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Additional measures needed to ensure clove industry does not contribute to tree cover loss in Madagascar

Herizo T. Andrianandrasana [a,*], Marco Campera [b], Fabiola F. Viraina [c], Peter R. Long [b], Nikoleta Jones [a]

[a] Global Sustainable Development, School for Cross Faculty Studies, University of Warwick, UK
[b] School of Biological and Medical Sciences, Oxford Brookes University, UK
[c] DREDD Atsinanana, Ministry of the Environment and Sustainable Development, Madagascar

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ABSTRACT

This paper explores the relationship between clove essential oil processing and tree cover loss, with a comparison to the incidence and effect of wildfires in Analanjirofo in eastern Madagascar between 2012 and 2021. We used Generalised Additive Mixed Models with the proportion of tree cover left around chef-lieu municipalities as response variables. The number of fires detected, the number of traditional and modern clove processing facilities in the municipality, and overlap with Protected Areas, and the number of villages in the municipality were set as fixed factors. Tree cover loss was associated with increased number of traditional and modern facilities. Clove operators show a motivation to keep using traditional facilities since they are more feasible, produce higher quality of clove oil, and reinforce social cohesion. The number of the traditional facilities per municipality remains 2.9 times higher than modern facilities despite their promotion since 2011. The use of the modern facilities is motivated by the lower wood consumption and shorter distillation time. Wildfires, often related to slash-and-burn agriculture, remain a major environmental threat to forest, especially in remote areas and more fires were detected in areas with higher tree cover. The overlap of municipality with Protected Areas has no effect on tree cover loss. Expanding the Agroforestry Systems (AFS) around municipalities and ensuring that they can produce enough fuelwood will improve the clove sector and thrive local economy. Controlling wildfires, developing a long-term clove industry management plan, and improving commercialisation policies could be immediate priorities for achieving sustainable development in the region.

1. Introduction

Madagascar is one of the world's most important biodiversity hotspots, with high levels of endemism which include 90 % of plants and 85 % of animal species found nowhere else (Myers et al., 2000; Goodman and Benstead, 2003; Raik, 2009); however it is also a key clove-producing country (Danthu et al., 2014). With 40,000 t of cloves worth 224 million US $ exported in 2022, and 22,000 t worth 117 million US $ exported in 2021, 12 % of the global market, the sector makes Madagascar the world's top clove exporters (EDBM, 2020; OEC, 2023). Discovered around the 1st century BCE, the clove was first referenced in the Chinese literature during the Han dynasty in the 3rd century BCE (Hussain et al., 2017; Hancock, 2021). Scientifically named *Syzygium aromaticum* (Myrtaceae), the clove tree was first introduced to Nosy-Boraha (St. Marie), eastern Madagascar, in 1827 (Levasseur, 2012). Clove is among Madagascar's top 10 exports representing 7.8 % of the total (Workman, 2023); it is one of the most valued agricultural products in the country (Cocoual and Danthu, 2018). The case of clove essential oil distillation in Analanjirofo region of north-eastern Madagascar deserves special attention because this region has the highest concentration of clove plantations in the country (Danthu et al., 2014) and cloves and their by-product industry constitute the primary source of income in the region, contributing up to 60 % of farmers' earnings (Michels et al., 2011; Penot et al., 2015).

Analanjirofo comes from two words: ‘anala’ meaning forest, and ‘jirofo’ meaning cloves; it is the region of clove trees. Inhabited by 685,362 inhabitants (Table 1), the Analanjirofo region (1.05 million hectare) which consists of four districts including Fenerive-Est, Soanierana-Ivongo, Nosy-Boraha (St. Marie), and Vavatenina has a unique biodiversity with four protected areas NAP Pointe à Larré (2870 ha),

* Corresponding author: Global Sustainable Development, School of Cross-Faculty Studies, University of Warwick, Ramphal Building, Coventry CV4 7AL, UK.
E-mail address: herizo.andrianandrasana@warwick.ac.uk (H.T. Andrianandrasana).

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Ambatovaky Special Reserve (65,000 ha), NAP Tampolo (675 ha), and 45 % of Zahamena National Park (29,221 ha) covering in total 97,766 ha, 9.33 % of the territory (MEDD, 2015; MNP, 2020) and an exceptional capacity for cash crops: cloves, *Litchi chinensis* 'lychee', *Vanilla planifolia* 'vanilla', and *Cinnamomum verum* 'cinnamon'.

Due to its eugenol content, the clove essential oil is highly demanded for food, soaps, perfume, cosmetics, and antiseptics, but also for medical reasons such as anti-inflammatory, analgesic, anaesthetic, anti-nociceptive, and anticancer (Razafimamonjison et al., 2014; Haro-González et al., 2021). The clove is also a very effective antifungal due to its strong inhibition effects on a variety of food-source bacteria (Park et al., 2007; Rana et al., 2011; Kumar Pandey et al., 2022).

The first distillation of the clove oil of Madagascar took place in Nosy-Boraha (St. Marie) district in 1911 (Rahonintsoa, 1978), then in Soanierana-Ivongo district in 1950 (Fig. 1) (Dufournet, 1967). The clove planting systems in Analanjirofo have evolved moving from monoculture techniques (1896–1950) to complex clove Agroforestry System (AFS) which is more beneficial economically and ecologically in late 90s (Panco et al., 2013; Cocoual and Danthu, 2018; Arimalala et al., 2019; Michel et al., 2021). Farmers have always been keen to sell clove buds to collectors, with a local price ranging from 1.50 US $ in 2014 to 6.75–7.50 US $ per kg in 2022. However, the significant drop in the clove bud price (0.25 US $ per kg) in 2011 led to a shift towards the distillation of essential oil, which could generate higher revenue (10 US $ per kg).

The amount of essential oil produced in the region depends on the fluctuation of the price of clove and the climatic hazards (Penot et al., 2015). In 2012, a peak of 22,000 t in exported quantities of cloves was recorded in the Analanjirofo region. In the same year, the production of essential oil reached its lowest figure of 1100 t. However, in 2014, the production of clove buds decreased to 11,000 t (a 50 % decrease from the 2012 figure) due to the overproduction of clove essential oil from 1100 t to 2000 t. In 2018, the local price of clove essential oil was highest, 14 US $ per litre (Appendix 1) with highest export (3000 t) (EDBM, 2019).

Two types of clove stills are used in Analanjirofo region: the traditional type (325 US $) and the modern type (650 US $) (Tirel et al., 2015). According to data from local municipalities, the Analanjirofo region officially holds 2531 clove stills while we know that many stills are not declared to avoid tax payment (Fig. 1, Table 1). There are two different clove oil marketing systems: 1) selling the essential oil per litre to mobile collectors '*baolava*', or to collectors from chef-lieu municipalities; 2) exchanging the oil with basic necessities e.g., rice, coffee, or sugar. Collectors take advantage of poor road infrastructures and insecurity to maximise their benefits.

The following laws are in force to regulate the planting of cloves and the distillation of essential oils: law n°212-GG on 07 January 1950 related to the clove export quality act; regional law n°04/11-REG/AROFO/SG/DAGT/AE in 2011 fixing the tax payable on each distillation equipment and the period for cutting clove leaves and distilling clove essential oil; law n°30,423–2014 on 10 October 2014 related to the organisation and management of the clove sector in Madagascar; and annual law fixing the opening date for clove marketing in the region.

Having a clove plantation is a social status giving reputation to a household. Clove trees begin to produce buds from the 8th year, reach their maximum productivity at 20th year and remain productive until 50–60 years (Panco et al., 2013; Arimalala et al., 2019). The frequency of clove processing is very high between June and September. Most cash generated by the clove industry is used to celebrate the country's Independence Day (26th of June), support the ancestors' ritual ceremony 'tsaboraha' by organising community food "tokobe", and prepare children's education.

The purpose of this paper is to check whether clove industry is an additional environmental pressure contributing to the heavy loss of tree cover in eastern Madagascar including humid primary forest which already shrank by 21 % between 2002 and 2023 (Global Forest Watch, 2023). The frequency of fires in the eastern Madagascar, including Analanjirofo region, has increased over time (Kull, 2002), and now the coastal forest has similar number of fires than the highlands (Fernández-García et al., 2024). We examine the potential links between tree cover loss and key anthropogenic activities including fires and clove processing facilities between 2012 and 2021 in order to raise awareness, and provide recommendations towards sustainable development and preservation of biodiversity of the region. This is important as by 2050, the country risks to lose up to 93 % of its natural forest present in 2000 if deforestation continues (Vieilledent et al., 2020). Also, the 75.2 % of Madagascar's population is poor, with 14.8 % malnourished (World Bank, 2024) and 69.1 % deprived of the basic needs (Alkire et al., 2021). At a current population of 30 million people, projected to grow to 52 million by 2050 (World Population Review, 2024), the country is not expected to meet the first Sustainable Development Goal 'eradication of poverty' by 2030 (Pettersson et al., 2023). We believe that the clove industry can help greening the landscape while reducing poverty.

