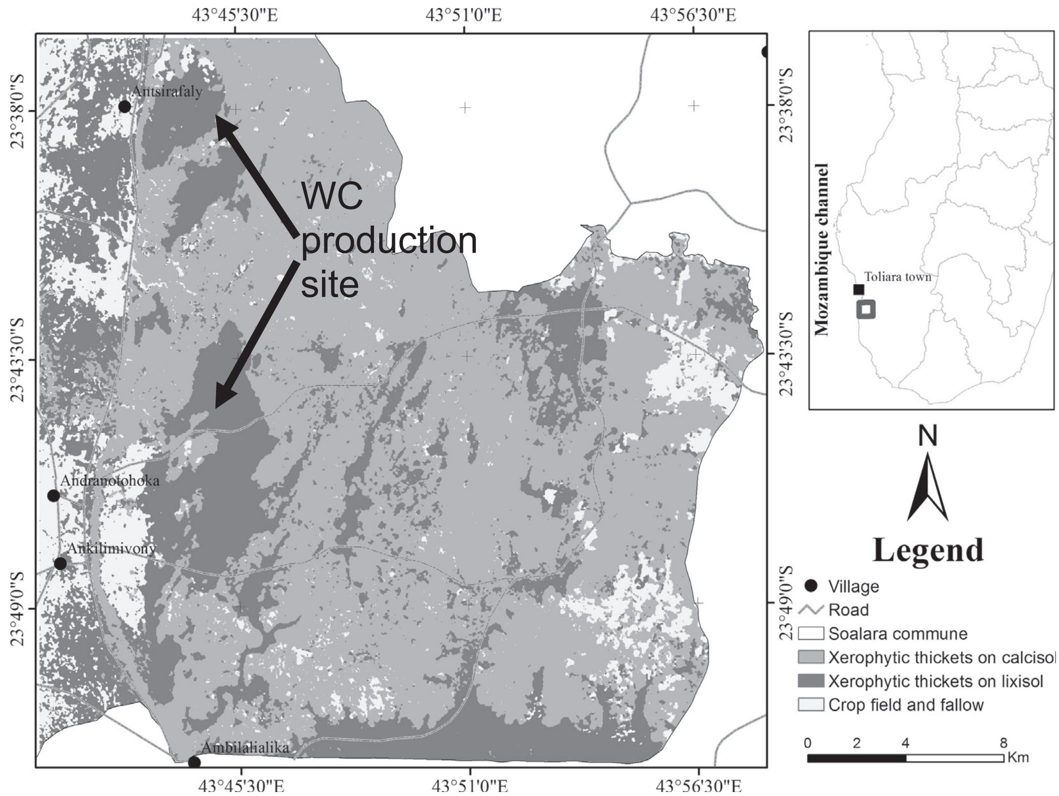

Fig. 1. Study site.

Table 1
Sampling design.

Soil type	Distance from village	Abbreviations	Number of 20 m × 20 m plots (species census)	Number of 4 m × 4 m plots (biomass and productivity)
Lixisol	Near villages (≤4 km)	SN	5	10
	Far from villages (>4 km)	SF	5	10
Calcisol	Near villages (≤4 km)	CN	5	10
	Far from villages (>4 km)	CF	5	10

on each 4 × 4 m^2 plot were counted to estimate how long shrubs had grown on the study site (Fig. 2). To date, only Gaspard (2016) has conducted a dendrochronological study on shrubs in a semi-arid zone of Madagascar in which she has demonstrated the annuality of the shrub growth rings of 9 shrubby species. The semi-arid climate of the study site, with a short rainy season followed by a long dry season, makes assumptions about the annuality of shrub growth rings plausible. Their number would thus correspond to shrub age. In total, 40 trunks belonging to 20 shrub species were harvested.

A disc was taken from the trunk with the largest diameter at a height of 30 cm when the first ramification appeared above this height and at the soil level when the first ramification appeared at or below 30 cm. In fact, shrubs in the study site generally

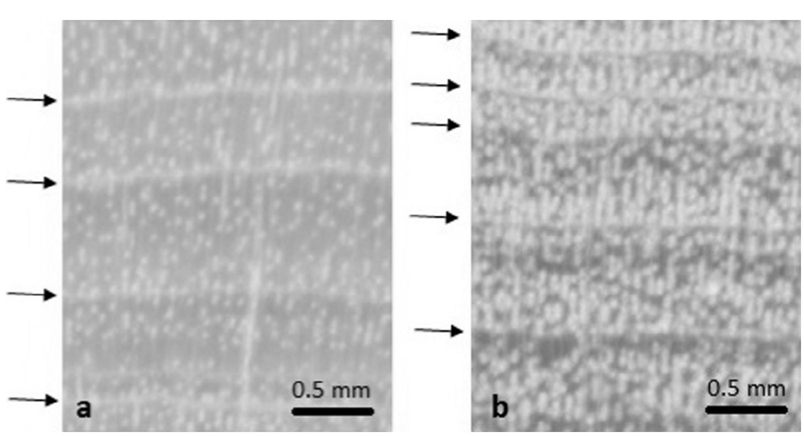

Fig. 2. Examples of macroscopic features of growth rings. Arrows indicate the growth boundaries: (a) *Cedrelopsis grevei*, (b) *Terminalia gracilipes*.

present a first branch ramification under a height of 50 cm and multi-branched individuals are frequently observed. Discs were dried in atmospheric conditions and were sanded progressively with sandpaper with a grain of P60 up to a grain of P800. Good polishing is needed to identify the anatomic characters of wood linked to ring limits (Maingi, 2006). Once sanded, the surface of the discs was examined macroscopically using a stereomicroscope to identify the occurrence of growth zones. All tree rings were marked with a pencil along 3 radii. The ring outline was followed every 5 rings to check if missing or false rings occurred and to avoid counting errors. When these were the case, individual tree rings were followed and missing/false rings were identified and corrected. After the tree rings were marked, the growth rings of each disk were counted.

