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Abstract

Slash and burn is a land use practice widespread all over the world, and nowadays it is formally recognized as the principal livelihood system in rural areas of South America, Asia, and Africa. The practice consists of a land rotation where users cut native or secondary forest to establish a new crop field and, in some cases, build charcoal kilns with the cut wood to produce charcoal. Due to several socio-economic changes in developing countries, some scientists and international organizations have questioned the sustainability of slash and burn since in some cases, crop yield does not justify the soil degradation caused. To estimate the soil quality in agricultural and forest soils at different ages of the forest-fallow period (25, 35, and 50 years), this survey investigated rural areas in three locations in Manica province, central Mozambique: Vanduzi, Sussundenga, and Macate. Soil profiles were trenched and sampled with a pedological approach under crop fields and forest-fallow. The chronosequence was selected to test the hypothesis that the increase in forest-fallow age causes an improvement of soil fertility. Results highlighted discrete variations among locations in mineralogy, Al- and Fe-oxyhydroxides, sand, silt, pH, total organic carbon, humic carbon, total nitrogen, available phosphorous, chloride, nitrate, fluoride, and ammonium. Few differences in mineralogy, Fe-oxyhydroxides, available P, chloride, and nitrate were detected between crop fields and forest-fallow within the same location. Such differences were mostly ascribed to intrinsic fertility inherited from the parent material rather than a longer forest-fallow period. However, physicochemical soil property improvement did not occur under a forest age of 50 years (the longest forest-fallow considered), indicating that harmonization of intrinsic fertility and agronomic practices may increase soil organic matter and nutrient contents more than a long forest-fallow period.

Keywords:

Soil fertility, sustainability, slash and burn agriculture, tropical soils, forest-fallow