It is hypothesised that municipalities with higher number of clove processing facilities have higher tree cover loss due to utilisation of fuelwood in the distillation process. Also, the influences of adopting the AFS on clove essential oil production and tree cover requires investigation.

Our research questions include:

- How did tree cover loss, fire frequency, and the number of clove processing facilities change over time?
- Was the overall change in tree cover associated with the number of traditional and modern clove processing facilities?
- What differs the effect of the variables fire frequency, number of villages, overlap with protected area, and the number of clove stills on tree cover?

Answering these questions will ultimately improve clove industry and contribute to addressing wider environmental and economic issues across Madagascar, and elsewhere. It is a scientific contribution to the study of the socioecological complexities for the best of human well-being and the environment.

2. Materials and method

2.1. Unit of analysis

The unit of analysis is the municipality, which is the second-smallest

Table 1
Attributes of the four districts of the Analanjirofo region, north-eastern Madagascar.

District	Area hectares	No. of municipalities	No. of villages	No. of inhabitants	No. of traditional stills	No. of modern stills
Ste Marie	17,477	1	17	28,467	27	0
Soanierana-Ivongo	439,778	9	106	150,841	444	25
Fenerive-Est	295,866	14	211	303,525	879	228
Vavatenina	294,930	11	113	202,529	393	340
Total	1,048,051	35	447	685,362	1743	593
Cumulated number of stills						2336

Sources: GADM, Analanjirofo region, field survey in Oct-Dec 2022 and June 2024.

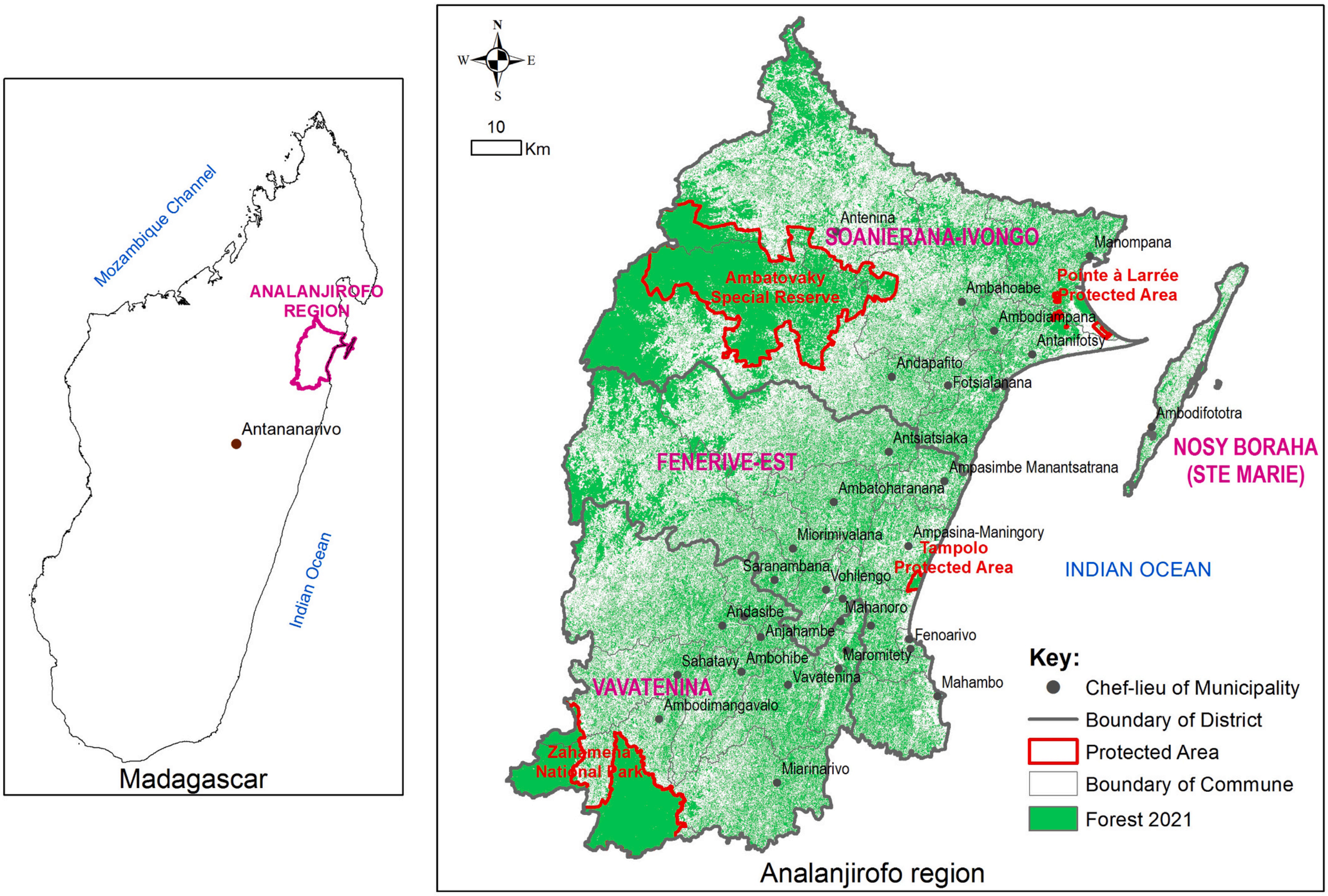

Fig. 1. Location of Analanjirofo region, north-eastern Madagascar with its four protected areas. Green colours represent tree canopy cover greater than 50 % according to Hansen Global Tree Cover data, 30 m resolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

administrative division in Madagascar. Inhabited by about 20,000 inhabitants, a municipality is managed by a decentralised territorial community led by a mayor. Some 34 municipalities were identified in the three districts, of which two were not found in the DAGM database of Global Administrative Areas. Each municipality is expressed as a polygon to calculate annual environmental variables over the study period 2012–2022, using *zonal statistics* function in ArcGIS 10.8.2 (ESRI Inc, 2021). Data of four key environmental parameters were collected for each municipality: mean forest cover, number of detected fires, overlap with Protected Areas, number of clove processing facilities, and the number of villages or *fokontany*, the country's smallest administrative division, based on FTM records (Foiben-Taosarintanin'i Madagasikara - National Geographical and Hydrographical Institute). Python scripts were written to disaggregate the forest cover grid file data and VIIRS fire alert point data for each year over 2012–2021 into individual values for each municipality (Table 2, Fig. 2–3). GIS data were projected to Tananarive 1925 Laborde Grid when calculating the extent of polygons.

2.2. *Collection of cloves' essential oil and distillery data*

The number and location of each type of processing facility between 2012 and 2021 were collated from the archives of each municipality between October and December 2022. The annual register was obtained from local mayors or their representatives while the number of essential oil processing operators was recorded to understand the production system. Some 59 villages were visited during field surveys in Oct-Dec 2022 and June 2024 (Appendix 2); they were chosen based on the importance of the clove sector in the area. We performed a spatial analysis looking at links between the number of stills per municipality and key environmental parameters towards understanding the structure of the clove essential oil production in the region.