2.4.3. Biomass productivity calculation

Above ground biomass productivity (AGBP) on each $4 \times 4\ m^2$ plot can be estimated by Eq. (2):

$$AGBP_{ij} = AGB_{ij}/RN_{ij}, \tag{2}$$

where $AGBP_{ij}$ is the above ground biomass productivity (t ha^{-1} $year^{-1}$ of dry mass) of the ith $4{\times}4\ m^2$ plot in the jth $20 \times 20\ m^2$ plot, AGB_{ij} is the above ground biomass (t ha^{-1} of dry mass) of the ith $4{\times}4\ m^2$ plot in the jth $20 \times 20\ m^2$ plot and RN_{ij} is the growth ring number of the ith $4{\times}4\ m^2$ plot in the jth $20 \times 20\ m^2$ plot.

ANOVA by the four treatments were applied to AGBP associated with (i) ≤3 cm AGB, (ii) >3 cm AGB and (iii) the entire AGB. ANOVA by the four treatments combining soil type and distance from villages were also applied to ring number.

2.5. Ecological sustainability of woody charcoal (WC) production

The analysis of the ecological sustainability of WC production consists of comparing the productivity of xerophytic thickets (XT) to the annual above ground biomass loss (AGBL) due to WC production activity. Above ground biomass (AGB) from >3 cm diameter trunks can only be used for WC production, ≤3 cm diameter twigs and branches serve to light the fire in the kiln. Furthermore, as only individuals belonging to species with hard wood can be used for the production of WC, the AGB for WC production in the jth $20 \times 20\ m^2$ plot can be estimated by Eq. (3):

$$AGB_{WCj} = (D_{wcj}/D_j) \times AGB_{j>3cm}, \tag{3}$$

where AGB_{WCj} is the above ground biomass for WC production on the jth plot (t ha^{-1} of fresh mass), D_{wcj} is the density of individuals belonging to species used for WC production on the same plot ($400\ m^{-2}$), D_j is the total density of shrub on the jth plot ($400\ m^{-2}$), $AGB_{j>3cm}$ is the above ground biomass from the >3 cm subset on the jth plot (t ha^{-1} of fresh mass), which is the mean of the above ground biomass from the >3 cm subset on the two $4{\times}4\ m^2$ plots within the jth $20 \times 20\ m^2$ plot.

The available AGB for WC production on the current production site is given by Eq. (4):

$$B_{wc} = E(AGB_{WCj}) \times S, \tag{4}$$

where B_{wc} is the available above ground biomass for WC production on the current production site (t of fresh mass), $E(AGB_{WCj})$ is the mean of above ground biomass for WC production (t ha^{-1} of fresh mass), S is the area of the current WC production site (ha; around 8399.70 ha according to data from Randriamalala et al., 2015).

Woody biomass productivity for WC production on the ith $4{\times}4\ m^2$ plot of the jth $20 \times 20\ m^2$ plot can be estimated by Eq. (5):

$$AGBP_{WCij} = AGB_{WCij}/RN_{ij}, \tag{5}$$

where $AGBP_{WCij}$ is the above ground biomass productivity for WC production on the ith $4{\times}4\ m^2$ plot of the jth $20 \times 20\ m^2$ plot (t ha^{-1} $year^{-1}$ of fresh mass), AGB_{WCij} is the above ground biomass for WC production on the ith $4{\times}4\ m^2$ plot of the jth $20 \times 20)\ m^2$ plot (t ha^{-1} of fresh mass), RN_{ij} is the growth ring number on the ith $4{\times}4\ m^2$ plot of the jth $20 \times 20\ m^2$ plot.

The above ground biomass productivity for WC production on the jth $20 \times 20\ m^2$ plot ($AGBP_{wj}$) is the mean of the two $AGBP_{WCij}$ on the same plot.

The total woody biomass productivity for WC production on the current production site can be estimated by Eq. (6):

$$BP_{wc} = E(AGBP_{WCj}) \times S, \tag{6}$$

where BP_{wc} is the available above ground biomass productivity for WC production on the current production site (t $year^{-1}$ of fresh mass), $E(AGBP_{WCj})$ is the mean of above ground biomass productivity for WC production (t ha^{-1} $year^{-1}$ of fresh matter) and S is the area of the current WC production site (ha).