1 Introduction

Slash and burn agriculture is widespread in tropical and sub-tropical regions all over the world (Li et al., 2014; Mukul and Herbohn, 2016) and occupies an important role in subsistence and cultural identity (e.g., Brady, 1996; van Vliet et al., 2012; Mukul and Herbohn, 2016). Paleoecologists have observed that, in the Amazonian basin, the first adoption of slash and burn practice dates to the pre-Columbian population (Arroyo-Kalin, 2012). On a global scale, an estimation by Hauser and Norgrove (2013) reported that 36 million km^2 of land was under slash and burn system, about 1/3 of the global soil resource. In terms of the population involved, FAO/UNDP/UNEP (2008) roughly estimated that over 500 million people were using slash and burn in 1982; however, these data are difficult to recollect (Mertz et al., 2009) and must have certainly changed in the last 40 years. Slash and burn consisted, and still consists, in cutting, burning, and farming different forest areas in rotation, often with the cut stems and branches used to create charcoal kilns (3-6 per hectare), while stubbles are burnt in situ (e.g., Brady, 1996; Brown, 2006; Riahtam et al., 2018). In some areas, the charcoal produced by charcoal kilns is sold in local markets (Kabisa and Ncheengamwa, 2020), while the very small fragments are incorporated with ashes into the soil by a basic plough to obtain a small increment of soil fertility and crop production (e.g., Rumpel et al., 2006; Gay-des-Combes, 2017; Selvalakshmi et al., 2018). The cleaned-up area is proportioned to family food requirements, and users continue to exploit it until the productivity goes below the sustenance threshold (Jakovac et al., 2016); after that, they move to another forest spot. The once cultivated areas are left to long fallow, with progressive regeneration of spontaneous vegetation and development of a secondary forest. The latter will be cut down again to begin a new cropping cycle (Gonçalves Lintemani et al., 2019; Hauser and Norgrove, 2013). This system has gone on for centuries in most of the suitable regions where peasants are pushed by environmental conditions to apply it for obtaining essential goods (e.g., Tschakert et al., 2007; Edivaldo and Rosell, 2020). In the last 4-5 decades, exploitation intensity has changed in slash and burn systems concurrently with *i*) the demographic increment and the subsequent need for more cultivable land (Kilawe et al., 2018), *ii*) economic policies pushing to convert traditional cultivations into cash crops (Vongvisouk et al., 2014; Wood et al., 2016; Kilawe et al., 2018), and *iii*) the necessity to obtain products to sell in local markets to achieve a small income (Ickowitz, 2011). Therefore, while once the area was left to fallow to recover to forest (hereinafter referred to as forest-fallow) over periods of 50-100 years, in the last decades the forest-fallow period has been progressively shortened to 10-20 years (Juo and Manu, 1996). The forest-fallow length is considered one of the main limitations of this land use system since it is expected that the soil needs many decades to restore fertility after cultivation. Fachin et al. (2021) studied revegetated soils in Paraná (Brazil) submitted to slash and burn system following a fallow chronosequence from one month to 12-years and found that chemical properties did not directly increase with the fallow age and development. Other issues raised by the shortened forest-fallow period, which is a form of deforestation (Dirac Ramohavelo, 2009; Mukul and Herbohn, 2016), are the reduced capability of carbon sequestration and storage (Kotto-Same et al., 1997), the erosion and loss of soil nutrients (Runyan et al., 2012; Thomaz, 2013), and the reduction of forest products like charcoal, medicines, fruits, nuts, and artisanal materials (Junsongduang et al., 2013). All over the world, many authors studied these effects from various points of view by investigating the soil physicochemical properties (e.g., Alegre and Cassel, 1996; Fachin et al., 2021; Rumpel et al., 2006), plant biodiversity, and vegetation dynamics (e.g., De Wilde et al., 2012; Randriamalala et al., 2019), the release of greenhouse gases (Davidson et al., 2008; Dhandapani and Evers, 2020), the chemical composition of charcoal, the stable soil C stocks (Selvalakshmi et al., 2018), and the microbiota composition (Aboim et al., 2008; Kukla et al., 2019). For most of these investigations, slash and burn is considered not sustainable any longer from social and environmental points of view. However, in addition to the shortened forest-fallow, other factors should be considered as limiting the sustainability of this practice: *i*) extreme climatic conditions; *ii*) quartz-rich soil parent materials and generally edaphic conditions (Kleinman et al., 1995); *iii*) agroecological settings i.e., the number of fallow/cropping cycles, fallow species succession, use of fertilizers, soil management (e.g. Styger et al., 2007; Mertz et al., 2008; Coomes et al., 2017); *iv*) technical efficiency at farming, infrastructure, and policy level (Binam et al., 2004).

Because of the crucial role of slash and burn in many economies of developing countries, soils of three locations in central Mozambique where the slash and burn system has been historically practiced were investigated. The locations were selected based on the different length of the forest-fallow and cultivation period, obtaining a chronosequence of 25, 35, and 50 years for the forest-fallows and a chronosequence of 1, 2, and 16 years for the crop fields. In each location, both crop field (CF) and forest-fallow (FF) were considered.

This work aimed to evaluate the impact of the slash and burn system on soil properties and fertility. Specifically, the morphological, mineralogical, and physicochemical (including soil texture, extractable Al- and Fe-oxyhydroxides, and water-soluble ions) soil properties were investigated to assess if and how several years of forest-fallow can influence the fertility of the revegetating areas. Two hypotheses were tested: 1) the longer the forest-fallow, the higher the recovery of the soil fertility as a result of organic matter accumulation; 2) the soils under FFs are more fertile than those under CFs.

2 Materials and methods

2.1 Characteristics of the locations and selection of the study areas

Details about agroecological, geological, and social background are reported at Point 1 of Supplementary Materials. Following the Köppen-Geiger climate classification, the climate of the R4 agroecological region is humid sub-tropical, with a warm temperate climate with a dry and cold season from April to September and a hot and rainfall season from October to March (Kottek et al., 2006; Belda et al., 2014), with frequent storms and cyclones. The soil parent rock at Vanduzi and Sussundenga was a granitoid rock (possibly gneissic-granite) belonging to the Barue Magmatic Arc (Wijnhoud, 1997; Chaúque et al., 2019), while at Macate it was a migmatitic paragneiss belonging to the supracrustal rocks of the Chimoio group (Chaúque et al., 2019) (see Supplementary materials).