2.3. *Extraction of forest cover data*

Raster files of historical forest cover and loss year data (2012–2021) corresponding to three tiles (10S 040E, 20S 040E, and 10S 050E)

Table 2
List of variables at municipality level in Analanjirofo region, **north-eastern Madagascar,**

Variables	Source	Resolution	Unit	Type	Category
Proportion of forest cover	Global Hansen Forest	30 m	Number	Proportion	Response
Percentage overlap with protected area	Ministry of the Environment and Sustainable Development of Madagascar	–	%	Proportion	Predictor
No. of traditional stills	Municipalities	–	Number	Continuous	Predictor
No. of modern stills	Municipalities	–	Number	Continuous	Predictor
No. of detected VIIRS fires	Visible Infrared Imaging Radiometer Suite (VIIRS)	375 m	Number	Continuous	Predictor
No. of villages (fokontany)	FTM	–	Number	Continuous	Predictor

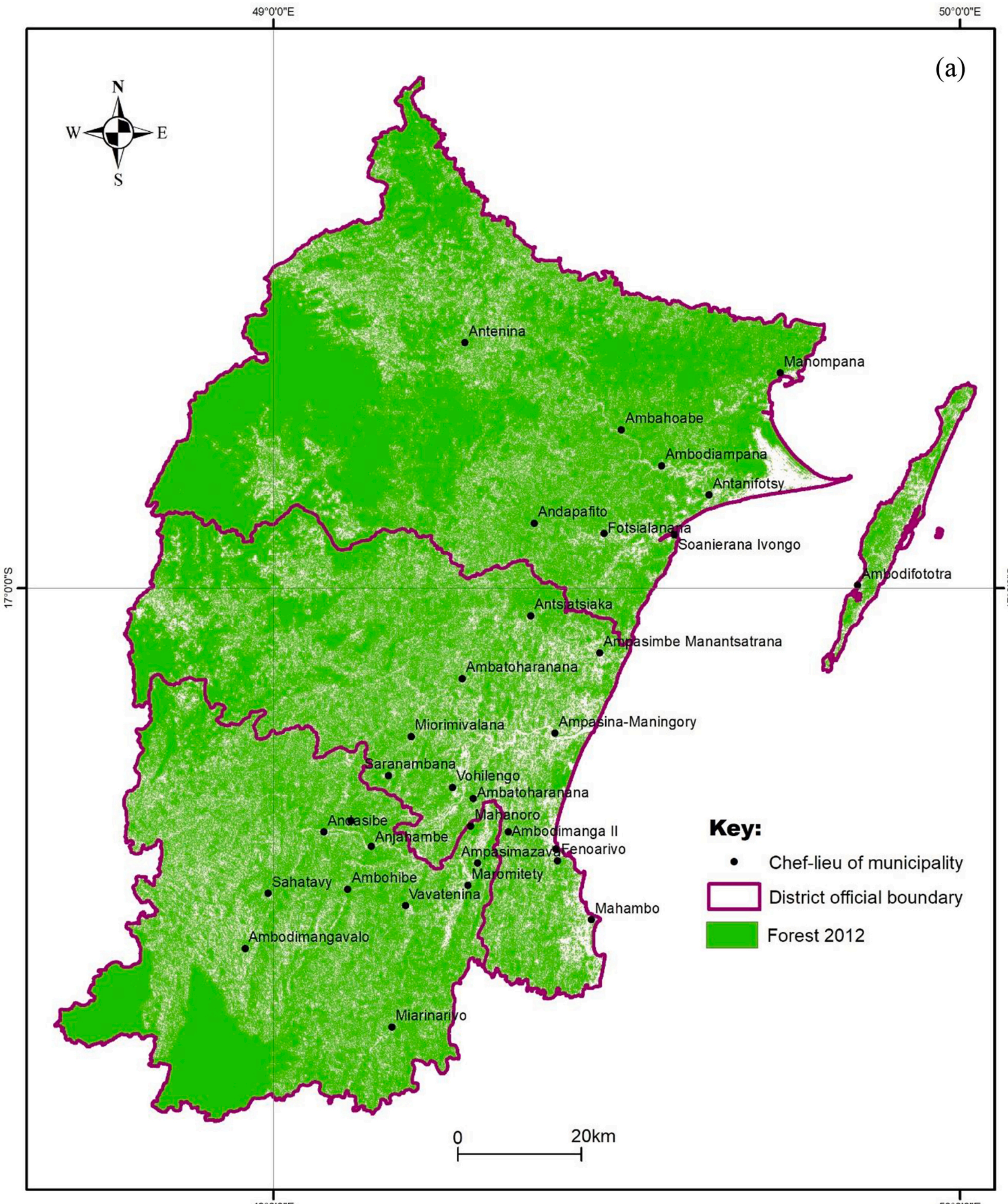

Fig. 2. Changes in tree cover in Analanjirofo region, north-eastern Madagascar, between 2012 (a) and 2021 (b) according to Hansen Global Tree Cover data, 30 m resolution. Green colour represents pixels with canopy cover greater than 50 % including natural and artificial forest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

covering Madagascar (30 m resolution) were downloaded from the 10 × 10 degree granules Global Tree Cover dataset (Hansen et al., 2013). Using TerrSet (Clark Labs, 2022) and ArcGIS 10.8.2 script geoprocessing (ESRI Inc, 2021), the raster files were mosaiced and clipped to the border of the study area. Tree cover refers to all pixels that have a canopy cover greater than 50 % (Hansen et al., 2013); this includes natural and artificial forest including vegetation cover in the clove AFS. The extent of forest in each municipality was calculated using *Spatial join* function in Arc GIS 10.8.2 (ESRI Inc, 2021) and *zonal statistics function* in QGIS 3.12.0 (QGIS Development Team, 2020). A limitation of this study

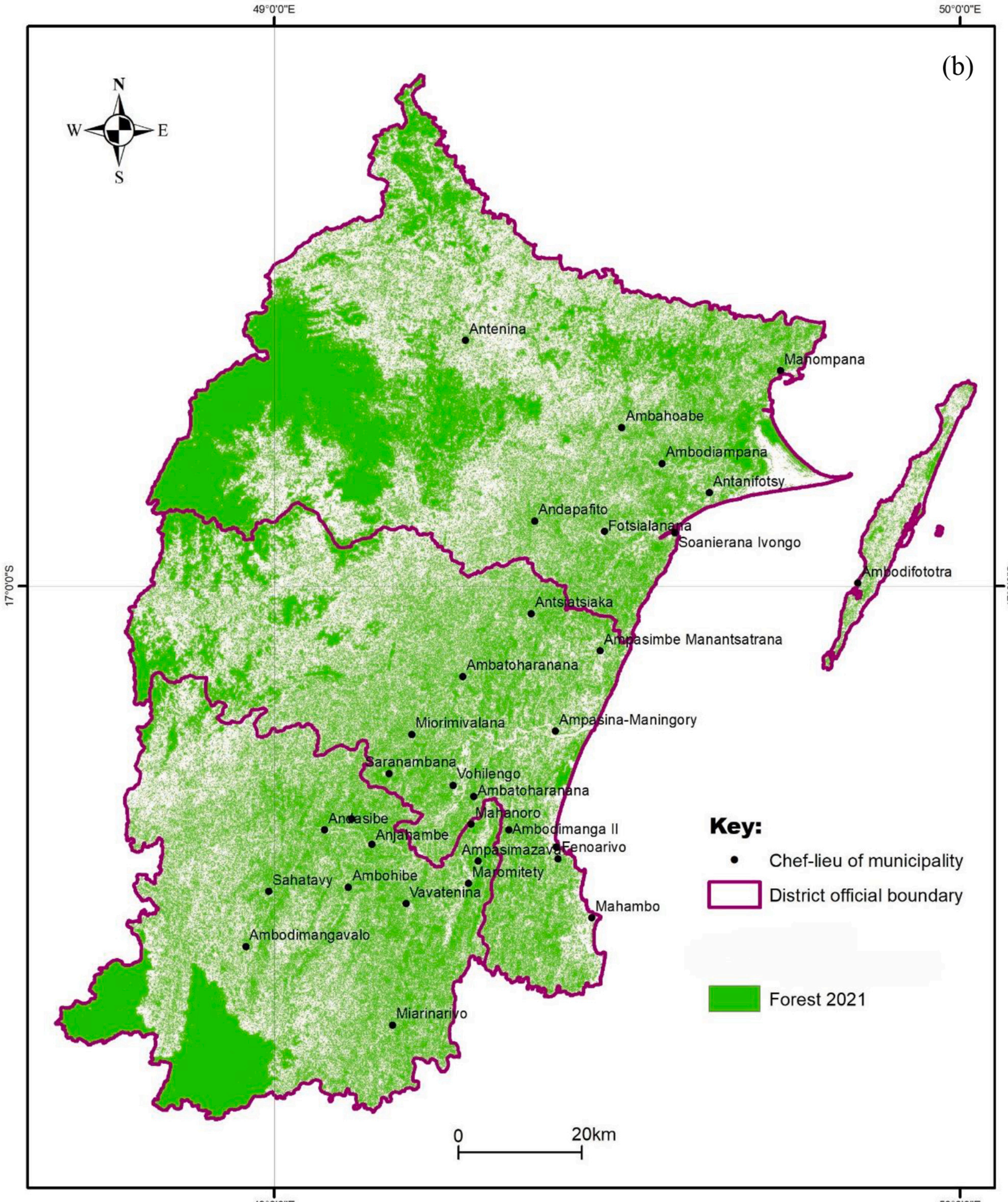

Fig. 2. (*continued*).

is that using the Hansen Global Tree Cover data, we could not isolate the effect of fuelwood removal to feed clove processing facilities from other sources of tree cover loss.