The maximum WC production of the current production site can be estimated by Eq. (7):

$$WC_{max} = BP_{wc} \times CY, \tag{7}$$

where WC_{max} is the quantity of woody charcoal production corresponding to XT productivity (tWC $year^{-1}$), BP_{wc} is the available above ground biomass productivity for WC production on the current production site (t $year^{-1}$ of fresh mass), CY is the carbonisation yield (rate of WC produced/woody biomass used). The carbonisation yield taken into account is the 0.125 value estimated by Ramaroson (2014).

The annual AGB loss due to WC production is determined by Eq. (8):

$$AGBL = (WCP/CY) - BP_{wc}, \tag{8}$$

where AGBL is the annual above ground biomass loss due to WC production (t $year^{-1}$ of fresh mass), BP_{wc} is the available above ground biomass productivity for WC production on the current production site (t $year^{-1}$ of fresh mass), WCP is the annual WC production of the Soalara commune (t WC), CY is the carbonisation yield.

A WC production practice is not ecologically sustainable if the AGBL value is positive. When this is the case, the duration of the period before the extinction of the WC species on the WC production site can be estimated by Eq. (9):

$$T = B_{wc}/AGBL, \tag{9}$$

where T is the period before WC species extinction on the study site (year), B_{wc} is the available above ground biomass productivity for WC production on the current production site (t $year^{-1}$ of fresh mass), AGBL is the annual above ground biomass loss due to WC production (t $year^{-1}$ of fresh mass).

The errors associated to B_{wc}, BP_{wc} and T calculations can be estimated by applying the errors propagation principle (Ku, 1966; Farrance and Frenkel, 2012): if Y is a function of $X_1, X_2 \ldots X_n$ variables with uncertainties $\delta X_1, \delta X_2 \ldots \delta X_n$, the error associated to Y can be calculated by the general equation (10):

$$\delta Y^2 = ([dY/dX_1] \times \delta X_1)^2 + ([dY/dX_2] \times \delta X_2)^2 + \ldots + ([dY/dX_n] \times \delta X_n)^2, \tag{10}$$

where dY/dX_i is partial derivative of Y with respect to X_i.

X_i variables represent E(NS), E(SW), $E(AGB_{WCi})$ and $E(AGBP_{WCi})$ of Eqs. (1), (5) and (6) and δX_i are their standard errors.

3. Results

3.1. WC production and XT productivity

The mean weight of a WC sack from Soalara commune was 24.83 ± 0.76 kg and the mean daily number of WC sacks unloaded in Mahavatsy II harbour was 77.31 ± 14.25. Consequently, the WC production of the Soalara commune in 2013 was estimated to be 600.90 t.

The mean growth ring numbers in the four treatments ranged from 79 to 59. As the trunks harvested for ring number counting have the largest diameter, they are assumed to be the oldest individual shrubs on each plot, and the average maximum age of the plots ranged between 59 and 79 years. The mean ring numbers did not vary significantly with soil type nor with distance from village ($F = 1.512$, $p > 0.05$).

The mean total above ground biomass productivity (AGBP) varied from 0.38 to 0.99 t ha^{-1} year^{-1} of dry mass. The mean AGBP associated to the $\leq$3 cm trunk subset did not vary significantly with soil type nor with distance from village ($F = 0.441$; $p > 0.05$) (Fig. 3a). However, the mean AGBP associated to the >3 cm trunk subset and the total AGBP in lixisol increased with distance from village ($p < 0.01$) while the same categories of AGBP on calcisol did not vary with distance from village ($p > 0.05$; Fig. 3b and c).

Trunk biomass and total above ground biomass globally increase with growth ring number and reach a peak at 100–120 years according to the polynomial models linking these two kinds of variables (Fig. 4a and b). However such peak period estimation is not accurate because of great variability of AGB and trunk biomass that results in weak correlation between these variables and growth ring number ($r^2 = 0.37–0.39$): growth ring number explains less than the half of AGB and trunk biomass variability.

3.2. XT resilience to WC production and the sustainability of this practice

The available AGB for WC production on the current WC production site was 56362.72 t of fresh mass, and the corresponding AGBP was 862.55 t year^{-1} of fresh mass. This productivity is the equivalent of 107.82 t of WC which is largely lower than the WC production in 2013 (600.90 t). Consequently, the annual WC biomass loss was 3944.64 t year^{-1} of fresh mass and it is estimated that mature individuals belonging to WC species will disappear in less than 15 years (Table 2).

4. Discussion

4.1. Delicate shrub dendrochronology and stand age estimation

A dendrochronology approach to estimate the ages of shrubs is delicate due to their multi-trunks character. Zimowski et al. (2014)