With repeated surveys in the three districts, it was ascertained that in some fields the remainders of previous charcoal kilns were even more than 20 per hectare and, in some cases, charcoal kilns had been superimposed one over the other several times. As witnessed by the presence of charcoal kiln residues, all the surveyed forests were areas left to long fallow after cropping in which a *miombo* forest developed, as also reported by Montfort et al. (2021). Details on *miombo* are presented at Point 2 of Supplementary materials. In all cases, it was also ascertained that conditions of the forest-fallow were rather poor in terms of the number and species of trees (Table 1); thus, in interviews, farmers claimed that both biodiversity and tree density were higher 60-70 years ago. In each district, a study area was selected following information obtained mainly by interviews for Vanduzi and Macate, while for Sussundenga information was also retrieved from documents provided by the Research Station at IIAM (Mozambican Institute of Agricultural Research). The selected study area included both CF and FF representative of the R4 agroecological region to form a FF chronosequence: 25 years at Vanduzi, 35 years at Sussundenga, and ≈50 years at Macate. The CFs close to the FF areas were cultivated with annual and/or pluriannual crops established with the slash and burn system.

The main characteristics of the study areas are reported in Table 1 and briefly below.

- *Vanduzi* study area was on a gentle slope (3%), at an altitude of 658 m. CF was established one year before the survey by shallow ploughing (about 10 cm) to be devoted to vegetable garden/banana orchard managed with manual hoeing and irrigation, without fertilizer application. FF was a < 25 years old *miombo* moderately vigorous with crown-gaps and renewal, whose regrowth was disturbed by occasional grazing and low-intensity fires, and used to obtain firewood, timber, and charcoal. The main tree species was *Mangifera indica* L. (about 20% of tree abundance), remainders of an abandoned crop field with sparse mango plants, together with species typical of *miombo* (about 80% of tree abundance).
- *Sussundenga* study area was in an area with a gentle slope (2-4%), at an altitude of 649 m. CF was established two years before the survey after shallow ploughing with cow traction (8-10 cm). The field was cultivated with maize, without irrigation and fertilizer application, and sowed after the burning of plant residues and shallow ploughing with cow traction. The average maize grain yield was estimated to be 1.0-1.1 Mg ha^{-1} y^{-1}. Documents attested that FF was 35 years old

miombo; it appeared moderately vigorous with the presence of gaps and renewal and was occasionally used as a source of timber.

- *Macate* study area was in an area with a gentle slope (3%), at an altitude of 555 m. CF was established after shallow ploughing with cow traction (8-10 cm) and continuously cultivated with maize for 16 years with manual hoeing and without irrigation and fertilizer application. Yield roughly ranged between 1.1 to 1.5 Mg ha^{-1} y^{-1}. Crop residues were commonly used for mulching and, only at the end of the 2017 wet season, a controlled crawling fire was applied to reduce the invasive *Mucuna pruriens* DC. FF was ≈50 years old *miombo*, vigorous, without gaps but with renewal. It has been and is used as a source of timber, firewood, and game.

To prove the age of the forest-fallow, with the counting of tree rings being useless, we ascertained that the average tree diameters of the ubiquitous *Brachystegia spiciformis* trees of Macate (33 cm) was higher compared with that of Sussundenga (26 cm) and Vanduzi (16 cm) trees.

2.2 Soil sampling procedure

In March 2017, in each of the three study areas, a geomorphological and soil survey was run to select sampling sites with similar exposure and slope (Table 1). In doing this, several mini-pits and auger holes were opened before choosing the best position where to dig the soil profiles. Soil profiles were trenched (0.8 m of width) in both CFs and FFs, all within a surface of ≈1 ha (Fig. 1).