2.4. Extraction of fire data

Fire data, 0.375 km resolution, comes from Visible Infrared Imaging Radiometer Suite (VIIRS) near-real-time active fires, produced since 2011, orbiting the earth at 834 km altitude on a daily basis. VIIRS is a key instrument aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 satellites. The number of VIIRS active fire alerts per municipality per year was extracted using ArcGIS 10.8.2 ESRI Inc, 2021). VIIRS data are widely used by the Malagasy Ministry of the Environment and Sustainable Development, including the Regional Direction of the Environment and Sustainable Development in Analanjirofo, to monitor fires and deliver warnings to

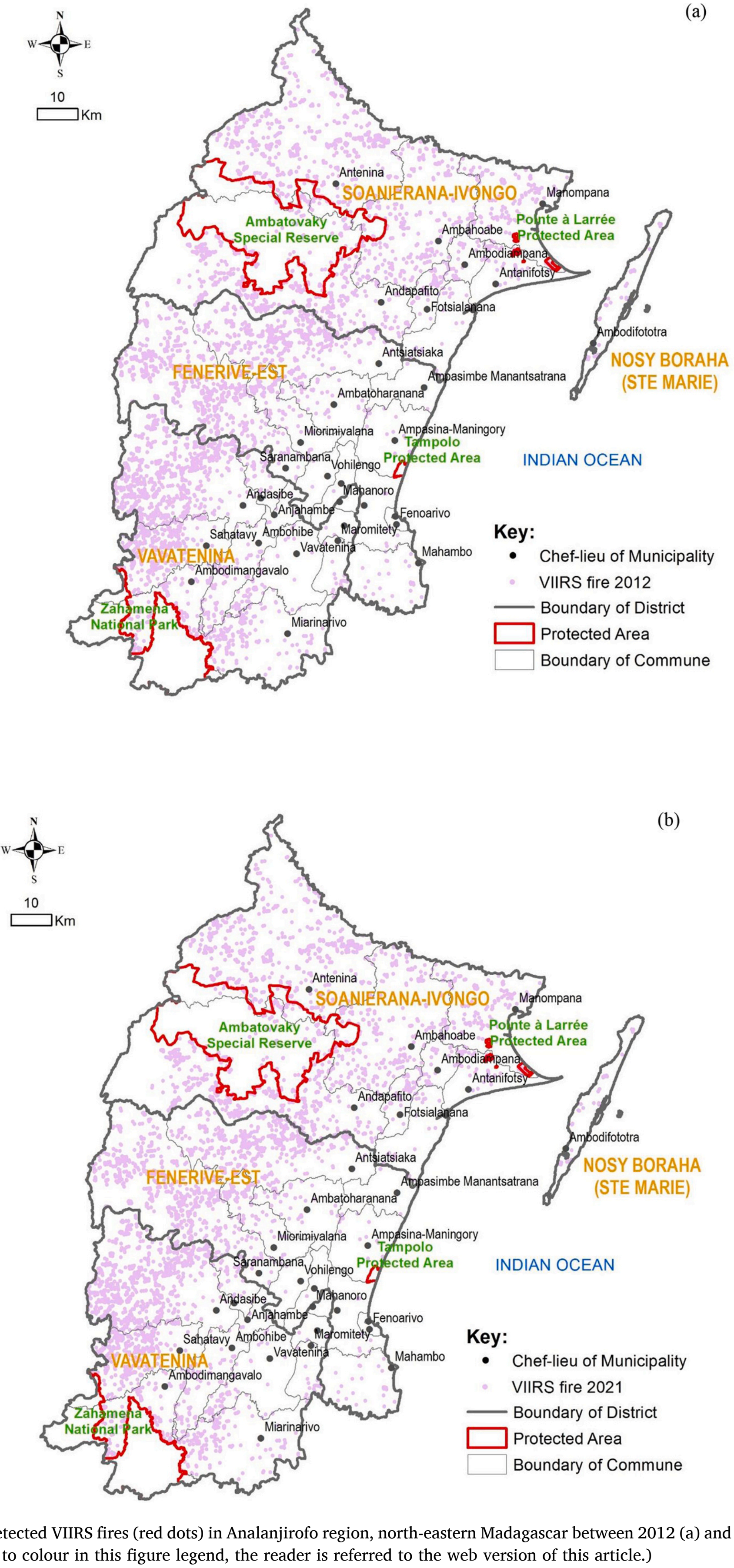

Fig. 3. Changes in number of detected VIIRS fires (red dots) in Analanjirofo region, north-eastern Madagascar between 2012 (a) and 2021 (b), 375 m resolution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

local emergency teams (village chiefs, local community members, or park rangers). So far, VIIRS data are the most accurate records available for assessing the impacts of fires (Elvidge et al., 2021). An active fire location point shape file represents the centre of 375 m pixel that is flagged by the algorithm as containing fires detected (Fig. 3).

2.5. Data analysis

We carried out statistical analysis using R v4.2.3 (R Core Team, 2023). We used Generalised Additive Mixed Models (GAMMs) with the proportion of tree cover in each municipality as response variable, the number of fires detected, the number of traditional and modern clove processing facilities, the percentage overlap with protected areas, and the number of villages in each municipality as fixed factors. We used GAMM as they provide a flexible approach which does not assume a linear or other parametric form of relationship a priori; GAMM can be used to reveal and estimate non-linear effects of the covariate on the dependent variable (Wood, 2017). Via the gam command in the package 'mgcv', we used full restricted maximum likelihood method for model selection, *s* as smooth term, and thin plate regression spline (Wood, 2017), with two nested terms, municipality by district and year by district, as random effects. We checked the model residuals via the appraise command, and plotted the partial effect via the draw command from the package 'gratia'. We considered significant values when the smooth term ±95 % confidence interval was higher or lower than the reference value (i.e., not crossing the reference line).

3. Results

3.1. Decrease in forest cover in Analanjirofo region between 2012 and 2021

In 2021, the Analanjirofo region had 595,064 ha of tree cover; the district of Soanierana-Ivongo had the largest forest cover at 255777 ha, followed by the district of Vavatenina at 172429 ha, Fenerive-Est at 160083 ha, and Nosy-Boraha (St. Marie) 6775 ha. Processing of Hansen Global Tree Cover data indicates that the tree cover in the four districts decreased from 822,526 ha to 595,064 ha, equivalent to a loss of 227,462 ha (28 %) over the period 2012–2021 (Appendices 2, 3). On average, the rate of tree cover loss in each municipality was 2.75 % per year (Fig. 4) with the highest value (58.46 %) is in the district of Vavatenina, followed by the districts of Sianierana-Ivongo (58.16 %), Fenerive-Est (54.11 %) and Nosy-Boraha (St. Marie) (38.76 %). Over the period 2012–2021, the absolute percentage in tree cover decreased from 83.43 % to 58.16 % for Soanierana-Ivongo, 77.54 % to 58.46 % for Vavatenina, 72.87 % to 54.11 % for Fenerive-Est, and 64.70 % to 38.76 % for Nosy-Boraha (St. Marie) (Appendices 2, 3). The region of Analanjirofo lost forest faster in the areas more distant from the chef-lieu of the municipality.

3.2. Overlap between municipalities and protected areas

On average there is an overlap of 4.05 % between municipalities and Protected Areas. This has no effect on changes in tree cover or in number of clove processing facilities. Municipalities in the district of Soanierana-Ivongo present the highest percentage overlap with Protected Areas (7.47 %) followed by the district of Vavatenina (6.06 %) and the district of Fenerive-Est (0.27 %). So far, the district of Nosy-Boraha has no officially designated Protected Area despite some effort of creation (Appendix 5).

3.3. Changes in VIIRS fire density in Analanjirofo region between 2012 and 2021

Between 2012 and 2021, 43,751 VIIRS fires were detected in the four districts covering Analanjirofo region; including 19,770 fires in Soanierana-Ivongo district, followed by the district of Vavatenina (12,017 fires), Fenerive-Est (11,558 fires), and Nosy-Boraha (St. Marie) (406 fires). Processing of VIIRS fire data indicates that the burning is stable in the four districts over the period 2012–2021 with the period 2013–2016 presenting the highest frequency (more than 5200 VIIRS fires) and the year 2019 presenting the lowest burning with 2720 VIIRS fires detected (See Fig. 5) (Appendix 6).