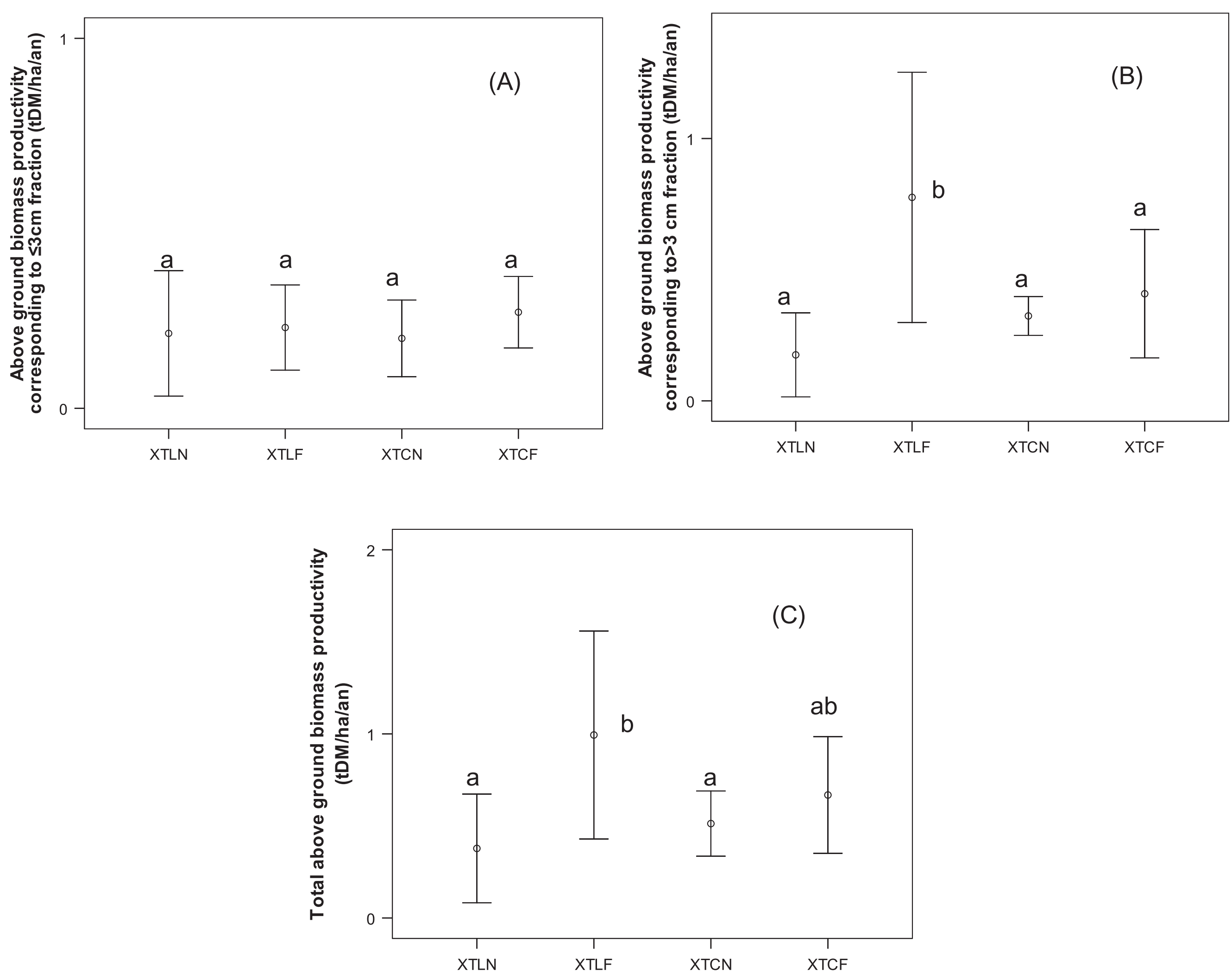

Fig. 3. Xerophytic thickets productivity. (a) Stem and twig (<3 cm; tDM ha^{-1} year^{-1}), (b) trunk (>3 cm; tDM ha^{-1} year^{-1}), (c) total above ground biomass productivity (tDM ha^{-1} year^{-1}). DM: dry mass; XTCF: Xerophytic Thickets on Calcisol Far from villages; XTCN: Xerophytic Thickets on Calcisol Near villages; XTLN: Xerophytic Thickets on Lixisol Near villages; XTLF: Xerophytic Thickets on Lixisol Far from villages; Vertical bar: Standard error ($p < 0.05$). Different letters, a, b and ab indicate significant differences among treatments after post hoc comparisons at a significance level of 0.05.

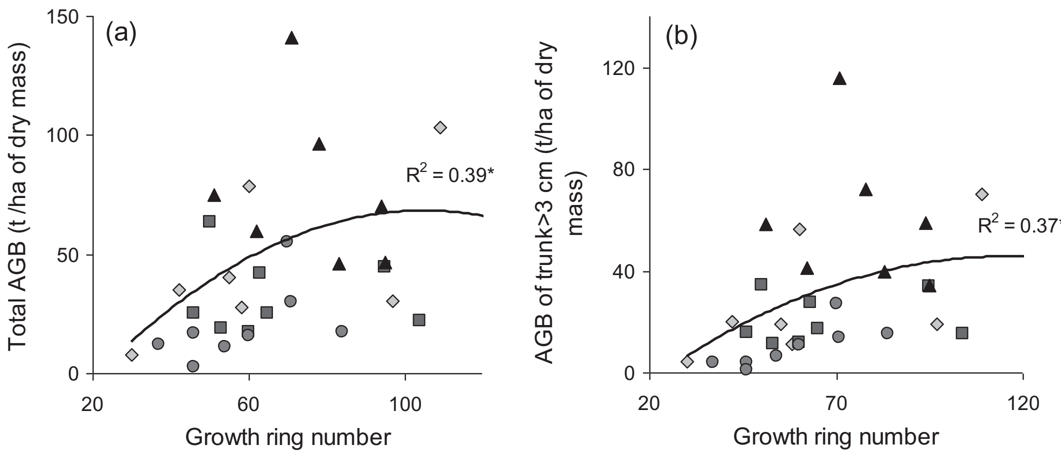

Fig. 4. Above ground biomass accumulation (a) total above ground biomass productivity (tDM ha^{-1} year^{-1}), (b) runk (>3 cm; tDM ha^{-1} year^{-1}). DM: dry mass; black triangle: Xerophytic Thickets on Lixisol far from villages; grey diamond: Xerophytic Thickets on Calcisol Far from villages; white rectangle: Xerophytic Thickets on Calcisol Near villages; black circle: Xerophytic Thickets on Lixisol Near villages.