In the FFs, profiles were opened at 1-1.5 m downslope from the trunk of one of the biggest *Brachystegia spiciformis* Benth. trees, where the stem influence was considered null. In the CFs, profiles were opened in the middle of their extension. The maximum distance between CF and FF was about 60 m at Macate and Sussundenga, while at Vanduzi FF and CF sites were at a distance of about 700 m. In all cases, sampling sites were at least 30 m from the rather sharp CF-FF transition, a distance that was considered sufficient to avoid considerable edge effects. As a replicate, a second soil survey was made in November 2017, in which soil profiles located a few meters from the previous ones were opened. As a whole, 12 profiles were sampled (3 locations per 2 land uses per 2 replicates).

The soil profiles were morphologically described per Schoeneberger et al. (2012) and about 4 kg of soil sample from each genetic horizon were collected. During the field activities, the collected samples were maintained inside a portable fridge and, once in the laboratory, they were air-dried, sieved at 2 mm to remove the skeletal particles, and maintained at 4°C for a maximum of one week before the analyses.

2.4 Soil analyses

Soil mineralogical assemblage was evaluated by X-ray diffractometry on manually compressed powdered samples by using a Philips PW 1830, which produced a Fe-filtered Co Kα1 radiation, operating at 35 kV and 25 mA. The identification of the minerals was done based on their characteristic peaks (Brindley and Brown, 1980; Dixon and Schulze, 2002). A semi-quantitative assessment of the mineralogical assemblage was obtained by estimating the area of the primary peaks by multiplying the peak height by its width at half-height (Cocco et al., 2015).

The particle-size distribution was determined by the pipette method (Day, 1965) after the dissolution of organic cements by NaClO at pH 9 (Lavkulich and Wiens, 1970). The sand (2-0.05 mm) was separated by wet sieving, while silt was separated from clay by column sedimentation at 19-20°C air temperature. The pH was determined potentiometrically in water (1:2.5 solid:liquid ratio), using a combined glass-calomel electrode immersed into the suspension. The content of total organic C (TOC) was estimated by K-dichromate digestion, heating the suspension at 180°C for 30 min (Allison, 1965), and the humic C (HC) was determined by the Walkley-Black method (Nelson and Sommers, 1996). The total nitrogen (TN) was determined by the Kjeldahl semi-micro method and the potentially plant-available phosphorous (AvP) was estimated according to Olsen et al. (1954).

The amounts of Al and Fe forming pedogenic oxyhydroxides were estimated by extraction with dithionite-citrate-bicarbonate (DCB) treatment (Jackson, 1958), using 30 ml of mixed solution plus 1 g of Na-dithionite to treat 2 g of soil sample; the extraction was repeated two times and then washed twice. The total extract was filtered with an ashless Whatman 42 filter paper, and the Al and Fe in solution were determined by Optical Emission Spectrometer – Optima 8300.

Soluble ions were extracted by distilled water (1:10 solid:liquid ratio). After gentle stirring for 1 min, the suspension was left to rest for few minutes and the supernatant was filtered with ashless Whatman 42 filter paper. The concentration of anions (chloride, fluoride, sulphate, nitrate, phosphate, nitrite, bromide, acetate, oxalate, and formate) and cations (calcium, magnesium, potassium, sodium, ammonium, and lithium) was determined in the solution by a Dionex ICS-900 Ion System Chromatograph equipped with IonPac AS23 column for anions and IonPac CS12 column for cations, using a 0.5 M Na-bicarbonate solution as eluent. The concentration of bicarbonate ions was obtained from the difference between the summation of cations and the summation of anions.