3.4. Changes in the number of traditional and modern processing facilities in Analanjirofo region between 2012 and 2021

In 2021, the three districts had in total 2336 clove processing facilities including 1743 traditional stills (74.61 %) and 593 modern stills (25.39 %). In the same year, the number of traditional stills was 2.9 times higher than modern stills (Table 3) with remarkable adoption of modern stills in the district of Vavatenina. The district of Fenerive-Est had the highest number of stills (n = 1107), including 879 traditional and 228 modern types, followed by Vavatenina (n = 733) with 393 traditional stills and 340 modern stills, Soanierana-Ivongo (n = 469) with 444 traditional stills and 25 modern stills. The district of Nosy-

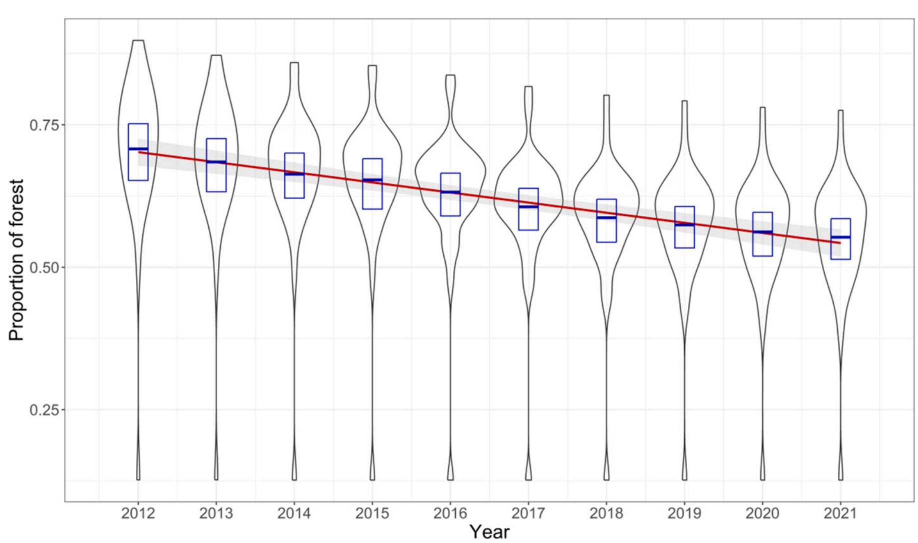

Fig. 4. Violin plots, means and 95 % CI, and trendline showing the changes in tree cover per municipality in Analanjirofo region, north-eastern Madagascar, between 2012 and 2021 according to Hansen Global Tree Cover, 30 m resolution.

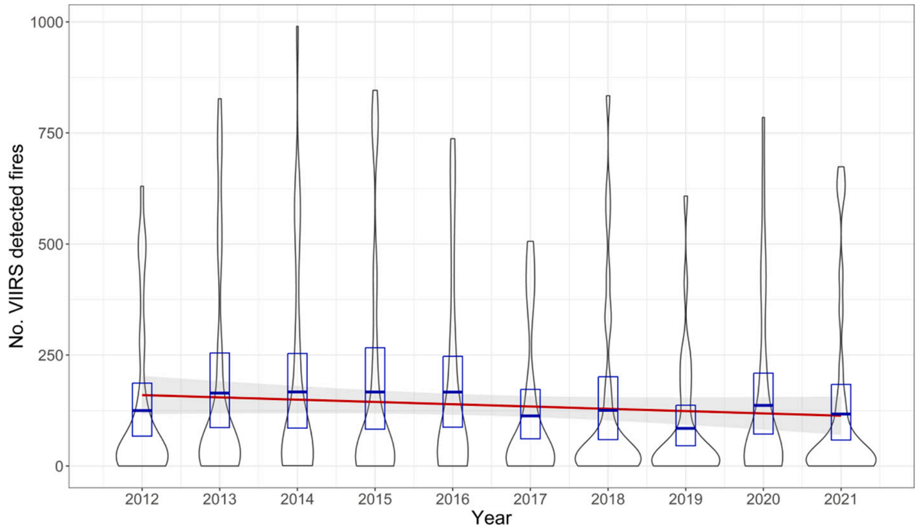

Fig. 5. Violin plots, means and 95 % CI, and trendline showing the changes in the number of VIIRS-detected fires per municipality in Analanjirofo region, north-eastern Madagascar, from 2012 to 2021, 375 m resolution.

Table 3
Changes in number of traditional and modern facilities per district in Analanajirofo region, north-eastern Madagascar, over the period 2012–2021.

	Fenerive-Est		Soanierana-Ivongo		Ste Marie		Vavatenina	
Year	No. of traditional stills	No. of modern stills	No. of traditional stills	No. of modern stills	No. of traditional stills	No. of modern stills	No. of traditional stills	No. of modern stills
2012	315	0	271	0	8	0	190	0
2013	421	0	317	0	8	0	248	0
2014	592	2	390	1	11	0	335	0
2015	618	2	388	1	12	0	334	0
2016	608	0	417	1	15	0	370	0
2017	797	0	436	0	19	0	410	0
2018	871	1	477	0	21	0	491	8
2019	962	5	468	1	24	0	537	80
2020	931	50	479	7	25	0	507	160
2021	879	228	444	25	27	0	393	340

Boraha (St. Marie) has the lowest number of stills ($n = 27$) which are all traditional. The number of traditional stills increased from 25 to 60 per municipality between 2012 and 2019 and remains around 53 per municipality between 2019 and 2021. No modern stills were officially recorded until 2011. However from 2018 onwards, the number of modern processing facilities increased from three per municipality to 18 per municipality, stagnating around 21 stills per municipality in 2021 (Figs. 6, 7).

3.5. *Interaction between clove distilleries and environmental parameters in Analanjirofo region over the period 2012–2021*

The increase in number of traditional and modern clove processing facilities was associated with the decrease in tree cover at each municipality ($p \leq 0.001$). The overlap of municipalities with Protected Areas and the number of villages in the municipality had no effect on tree cover (Table 4, Fig. 8). There are more fires in areas far away from the Chef-lieu of municipalities and with higher tree cover (Fig. 3).

4. Discussion

Our results reveal that the use of both traditional and modern clove facilities is associated with the reduction of tree cover. Overall, the amount of biomass used (not only by the clove oil distillation but the use of wood in general) was less than the amount of biomass produced by the ecosystem including the AFS. The number of traditional clove facilities has not really gone down despite the promotion of modern facilities since 2011. From 2018 onwards, there was a general adoption of modern clove facilities, even if their installation cost was significantly higher compared to traditional stills. Many of the essential oil producers who use modern facilities tend to distil fallen clove leaves and branches, locally called ‘karetsika’ or recycle wastes that are still rich in eugenol. The issue is that there is no guarantee that the quality of clove essential oil is higher when using the modern stills. The clove planting systems have been revitalised since late 1990s, adopting complex AFS structures where cloves can represent up to 70 % of perennial species (Michels et al., 2011). Panco et al. (2013) describes three clove planting systems: 1) monoculture planted over 1896–1950 which became less productive around 1980s due to age, cyclones and diseases; 2) the park system (which emerged around year 2000) where clove trees killed by cyclones or insects were replaced with new clove saplings; and 3) the Agroforestry System for cloves (AFS) which combine cloves, fast growing trees and fruit trees. The AFS is subdivided into a) the simple AFS presenting two perennial crops covering about 85 % of the landscape e.g. cloves 46 % and coffee 38 %; and b) the complex AFS: perennial plants and fruit trees e.g., clove 45–60 %, with fruit trees 10–20 %, and firewood or biomass e.g., *Harungana madagascariensis* ‘arongana’, *Albizia lebbeck* ‘bonara’, *Grevillea* sp., 11–15 %. Complex AFS can merge cloves with different fruit trees e.g. *Coffea* sp. ‘coffee’, *Citrus* sp., herbaceous plants or lianas e.g. *Vanilla planifolia*, and remaining of native forest trees (Arimalala et al., 2019; Michel et al., 2021). In Vavatenina district alone, the areas covered by the complex AFS grew from nothing in 1966 to 20 % of territory in 1996 (Mariel et al., 2016). More dynamic and productive than other clove planting systems, the complex AFS has been