Table 2
Analysis of woody charcoal production sustainability (value ± error calculated through error propagation principle).

Parameters	Unit	Values	Relative error
CY	–	0.125	
S	ha	8 399.70	
B_{wc}	t of fresh mass	56362.73 ± 23 746.79	0.42
BP_{wc}	t year^{-1} of fresh mass	862.55 ± 317.85	0.37
WC_{max}	t WC	107.82 ± 39.73	0.37
WCP	t WC	600.90 ± 112.31	0.19
AGBL	t year^{-1} of fresh mass	3944.64 ± 953.01	0.24
T	Year	14.29 ± 6.97	0.44

AGBL is annual above ground biomass loss due to WC production; BP_{wc} is the available above ground biomass productivity for WC production in the current production site; B_{wc} is the available above ground biomass for WC production in the current production site; CY: Carbonisation yield; T: duration of period before WC species extinction; WC_{max} is quantity of woody charcoal production corresponding to XT productivity; WCP: WC production of the Soalara commune in 2013.

solved this problem by counting the growth rings of all of the branches of a sampled shrub and associating its age with the maximum growth ring number. However, most shrub dendrochronology studies tackle this multi-trunk issue by taking the trunk sample at the root collar segment which is expected to be the part of the trunk with the highest number of growth rings (Liang et al., 2012; Xiao et al., 2012; Oddi and Ghermandi, 2015). In our case, a transversal section of the sampled shrub was taken at a height of 30 cm when the first ramification appeared above this height and at the soil level when the first ramification appeared at or below 30 cm.

The age of a stand was estimated using the number of growth rings of the shrub with the largest diameter trunk in the sampled area. This was justified by the generally positive correlation between shrub diameter and age (O'Donnell et al., 2010). However, the specific gravities of the sampled shrubs were not measured and this may have introduced a bias in the shrub diameter/age relation. A repetition of the observations, on two 4×4 m^2 plots per 20 × 20 m^2 plot and five 20 × 20 m^2 plots per XT type, may reduce such a bias. Furthermore, our objective was not to estimate stand age but rather the age of the part of XT included in the sampled area (4×4 m^2 and 20 × 20 m^2 plots) to estimate the duration of the production of the biomass in this area.

4.2. Weak productivity of XT

There are few studies on tropical forest productivity, and most concern tropical rain forests and use allometric and diachronic methods (Chave et al., 2001, 2008; Hertel et al., 2009; Vasconcelos et al., 2012). However, the method used in this study was direct (destructive total harvest method), which may better estimate AGB. Relative errors (SE/mean) of XT productivity ranged from 0.12 to 0.28 (Fig. 3). These error values are lower than those associated with tree AGB increase in French Guyana rain forests (Chave et al., 2008; 0.30–2.40). These error values are also lower than errors associated with carbon stock increase in temperate forests of New Zealand (Holdaway et al., 2014; 0.65) and lower than annual productivity errors associated with annual productivity of Norway spruce (Bouriaud et al., 2015; 0.40). However, our relative error is higher than those of AGB increases in tropical rain forests of Indonesia (Hertel et al., 2009; 0.05) and those of annual net primary productivity of tropical rain forests in Eastern Amazonia (Vasconcelos et al., 2012; 0.04–0.13). The spatial heterogeneity of XT in the study site and small size of the biomass sampling area (4×4 m^2) may be a source of errors (Chave et al., 2001).

The semi-arid character of the study site's climate favours discrete shrub growth during the rainy season and facilitates the counting of growth rings. However, we do not know if the rings strictly represent annual growth, and this is a source of uncertainty with regard to the estimation of above ground biomass productivity. Gaspard (2016) proved the annuality of the growth rings of 9 of the 20 sampled shrub species. Moreover, the annuality of semi-arid shrubs' growth rings is common (Liang et al., 2012; Xiao et al., 2012; Oddi and Ghermandi, 2015). Consequently, the annuality of shrubs' growth rings in the study site, a semi-arid zone, is also highly probable and do not considerably affect the accuracy of the estimation of shrub age.

The AGBP of XT on the study site is very low (one against ten) compared with those of rain forests in the Amazon and South Eastern Asia and with those of remnant *Eucalyptus camaldulensis* in

Table 3
Comparison of Above ground biomass productivity.