2.5 Statistical analysis

For each horizon, a single determination was performed for mineralogy, particle-size distribution, pH, TOC, HC, TN, AvP, and total extractable (pedogenic) Fe and Al. For the soluble cations and anions, two extractions per sample were obtained each, and the two values averaged to obtain more reliable results. R program (1.3.1093, R Core Team, 2014) was used for statistical analysis, that was run for soil physicochemical properties among soil profiles. The ANOVA at 5% significance was used to assess those physicochemical results obtained by the two surveys (Tables S1, S2, S3, and S4 of Supplementary materials). Therefore, the results of the two surveys were considered replicates, and the results of each horizon were used to calculate the weighted average based on the thickness of each horizon; the standard deviation was also calculated. Principal Component Analysis (PCA) [FactoMineR and factoextra R packages] for the entire dataset was impossible to compute since the cumulative variance percentages were > 60% over the third dimension. Therefore, PCA was performed for particle-size distribution, pH, TOC, HC, TN, AvP, and extractable Al and Fe in soil profiles (Fig. 2) to assess the structure of the main variables in the three study areas and in CF and FF. To further analyse the results, ANOVA was applied to enhance significant differences in soil profile properties among CFs and FFs from the three locations, and between CF and FF within each location. Data were tested for normality and homoscedasticity by performing the Shapiro-Wilk statistical test (stats R package) and by the Levene's test (car R package), both at 5% of significance level, respectively (Tables S5, S6, S7, S8, and S9 of Supplementary materials). Box and Cox transformation was used to transform the data in case they were not parametric (Meloun et al., 2005). If the transformed data were normally distributed, a post-hoc Tukey's Honest Significant Difference (HSD) test with $P \leq 0.05$ was used to compare the means. When normality was not respected, the Kruskal-Wallis test was applied. In the case of heteroscedasticity, the Welch one-way ANOVA test was performed. ANOVA tests were deemed significant when $P \leq 0.05$.

3 Results

3.1 Soil morphology and mineralogy

In all the locations (Vanduzi, Sussundenga, and Macate), the soils belonged to the order of Oxisols according to Soil Survey Staff (2014) or Ferralsols according to IUSS (2015), due to the presence of A (umbric) and Bo (oxic) horizons (Table 1). In general, A and Bo horizons showed red-yellowish colour and a good degree of aggregation made of blocks generally coarser in the A than in the Bo horizons. Such good state of aggregation, the coarse texture (mainly sandy loam), and the absence of redoximorphic features indicated these soils as well-drained and, consequently, with low to moderate water-holding capacity (Agrawal, 1991; Suzuki et al., 2007). Roots were rather abundant, from very fine to coarse in size, in the A and Bo horizons under FFs, while under CFs root density and size decreased along the profile and were absent in the cultivated soil of Macate. The A horizons under CFs always showed a charcoal content of <1%, while under FF charcoal fragments were found rarely in the subsurface horizons. Two of the three FFs presented organic horizons, identified as Oi horizons at Sussundenga and as Oi and Oe&Oa horizons at Macate. Only under CF at Vanduzi and FF at Sussundenga, soil tunnelling due to termites was found.

In all the soils mineralogical composition was dominated by quartz, with the highest contents at Sussundenga (90-95%) and the lowest at Macate (67-79%). A major variability in mineralogical composition was observed in the Macate soils, where plagioclases and kaolinite were present in higher quantities than in the Vanduzi and Sussundenga soils. Vanduzi showed the highest content of 2:1 clay minerals under CF and the lowest content of kaolinite under both land uses. Within each location, the only difference between land uses was observed at Macate, where a slightly higher content of 2:1 clay minerals was found in the FF soil than in the CF soil (Table 2).

3.2 *Physicochemical properties, including extractable (pedogenic) Al and Fe*

The PCA clearly separated soils of Macate from those of the other study areas mainly for the drivers of sand, silt, TOC, HC, TN, AvP, and extractable (pedogenic) Al and Fe variables, which were explained by the first component (PC1) for 47.5% and by the second component (PC2) for 24.3% of the variance (Fig. 2). In all the soils the particle-size distribution revealed a predominance of sand, followed by clay and silt. Both CF and FF soils of Sussundenga and FF soil of Vanduzi displayed higher content of sand than all the soils of Macate (Fig. 3A). The FF soil of Macate showed a major abundance of silt compared with FF soils of Vanduzi and Sussundenga (Fig. 3B). No significant difference was observed between CF and FF soils within each location (Fig. 3A, B, C). The Vanduzi soils were slightly acid, with values ranging from ≈6.3 to 6.8 (Fig. 3D). As expected, the contents of TOC, HC, and TN were low on absolute value but resulted higher in the CF soil of Macate than in those of Vanduzi and Sussundenga (Fig. 3E, F). Thus, while among FF soils no significant difference was observed for TOC and HC, TN displayed the highest concentrations in both CF and FF soils of Macate (Fig. 3G). Since the soil deficiency threshold for the adopted method is considered to be 23 mg kg^{-1} (Cardelli et al., 2017), the AvP content was always very low, with the highest content in the FF soil of Vanduzi, where it was also higher than in the CF soil (Fig. 3H). The total extractable Al ranged from 1.1 to 7.1 g kg^{-1} in all the soils, while Fe varied from 3.3 to 40.4 g kg^{-1} (Table 3). The soils of Macate showed the highest concentrations of extractable Al and Fe in both CF and FF soils. In addition, only at Macate, the FF soil showed a higher concentration of extractable Fe than the CF soil (Table 3).