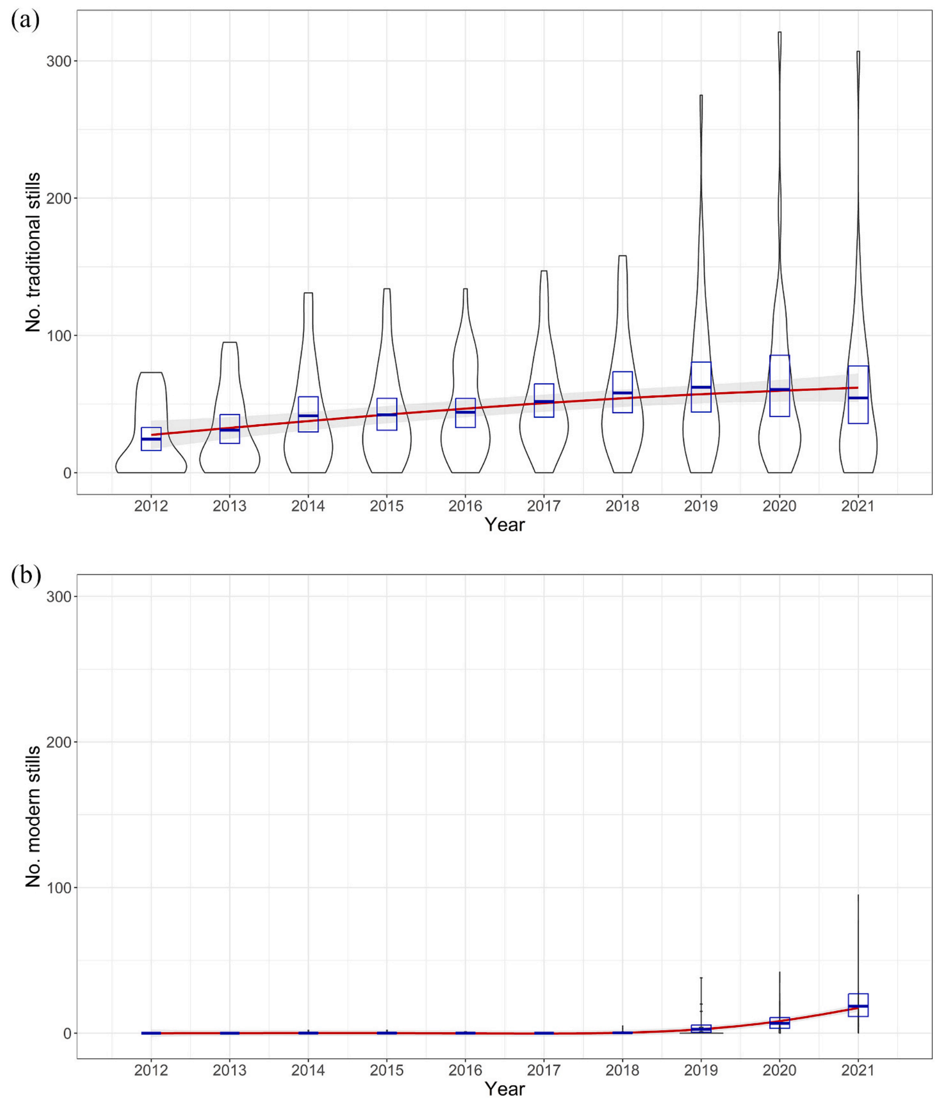

Fig. 6. Violin plots, means and 95 % CI, and trendline showing the number of traditional stills (a) and the number of modern stills (b) per municipality in Analanjirofo region, north-eastern Madagascar over the period 2012–2021.

widely adopted in the region as it produces multiple benefits e.g., food, fuelwood, fruits, and clove materials. This method has convinced local farmers as diversified AFS can promote economy, raise resilience against climatic disturbances (Mariel et al., 2023). Adapted to degraded and sloppy lands 'tanety', this complex clove AFS can increase agriculture yield and value deforested areas, thus lowering the need to practice 'tavy'. Supplying traditional or modern clove processing facilities, this AFS system has an important social and ecological relevance and can preserve the environment in the face of climate variability.

4.1. Wood consumption issue and other challenges in clove oil production

People in Analanjirofo complain about the high price of fuelwood that increased from 0.05 US $ per kg in 2015 to 0.13 US $ per kg in 2022. A traditional 1m^3 still with a capacity of 100–120 kg of biomass needs 500–750 kg of wood (25 % of which is dried wood) for 19–24 h of distillation to produce five litres of essential oil (Tirel et al., 2015). However, a modern 2m^3 still with a capacity of 200–250 kg of biomass needs only 250–300 kg of wood (50 % of dried wood) for 08–12 h of distillation to produce 10–11 l of essential oil (Tirel et al., 2015), indicating that a modern facility uses 50–60 % less firewood and spends 33–37 % less time than traditional facility. Also, traditional stills use 60 % more raw materials (clove leaves) to produce 22–33 % less essential oil while modern stills use less clove materials to obtain the same amount of essential oil (Appendix 7). Clove's essential oil producers prefer to use fresh wood, which often generates strong energy for a longer time; they do not have to use natural forest wood and can rely on planted trees, e.g., *Acacia mangium* or *Eucalyptus* sp. from the AFS close to villages. In case of emergency, they might be tempted to cut fruit trees such as *Artocarpus heterophyllus* 'jackfruit', *Manguifera indica* 'mango', *Artocarpus altilis* 'breadfruit' to process the distillation. Transporting wood requires effort and increases the oil production cost. Ensuring that the AFS can self-supply enough wood to meet the demand for households and distillations is key to ensure clove industry's sustainability.

4.2. Challenges in maximising clove industry benefits

Cloves leaf essential oil is the most commercialised in the region due to the availability of raw materials (Schweitzer and Ranaivosoa, 2007). Different parts of the clove tree such as buds, claws and leaves can be used in the distillation process to produce different qualities of essential oil. This could be beneficial for local farmers as they need to bring regular silvicultural care to their plantation e.g., controlling the height by cutting 50 cm from the top. Clove trees are kept at a low enough

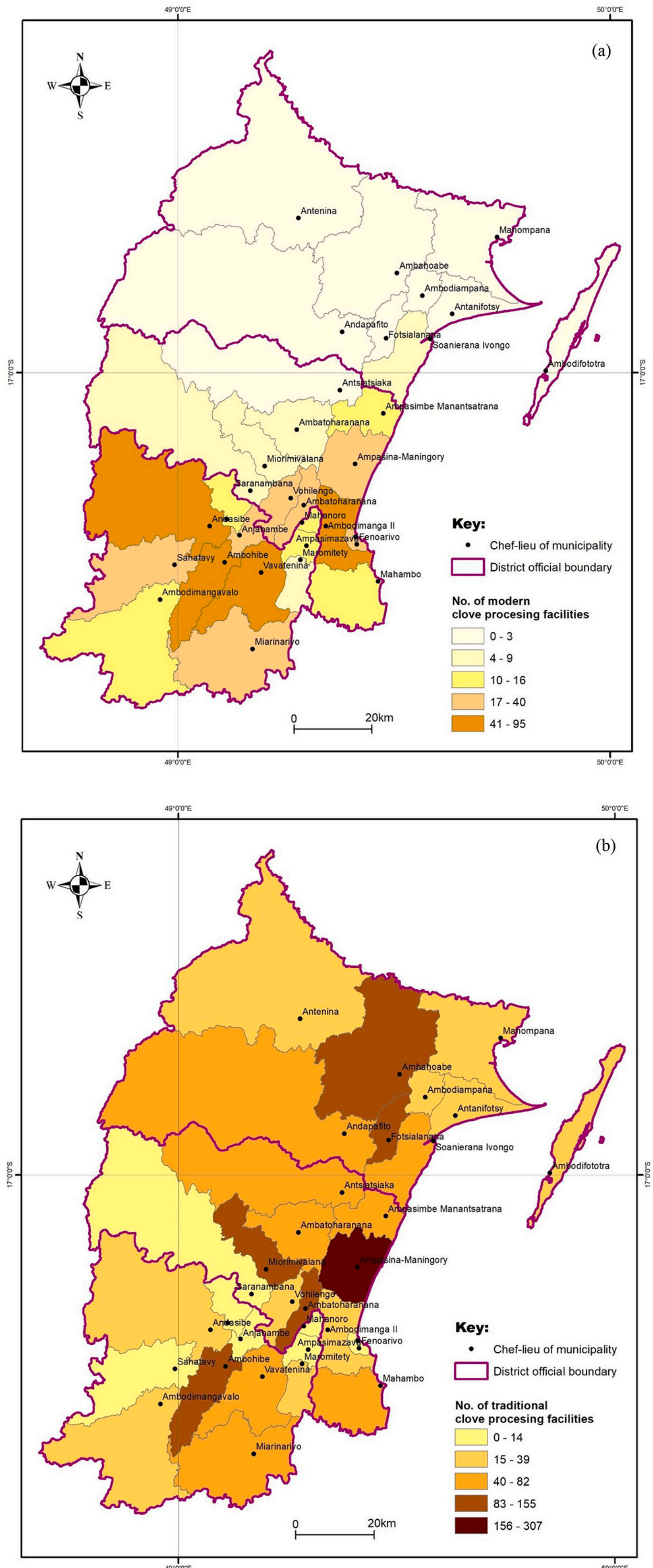

Fig. 7. Changes in number of traditional (a) and modern (b) clove processing facilities at municipality level in Analanjirofo region, north-eastern Madagascar, over the period 2012–2021.