Sources	Location	Vegetation type (1) or tree/shrubby species considered (2)	Annual rainfall (mm)	Above ground biomass productivity ($t\ ha^{-1}\ year^{-1}$ of dry mass)	Method
This study	South West of Madagascar	Xerophtic thickets (1)	418	0.38–0.99	Destructive total harvesting and tree ring counting
Rosenschein et al. (1999)	Central Kenya	Degraded shrubby/woody rangeland (1)	660	0.48	Allometric method
Smith et al. (2017)	Australia	*Eucalyptus camaldulensis* in woodlands (2)	470–600	5.08 (0.22–17.92)	Allometric method
Sanogo et al. (2016)	Southern Mali	*Vitellaria paradoxa* in fallow and parklands (2)	889–1126	0.11–0.22	Tree ring counting and allometric method
Vasconcelos et al. (2012)	Amazony, Brazil	Secondary forest (1)	2214–3241	4–10	Allometric method
Hertel et al. (2009)	Indonesia	Mature forest (1)	3534	5.62	Allometric method

woodlands of semi-arid Australia (Table 3). However, it is comparable to the annual biomass increment measured in comparable climatic conditions on severely degraded rangeland in Kenya, and to the annual biomass growth of *Vitellaria paradoxa* in fallows and parklands of southern Mali (Table 3).

The mean AGBP on lixisol, where WC is preferentially produced (Randriamalala et al., 2016), increased with the distance from villages (Fig. 3b and c). WC production, which is practiced on sites near villages, negatively affected XT AGBP. Such a finding is in contrast with what happens in rain forests. In fact, the biomass productivities of secondary forests and long fallows may be higher than those of primary forests (Finegan, 1992; Randrianarison et al., 2015). Pioneer species that occupy secondary vegetation generally grow faster than species characterising primary forests (Randrianarison et al., 2015), but this does not seem to be the case on the study site: the XT regeneration rate is low (Randriamalala et al., 2016) and the seedlings/saplings that occupy gaps grow slowly due to the arid climate. In fact, plants maximize their biomass production through a photosynthesis phenomenon during the wet season (Borchert, 1999; Eamus and Prior, 2001), which is very short on the study site (2–3 months a year).

4.3. Woody charcoal (WC) production is an unsustainable activity

The AGBP of the current WC production site is lower than the AGB required to produce the current WC production in Soalara commune. Mature individuals of shrubby species propitious for WC production will disappear within a period of 15 years if the current rhythm of WC production continues (Table 2). However, WC production is likely to increase with WC demand, which is increasing with population growth in Toliara (Gardner et al., 2015) where the WC production is exported. Consequently, the disappearance of mature individuals of the trees and shrub species which can be used for WC production may happen earlier than predicted in this study. In the end, only shrub species with soft wood like *Commiphora lasiodisca* (Burseraceae), *Gyrocarpus americanus* (Hernandiaceae) and *Operculycaria* sp. (Anacardiaceae) will remain on the current WC production site. Moreover, the mean ring number of the biggest shrubs on the study plots (>55) confirms the unsustainability of this WC production activity: over 55 years are needed for XT woody biomass to recover while the present exploitation rhythm corresponds to rotation periods of less than 20 years (Raoliarivelo et al., 2010).

4.4. Recommendations

No more than 862.55 t of WC biomass should be removed on the study site per year. The promotion of improved kilns with a higher carbonisation yield could increase corresponding WC production. However, even with improved kilns, it will be difficult for local WC producers to respect this limit because it would require carbonisation yields to increase up to 0.60 (ratio between the 2013 effective WC production and XT biomass productivity associated with the current WC production site), while the maximum observed carbonisation yields are under 0.30 (Girard, 2002; Chidumayo and Gumbo, 2013).

The alternatives are to (i) extend the WC production site to XT on calcisol, (ii) plant WC tree species to decrease pressure on natural XT, and (iii). develop other income generating activities to decrease interest in WC production.

The first alternative would temporarily decrease pressure on XT. However, it ultimately would lead to all of the XT being degraded. In fact, WC production on rocky calcisol is already practiced on the Belomotse plateau over 40 km north of the study site (Rabeniala et al., 2013; Randriamalala et al., 2017) where WC is produced on any substrate (both lixisol and calcisol). Wood extraction, mainly WC production on this site, has led to XT woody biomass depletion which has resulted in the extraction of shrub roots for WC production (Rabeniala et al., 2013). This extension of XT production on calcisol would involve additional work to dig kilns and would provide unsustainable income for local people.

The second alternative (tree plantation) has been promoted by NGOs intervening in southwestern Madagascar (WWF and GIZ) and fast growth exotic species such as *Eucalyptus* spp., *Prosopis justiflora*, *Azadirachta indica* and *Acacia mangium* have been recommended (WWF/CIRAD, 2006). A community tree plantation program was undertaken in the north of Toliara II District (50–120 km north of the study site), where higher annual rainfalls occur ($P = 600–800\ mm\ year^{-1}$), during the 2007–2012 period. The objective was to insure timber and WC biomass for the town of Toliara to decrease pressure on the surrounding dry forest, including the XT of the study site. This community tree plantation program was funded by the Tany Meva trust fund and was implemented by WWF. *Eucalyptus camaldulensis* and *Acacia mangium* tree species were planted on plots whose total area was about 400 ha. Results were mixed; while the survival rate of the trees planted was generally under 50%, the program demonstrated that tree plantations in the semi-arid southwestern region of Madagascar are possible. In fact, the mortality was essentially due to a late plantation period (end of rainy season) and a lack of plantation monitoring. The local people involved in this community tree plantation were motivated because there was a shortage of fuel wood and timber on their lands.