3.3 Water-soluble anions and cations

Formate and lithium were always below the detection limits, while bromide was detected in a very small amount (≈1 μeq kg^{-1}) only in the Ap horizon of Macate CF soil (Tables S10, S11). Significant (P<0.05) differences for anions were detected only for chloride, fluoride, and nitrate, whereas among cations only for ammonium (Fig. 4). Chloride concentration was similar in all the soils under CF (mean 496 μeq kg^{-1}), while under Macate FF soil it showed a higher value than in the Sussundenga soils (400 and 254 μeq kg^{-1} respectively). Chloride also differed between land uses in the Vanduzi soils, with higher concentrations in CF than in FF soils (408 and 318 μeq kg^{-1} respectively) (Fig. 4A). The nitrate concentration was higher at Macate than at Sussundenga for CF soils (342 and 58 μeq kg^{-1} respectively), and it was higher at Macate than at Vanduzi for FF soils (804 and 5 μeq kg^{-1} respectively) (Fig. 4B). Fluoride was the highest in the soils of Vanduzi and Macate, regardless of the land use (8 and 9 μeq kg^{-1} respectively) (Fig. 4C). Ammonium was higher in the soils of Macate and Sussundenga than in those of Vanduzi, independently of the land use (200, 215, and 20 μeq kg^{-1} respectively) (Fig. 4D).

4 Discussion

4.1 Impact of the forest-fallow length on soil properties and fertility

4.1.1 Soil morphological and physical properties

The predominant reddish colour of the soils and the abundance of quartz and sand particles underlined the strong weathering processes faced by the studied soils, where the more easily weatherable minerals in the upper soil meter have been removed by alteration. Similar results were reported by Sá et al. (1972) and FAO (1982) and attributed to the lateritization process that is responsible for the development of Oxisols (Van Wambeke et al., 1983; Soil Survey Staff, 2015).

This process is also responsible for the formation of a good soil structure because of the progressive increment of Al- and Fe-oxyhydroxides that act as cementing agents (Igwe et al., 2009; Krause et al., 2020). The small mineralogical variability among locations betrayed the different parent materials from which the soils have developed. In fact, the lowest quartz and the highest kaolinite contents in the soils of Macate were probably due to the composition of their parent rock, a migmatitic paragneiss, which is a lithology generally richer in fine-grained clastic sediments than the granitoid rocks of the other two sites. Crystalline rocks like granites and gneisses may contain intercalations of sedimentary silty or clayey beds (Gray et al., 2016), and this could be the explanation for the different particle-size distributions of these soils. The occurrence of tunnelling in the CF soil of Vanduzi and in the FF soil of Sussundenga was ascribed to attempts of termites to colonize these soils; as a matter of fact, no termite nests were observed in the hectare of the surface under study, nor in the close surroundings. Therefore, the small morphological and physical differences among locations appeared related to the composition of the parent rocks rather than to the uncultivated period duration, expressed by the forest-fallow age, or the cultivation period.