Table 4
Results of Generalised Additive Mixed Models (smooth terms) showing the influence of number of fires, number of traditional or modern clove facilities, the percentage overlap with protected area, and number of villages on the proportion of forest left in each municipality in Analanjirofo region**, north-eastern Madagascar.**

Response	Predictor	Edf	F	*p*-value
Proportion of forest	Density of fires	2.431	11.197	<0.001
	No. of traditional facilities	2.619	9.739	<0.001
	No. of modern facilities	1.001	10.348	0.001
	No. of villages	1.001	1.975	0.161
	Overlap with protected area	1.000	1.042	0.308
	Municipality by district	28.678	531.265	<0.001
	Year by district	34.254	184.372	0.030

r-squared = 0.913.

height to facilitate the collection of buds, leaves, and branches for feeding facilities. This technique makes clove plantations more resilient to cyclones and other disasters (Danthu et al., 2014). The production of essential oil requires permits from local and regional authorities, while transportation is regulated by the regional direction of agriculture and farming, and the regional direction of trade and industry.

Several new methods are already used to extract eugenol from cloves e.g., solvent extraction, hydro-distillation, supercritical carbon dioxide extraction; microwave-assisted extraction, ultrasound-based extraction lowering energy costs (Khalil et al., 2017). We know that the extraction of eugenol takes less time using very high temperatures (250–300C°) due to faster diffusion and better solubility of the analytes in water (Rovio et al., 1999). However, adopting these advanced methods in Madagascar present many challenges due to lack of infrastructures.

Ranoarisoa (2012) recommended a complete reform of the clove industry to achieve long-term success. Also, the clove plantations are old, and the conditions for regeneration are not being met (Danthu et al., 2014). It is time to shift from slash-and-burn rice farming and boost agroforestry systems (Mariel et al., 2023) and is therefore crucial to carry out a successful reforestation activity following the existing national strategies (MEDD, 2017a, 2017b, 2020) so that the production of clove essential oil has stable water supply with a neutral carbon footprint.

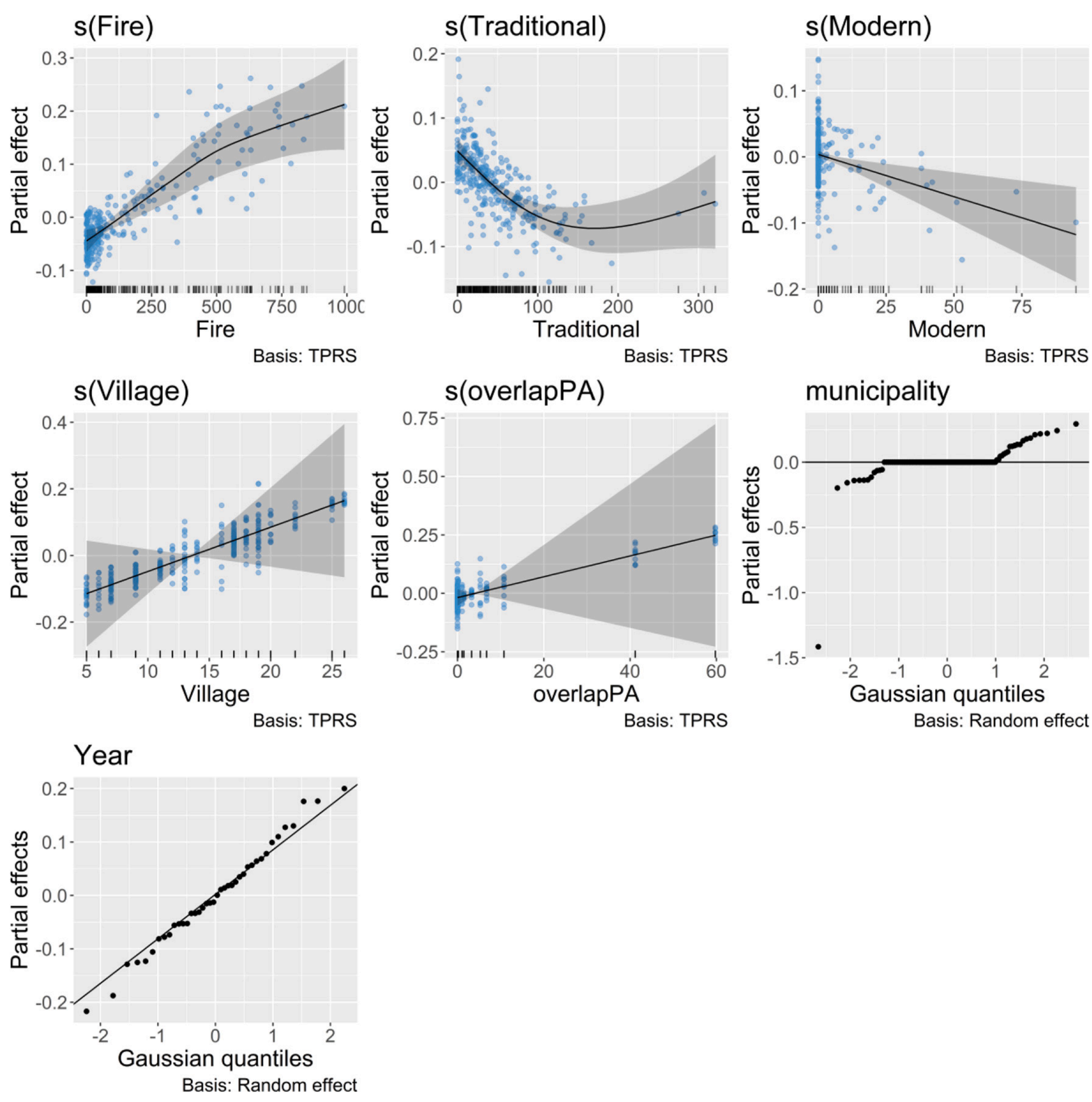

Fig. 8. Interactions between cloves' stills (traditional and modern), bushfire, number of villages, overlap with protected areas, and forest cover within municipalities in Analanjirofo region between 2012 and 2021.

5. Conclusion

The use of traditional and modern stills in the production of clove essential oil was associated with a decrease in tree cover at municipality level probably due to high wood consumption. However, wildfires, potentially linked with slash-and-burn techniques appear to be the most important threat to the forest causing higher tree cover loss in more remote areas. The market for clove oil is dynamic and research is being conducted around the world to improve the production techniques, especially through using less energy per unit of value produced.

Shifting from traditional facility to modern facility must be progressive because sharp change without accompanying measures may boost the production of lower quality essential oil which damages the sector. This can also have major negative impacts on tradition and social cohesion. Associated measures can include reinforcement of clove producers' cooperatives, capacity building of small holder farmers, and support to land tenure appropriation which represents one of the major causes of 'tavy'. Furthermore, the production and distillation techniques will need to follow the progress of technologies. AFS seems to play a key role in the clove industry system and in people's well-being in general by providing fuelwood and clove materials for distillation, and other benefits. It is important to expand AFS and increase their effectiveness to meet the requirement in fuelwood so that clove farmers are more resilient to eventual energy crisis. This will reduce farmers' dependence on slash-and-burn agriculture thus lowering the probability of tree cover loss.

Reinforcing the interaction between AFS, clove essential oil distillation and agriculture would improve natural resources management and enhance the motivation of local producers. Engaging clove essential oil operators in corporate responsibility and waste management regulations will help solve the high cost of fertilisers issue and maximise agriculture production. For example, converting clove facility residues into organic fertiliser will reduce pollution and maximise agriculture yield. It is important to develop a distribution map of clove processing facilities and clove AFS and feed it into the regional management plan to help coordinate development and conservation actions in the region.

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CRediT authorship contribution statement

Herizo T. Andrianandrasana: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Campera:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis. **Fabiola F. Viraina:** Writing – review & editing, Investigation, Data curation. **Peter R. Long:** Writing – review & editing, Resources, Methodology. **Nikoleta Jones:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Appendices

Appendix 1
Changes in price of clove and its essential oil in the Analanjirofo region.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Price of 1 kg cloves (US $)	4.75	5.00	5.75	4.00	5.00	5.00	4.25	5.00	5.75	5.75
Price of 1 l essential oil (US $)	10.00	7.75	8.50	8.88	9.00	9.06	13.93	8.55	9.25	9.25

Source: Municipalities in Analanjirofo region, north-eastern Madagascar.

Appendix 2
List of visited municipalities and villages to gather data about clove processing facilities, Analanjirofo region, north-eastern Madagascar.