The plantation of multiple use shrubs such as *Ziziphus* spp. (Rhamnaceae) could also be undertaken on the study site. The leaves and fruit of this shrub can be used as fodder for goats

(Andrianarisoa et al., 2014) and its wood is hard enough to serve as WC biomass (Razafintsalama et al., 2014). This exotic shrub is currently planted in house courtyards and in some crop fields but its density is still low (Rabeniala et al., 2009; Andrianarisoa et al., 2014). It therefore would be interesting to increase its density around villages to supply fodder for goats and woody biomass for WC production. An attempt to plant *Ziziphus spina-christi* was undertaken on the study site in 2012–2013 and had a survival rate of about 30% after one year (Andrianarisoa et al., 2014). A lack of monitoring and a late plantation period (end of February) were again the main cause of mortality (Andrianarisoa et al., 2014). The plantation of *Ziziphus* spp. can considerably reduce the pressure from both WC production and goat grazing on the XT of the study site. However, to anticipate the risk of this species invading XT, it should be planted in house courtyards and around crop fields, in areas near villages. This shrub plantation would provide two advantages: (i) a source of fodder for small ruminants, especially goats, and (ii) a source of biomass for WC production. In fact, fodder shortage during dry season makes this evergreen shrub valuable because its leaves serve as goats fodder and the whole leaves of a mature individual (2–3 m high) may cost around 2 Euros.

Assisted regeneration could also be undertaken in the study site in order to restore XT (Vieira and Sicariot, 2006; Shono et al., 2007). It consists mainly of (i) selecting and marking of valuable shrub species individuals for regeneration (WC species or fodder species or both of them) and (ii) protecting them from disturbance (fire and grazing) and weedy species competition. This assisted regeneration activity needs a limited financial and material means and depends essentially on the local people motivation to protect valuable species seedlings around their villages.

The last alternative consists of promoting traditional activities such as small ruminant (SR) breeding (goat and sheep) which encourages the conservation of thickets to serve as a forage resource (Randriamalala et al., 2016). Most households in the study are both SR breeders and WC producers (Rabeniala et al., 2009; Raoliarivelo et al., 2010). An improved breeding system may produce higher incomes than woody charcoal production (Masezamana et al., 2013). In fact, Andrianarisoa et al. (2014) showed that it is possible to control small ruminant reproduction on the study site by using a flushing technique (Molle et al., 1995 and 1997) to increase meat production and breeders' incomes. SR breeding and WC production activities exploit the same resource – XT vegetation – which is both a source of woody biomass and pastureland for SR, especially goats. However, although it has been shown that goats do not affect XT regeneration on the study site with the current stocking rate of one head per hectare (Randriamalala et al., 2016), particular attention should be given to the effects of SR on XT regeneration. In fact, SR are reputed to be detrimental to dry forests (Moser-Norgaard and Denich, 2011; Säumel et al., 2011). Meat production and the sale of live individuals should be promoted to limit the stocking rate on the study site because detrimental effects of SR on vegetation in semi-arid regions are mainly caused by high stocking rates (Rosa García et al., 2012). Appropriate pasture management, such as grazing rotation, can considerably reduce livestock pressure on pasture vegetation (Schlecht et al., 2006) and can be beneficial to biodiversity conservation. Under these conditions, SR breeding might be (i) a sustainable way to exploit XT vegetation and (ii) an efficient mean to alleviate poverty and malnutrition in the study site.

5. Conclusion

The XT on the study site are not resilient to WC production activity, which is contributing to reduce AGBP and will lead to the disappearance of mature individuals of species favourable to WC production in less than 15 years. Measures to reduce pressure on XT vegetation, such as (i) research into alternative activities and (ii) tree/shrub plantation inside and outside the study area, should be undertaken. A methodological challenge is to refine the evaluation of biomass productivity by verifying the yearly character of growth rings and to replicate the methodology in a larger area (e.g., the entire semi-arid region of southern and western Madagascar). Biomass productivity results from dendrochronology methods, which are more complicated and difficult to replicate, also should be compared to those of diachronic and allometric methods, which are easier to implement. Moreover, a more accurate analysis of WC production and consumption is needed. In fact, we only examined WC production for 2013, and In fact, we only examined WC production for 2013, and it would be interesting to analyse several year variations in WC production to build an accurate model to predict future fluctuations. Furthermore, research on XT restoration is strongly needed. These research efforts are urgent to avoid the irreversible degradation of XT.

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Appendix A

Woody charcoal species list and occurrence in type of soil and in distance from village.

ni: not identified species; column in grey indicates plots in the current woody charcoal production site.