4.1.2 Soil chemical properties

The relatively high pH values in the Vanduzi soils were ascribed to the higher presence of 2:1 clay minerals (mainly vermiculite), which offer a much higher buffering capacity than the other minerals present (Abate and Masini, 2005; Malandrino et al., 2006; Abollino et al., 2008). Because of this, the distinct parent material and related mineralogical assemblage appeared to be the main cause of the different soil pH values. TOC and HC were present in very low amounts, in line with the contents reported by Rafael et al. (2018) for Mozambican soils. However, since both TOC and HC contents were similar in the FF soils and were the highest in the Macate CF soil, deductions were that:

i) in this environment, a 50-years forest-fallow is not able to enrich the FF soils with organic matter. Studying the soil characteristics after slash and burn, Montfort et al. (2021) found that organic carbon stock in the upper 30 cm soil was similar in 20 and 25 years old *miombo* forests and mature woodland due to the rapid vegetation regeneration and that disturbances typical of slash and burn (biomass removal, fire, and soil tillage) can decline this content. Moreover, a study conducted by Williams et al. (2008) in arid Mozambican *miombo* forests reported no identifiable changes in soil organic C accumulation along a chronosequence in the re-growing miombo (for a maximum age of 30 years) due to the extremely slow input of organic matter to the soil; and that,

ii) for the higher TOC and HC contents in CF soils of Macate, it occurred for the soil cultivated for the longest time (16 years) compared to the soils of Vanduzi and Sussundenga (1 and 2 years, respectively). The reason was ascribed to the fact that, after the beginning of cultivation, the farmer has always practiced mulching in between and, with controlled crawling fires to reduce weeds. It is possible that mulching of crop residues combined with the scarce fire application has increased the organic matter content and reduced erosion so to maintain soil fertility that has supported the crop yields for all the cultivated years. This practice resulted ineffective for the AvP, whose generalized low values were attributed to the selective adsorption of phosphates on the abundant Fe- or Al-oxyhydroxides (Parfitt, 1989; González-Rodríguez and Fernández-Marcos, 2018; Rafael et al., 2020) and to the lack of fertilizer application. However, high contents of extractable Al and Fe have also a positive aspect, being the Al- and Fe-oxyhydroxides particularly involved in the stabilization of organic matter via the formation of complexes (Six et al., 2000; Verde et al., 2005; Zhao et al., 2017; Totsche et al., 2018) and in the formation of stable soil structure. The higher concentrations of organic matter in the soils of Macate, compared to Sussundenga and Vanduzi, are likely related to their higher concentrations of dithionite-extractable iron and aluminum.

The soils of Macate also showed the highest TN content. Trees in the Macate FF were vigorous and many belonged to the *Fabaceae* family, plants that are well-known for establishing symbiotic associations with N_2-fixing bacteria (e.g., De Boer and Kowalchuk, 2001; Franche et al., 2009). Also, the FF soils of Vanduzi and Sussundenga hosted leguminous plants, but they were less vigorous and subjected to frequent stresses due to fire applications for hunting purposes or disturbances to obtain firewood, timber, and charcoal. Being the FF of Macate older and less stressed, as demonstrated by the presence of a rather well-expressed litter (Oi and Oe&Oa horizons), than those of Vanduzi and Sussundenga, the relatively higher soil N content was ascribed to the presence of leguminous trees that enriched the soil because of 50 years of undisturbed plant-microbial association. For the CF, even though cultivated for 16 years with maize, the soil contained a relatively high TN content. Although a possible contribution of N_2 fixation due to annual leguminous weeds like *Mucuna pruriens* cannot be excluded, the relatively high TN content was ascribed to the continuous mulching (Fang et al., 2011; Dong et al., 2018) and the scarce fire application. In fact, N is an extremely volatile element that can be easily lost during the vegetation burning (Da Silva Neto et al., 2019).

In well-drained soils with acidic pH, low cation exchange capacity, and quartz dominated mineralogy like those here studied, fertility is extremely low (Eshett et al., 1989), and proper soil management including soil mulching and absence of fire is crucial to guarantee a minimum level of organic matter and nutrient stocks, able to support crop yields (Bahr et al., 2014; Temudo et al., 2017).