District	Municipality	Village	Date
Fenerive-Est	Betampona	Betampona	06 Oct 2022
Fenerive-Est	Betampona	Ambodimanga I	06 Oct 2022
Fenerive-Est	Betampona	Marovato III	07 Oct 2022
Fenerive-Est	Ambatoharanana	Ambodihazinina	11 Oct 2022
Fenerive-Est	Vohilengo	Vohilengo	23 Oct 2022
Fenerive-Est	Miorimivalana	Antsiradava	24 Oct 2022
Fenerive-Est	Miorimivalana	Anorimbato	24 Oct 2022
Fenerive-Est	Miorimivalana	Antsirabe	25 Oct 2022
Fenerive-Est	Ampasimbe Manatsatrana	Ampasimbe Manatsatrana	18 Oct 2022
Fenerive-Est	Ambanjan'i Sahalava	Ambanjan'i Sahalava	19 Oct 2022

(*continued on next page*)

Appendix 2 (*continued*)

District	Municipality	Village	Date
Fenerive-Est	Ambanjan'i Sahalava	Marokiso	20 Oct 2022
Fenerive-Est	Mahanoro	Mahatsara	08 Oct 2022
Fenerive-Est	Mahanoro	Mahanoro	09 Oct 2022
Fenerive-Est	Ambodimanga II	Marofinaritra	03 Oct 2022
Fenerive-Est	Ambodimanga II	Marovato I	04 Oct 2022
Fenerive-Est	Ambodimanga II	Ambodifolera	05 Oct 2022
Fenerive-Est	Ambodimanga II	Andapa II	05 Oct 2022
Fenerive-Est	Vohipeno	Vohipeno	26 Oct 2022
Fenerive-Est	Vohipeno	Anamborano	27 Oct 2022
Fenerive-Est	Vohipeno	Sahafotaka	27 Oct 2022
Fenerive-Est	Vohipeno	Andratambe	28 Oct 2022
Fenerive-Est	Vohipeno	Sahandray	28 Oct 2022
Fenerive-Est	Vohipeno	Antsiranamatso	29 Oct 2022
Fenerive-Est	Vohipeno	Ankobahoba	29 Oct 2022
Fenerive-Est	Ampasina Maningory	Ampasina Maningory	12 Oct 2022
Fenerive-Est	Ampasina Maningory	Rantolava	13 Oct 2022
Fenerive-Est	Ampasina Maningory	Tanambao Tampolo	14 Oct 2022
Fenerive-Est	Ampasina Maningory	Takobola	14 Oct 2022
Fenerive-Est	Ampasina Maningory	Bitavola	15 Oct 2022
Fenerive-Est	Ampasina Maningory	Ambull dozer	16 Oct 2022
Fenerive-Est	Ampasina Maningory	Marovato I	16 Oct 2022
Fenerive-Est	Ampasina Maningory	Ambatomitrozona	17 Oct 2022
Fenerive-Est	Mahambo	Marofinaritra	04 Nov 2022
Fenerive-Est	Mahambo	Namahoaka	05 Nov 2022
Fenerive-Est	Mahambo	Antsikafoka	05 Nov 2022
Fenerive-Est	Mahambo	Sambolaza	07 Nov 2022
Soanierana Ivongo	Soanierana Ivongo	Manankinany	07 Dec 2022
Soanierana Ivongo	Soanierana Ivongo	Manakatafana	07 Dec 2022
Soanierana Ivongo	Soanierana Ivongo	Antsiragavo	07 Dec 2022
Soanierana Ivongo	Soanierana Ivongo	Ambodivoanio	08 Dec 2022
Soanierana Ivongo	Soanierana Ivongo	Tsirarafana	08 Dec 2022
Soanierana Ivongo	Soanierana Ivongo	Ambinany	09 Dec 2022
Soanierana Ivongo	Soanierana Ivongo	Menatany	09 Dec 2022
Soanierana Ivongo	Manompana	Tanambao Ambodimanga	14 Dec 2022
Soanierana Ivongo	Manompana	Manompana	15 Dec 2022
Soanierana Ivongo	Antanifotsy	Marovinanto	16 Dec 2022
Soanierana Ivongo	Antanifotsy	Antanifotsy	16 Dec 2022
Soanierana Ivongo	Antanifotsy	Manjato	19 Dec 2022
Soanierana Ivongo	Antanifotsy	Antsiraka	17 Dec 2022
Soanierana Ivongo	Antanifotsy	Andrangazaha	21 Dec 2022
Soanierana Ivongo	Ambodiampana	Ambinanisakana	22 Dec 2022
Soanierana Ivongo	Fotsialanana	Fotsialanana	23 Dec 2022
Nosy-Boraha (St. Marie)	Ambodifototra	Ambodifototra	13 Jun 2024
Nosy-Boraha (St. Marie)	Lokintsy	Lokintsy	14 Jun 2024
Vavatenina	Vavatenina	Ampasimbola	10 Nov 2022
Vavatenina	Vavatenina	Mahanoro	11 Nov 2022
Vavatenina	Maromitety	Maromitety	12 Nov 2022
Vavatenina	Ampasimazava	Ambatomipaka	13 Nov 2022
Vavatenina	Ampasimazava	Ampasimbola	14 Nov 2022
Vavatenina	Ampasimazava	Ampasimazava	15 Nov 2022
Vavatenina	Anjahambe	Fiadanana	21 Nov 2022
Vavatenina	Anjahambe	Anjahambe	23 Nov 2022

Appendix 3
Changes in absolute tree cover per district (in hectares) in Analanjirofo region, north-eastern Madagascar over the period 2012–2021.

District	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Fenerive-Est	215,612	207,098	198,216	194,792	187,843	179,761	173,864	168,129	163,142	160,083
Nosy-Boraha (St. Marie)	11,308	11,008	10,455	10,094	9306	8477	7786	7502	7051	6775
Soanierana-Ivongo	366,925	353,454	336,837	329,237	314,000	293,782	276,885	269,048	261,789	255,777
Vavatenina	228,681	219,999	212,963	208,934	201,223	192,355	186,365	181,358	176,456	172,429
Total	**822,526**	**791,559**	**758,471**	**743,058**	**712,372**	**674,375**	**644,900**	**626,036**	**608,438**	**595,064**

Sources: Hansen Global Tree Cover 2024.

Appendix 4
Changes in percentage tree cover per district in Analanjirofo region Analanjirofo region, north-eastern Madagascar, over the period 2012–2021.

District	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Fenerive-Est	72.87	70.00	67.00	65.84	63.49	60.76	58.76	56.83	55.14	54.11
Nosy-Boraha (St. Marie)	64.70	62.99	59.82	57.76	53.24	48.50	44.55	42.92	40.34	38.76
Soanierana-Ivongo	83.43	80.37	76.59	74.86	71.40	66.80	62.96	61.18	59.53	58.16
Vavatenina	77.54	74.59	72.21	70.84	68.23	65.22	63.19	61.49	59.83	58.46
Mean	74.64	71.99	68.90	67.33	64.09	60.32	57.37	55.60	53.71	52.37

Sources: Hansen Global Tree Cover 2024.

Appendix 5
Percentage overlap between municipality and protected area in the Analanjirofo region, north-eastern Madagascar.

District	No. of Protected Areas	Name of Protected Areas	% overlap municipality with Protected Area
Fenerive-Est	1	Tampolo (675 ha)	0.27
Nosy-Boraha (St. Marie)	0	NA	0
Soanierana-Ivongo	2	Ambatovaky special reserve (65,000 ha), Pointe à Larré (2870 ha)	7.47
Vavatenina	1	45 % of Zahamena National Park (29,221 ha)	6.06
Overall	4		4.05

Appendix 6
Changes in number of detected VIIRS fires per district in Analanjirofo region over the period 2012–2021.

District	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
Fenerive-Est	1084	1578	1222	1333	1480	867	873	913	1108	1100	11,558
Nosy-Boraha (St. Marie)	31	33	53	22	56	34	44	27	56	50	406
Soanierana-Ivongo	1521	2218	2675	2431	2311	1723	2314	822	2091	1664	19,770
Vavatenina	1362	1431	1395	1550	1484	997	785	958	1116	939	12,017
Overall	3998	5260	5345	5336	5331	3621	4016	2720	4371	3753	43,751

Sources: NASA, NOAA 2022.

Appendix 7
Comparison of traditional and modern processing facilities.

Comparison elements	Traditional still	Modern still
Price (US $)	325	650
Distillation method	Hydro-distillation	Hydro-distillation
Quantity of clove's leaves used (kg)	250–300	100–115
Quantity of used fuelwood (kg)	500–750	250–300
Distillation time (hour)	19–24	12–16
Amount of essential oil produced (litre)	4.5–6	3.5–4
Annual distillation frequency	16	23
Eugenol rate (%)	84–88	75–81

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