Family	Genus and species	Number of plots			
		Calcisol		Lixisol	
		Far from village	Near village	Far from village	Near village
Acanthaceae	*Ruellia latisepala* Benoist	0	2	0	0
Acanthaceae	Ruellia sp.	0	2	0	0
Acanthaceae	*Barleria humbertii* Benoist	0	0	1	0
Amaranthaceae	*Celosia argentea* Linnaeus	0	0	0	1
Anacardiaceae	*Sclerocarya birrea* Hochstetter, Christian Ferdinand Friedrich	3	3	0	0

Apocynaceae	*Secamonopsis madagascariensis* Jumelle	4	5	4	1
Apocynaceae	*Tabernaemontana coffeoides* Bojer, Wenceslas (Wenzel)	0	0	1	0
Apocynaceae	Secamone sp.	1	1	0	1
Bignoniaceae	*Stereospermum euphorioides* Candolle	3	2	4	3
Bignoniaceae	*Rhigozum madagascariense* Drake	0	1	4	1
Boraginaceae	*Hilsenbergia croatii* J.S. Miller	2	2	0	0
Boraginaceae	*Hilsenbergia lyciacea* (Thulin) J.S. Miller	0	0	0	1
Boraginaceae	*Hilsenbergia randrianasoloana* J.S. Miller	0	0	0	1
Burseraceae	*Commiphora marchandii* Engler	3	1	1	1
Capparaceae	*Maerua filiformis* Drake	0	0	1	1
Combretaceae	Terminalia sp.	4	1	1	0
Combretaceae	*Terminalia gracilipes* Capuron	0	0	0	3
Combretaceae	*Terminalia ulexoides* H. Perrier	1	0	4	1
Combretaceae	*Terminalia fatraea* Candolle, Poiret	5	2	1	0
Didiereaceae	*Didierea madagascariensis* Baillon	0	0	3	5
Ebenaceae	*Diospyros manampetsae* H. Perrier	5	3	0	3
Ebenaceae	*Diospyros tropophylla* (H. Perrier) G.E. Schatz & Lowry	0	0	0	1
Ebenaceae	*Diospyros latispathulata* H. Perrier	0	1	3	3
Erythroxylaceae	*Erythroxylum leandrianum* Payens	0	1	0	0
Euphorbiaceae	*Givotia madagascariensis* Baillon	0	0	1	0
Euphorbiaceae	*Euphorbia laro* Drake	0	0	2	0
Euphorbiaceae	*Euphorbia stenoclada* Baillon	0	1	0	0
Euphorbiaceae	*Euphorbia fiherenensis* Poisson	4	1	0	0
Fabaceae	*Chadsia grevei* Drake	0	0	1	0
Fabaceae	*Dichrostachys alluaudiana* Viguier	1	0	0	0
Fabaceae	*Vaughania interrupta* Du Puy, Labat & Schrire	1	0	0	0
Fabaceae	*Dalbergia xerophila* Bosser & Rabevohitra	0	0	1	3
Fabaceae	*Dicraeopetalum mahafaliense* M. Peltier & Yakovlev	5	1	2	2
Fabaceae	Chadsia sp.	5	4	1	0
Fabaceae	*Acacia bellula* Drake	1	0	0	1
Fabaceae	*Mimosa delicatula* Baillon, Drake	2	0	0	0
Fabaceae	*Acacia pervillei* Bentham	1	0	0	0
Fabaceae	*Chadsia flammea* Bojer	0	0	2	3
Fabaceae	*Bauhinia grandidieri* Baillon	1	2	0	0
Fabaceae	*Tetrapterocarpon geayi* Humbert	3	1	1	3
Lamiaceae	Vitex sp.	0	1	0	1
Lamiaceae	*Karomia microphylla* (Moldenke) Fernandes	0	0	1	1
Malvaceae	*Adansonia rubrostipa* Jumelle, Perrier	0	0	1	0
Malvaceae	*Grewia tulearensis* Capuron	4	4	4	0
Malvaceae	*Helmiopsiella madagascariensis* Arènes	1	0	0	0
Malvaceae	*Grewia leucophylla* Capuron	0	0	3	1
Meliaceae	*Neobeguea leandriana* Leroy	1	0	1	0
Meliaceae	*Neobeguea mahafaliensis* Leroy	1	1	2	4
Meliaceae	*Cedrelopsis grevei* Baillon	5	2	2	0
ni1	ni1	0	0	1	0
ni2	ni2	0	0	0	1
ni3	ni3	4	4	1	0
ni4	ni4	2	1	0	0
ni5	ni5	0	0	3	0
Ochnaceae	*Ochna polycarpa* Baker	0	1	1	2
Olacaceae	*Olax dissitiflora* Olivier	2	0	1	0
Oleaceae	*Comoranthus obconicus* Knoblauch	1	1	0	0
Phyllanthaceae	*Securinega perrieri* Leandri	5	0	1	0
Rubiaceae	*Hymenodictyon decaryi* Homolle	0	0	1	0
Rubiaceae	*Tarenna grevei* (Drake) Homolle	1	1	0	0
Rubiaceae	Tarenna sp.	3	2	3	3
Rutaceae	*Zanthoxylum decaryi* H. Perrier	0	0	1	0
Salvadoraceae	*Salvadora angustifolia* Turrill	0	0	1	2
Scrophulariaceae	*Androya decaryi* H. Perrier	2	0	0	0
Solanaceae	*Solanum bumeliaefolium* Dunal	0	0	1	1
Talinaceae	*Talinella dauphinensis* Scott-Elliot	4	0	2	0
Talinaceae	*Talinella boiviniana* Baillon	0	0	1	0

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