4.1.3 Soluble anions and cations in soils

Well-drained and acid soils like those here studied are easily leached out of the most soluble ions (Juo and Manu, 1996), so it appeared reasonable that the water-extracted anions and cations assumed concentrations at the level of μeq kg^{-1}. Although in low concentrations, significant differences were observed for chloride, fluoride, nitrate, and ammonium. Chloride was detected in higher contents in the soil of Macate FF than in those of Vanduzi and Sussundenga. Among the several sources of chloride listed by Geilfus (2019), since for Mozambique there is no report accounting for halite rock outcrops except for a mixture of limestone and halite (Jofane formation) lying at 150-250 km from the study sites (Schlüter, 2008), notwithstanding the long distance between study sites and the Mozambique sea channel, the contribution of the airborne sea salts cannot be excluded. Especially at Vanduzi, the angular coefficient of the Cl/Na relationship of the soil extract was similar to that of the seawater (Keene et al., 1986) (Fig. S1 of Supplementary materials). Differences in fluoride content can be due to natural and anthropogenic sources (e.g., Ali et al., 2016; Mikkonen et al. 2018; Wang et al., 2019). Parent material is considered the most common source of fluoride, which is present in minerals like fluorites, apatites, and micas, which form granite and igneous rocks, but also in topaz, which is commonly associated with silicic igneous rocks, and cryolite, which comprises pegmatitic rocks (e.g., Battaleb-Looie et al., 2012; Mikkonen et al., 2018). In the soils, fluoride was detected at the highest concentrations under both CF and FF of Vanduzi and Macate, namely in soils with different parent rocks; because of this, the geogenic source of fluoride was considered irrelevant in determining the differences. Consequently, as largely reported in the literature (e.g., Feng et al., 2002; Choubisa and Choubisa, 2016; Wang et al., 2019), the relatively higher fluoride content in the soils of Vanduzi and Macate was ascribed to windblown materials coming from the surrounding mining activities devoted to the extraction and transformation of copper, nickel, gold, silver, iron, and bauxite, which are absent in a radius of at least 30 km from Sussundenga (Lehto and Gonçalves, 2008; MIREME, 2021). In the Macate soils, where there was the highest content of TN, also nitrate and ammonium were relatively abundant, possibly because of mulching. In fact, Yaşar Korkanç (2021) demonstrated that soil mulching with organic materials reduced nitrate and ammonium losses through water runoff when compared to uncovered plots and, for environments where rainstorms and cyclones are frequent, mulching could make the difference. In the Sussundenga soils, where fertilizer has never been used, only ammonium showed the highest concentrations possibly because of the ongoing mineralization of tree roots after the recent (one year) slash and burn (Juo and Manu, 1996; Vitousek, 1981; Béliveau et al., 2015). In addition, ammonium is the direct product of biomass burning (Knicker, 2007), and the recent slash and burn could have contributed to the ammonium release.

Therefore, concentrations of anions and cations were mainly ascribed to the arrival of windblown materials for chloride and fluoride, and to the soil management for nitrate and ammonium, with no relation to the different lengths of the forest-fallow period.

4.2 Comparison of soils under forest-fallow and cropping within the location

4.2.1 Soil morphological and physical properties

In each location, CF and FF soils were similar, and only at Macate, the FF soil contained a minimum amount of 2:1 clay minerals, which were absent in the CF soil. Even though forest vegetation is efficient in controlling soil erosion and runoff, especially when the understorey is thick and made of shrubs and herbaceous vegetation (Doerr and Cerdà, 2005; Thomaz, 2013), it is also true that in slash and burn systems, in addition to temperature fluctuations and direct rainfall, agronomic practices like tillage can increase mineral weathering (Lemenih et al., 2005). Therefore, it seems unrealistic that these differences in 2:1 clay minerals between FF and CF soils at Macate have been produced in only 16 years of cultivation. Because of this, we considered this as a condition ascribable to a site-specific difference of the parent material, which contained clay minerals or was more prone to produce clay minerals through weathering.

4.2.2 Soil chemical properties

Significant differences in chemical properties between CF and FF were observed only for AvP in the soils of Vanduzi. The slight P deficiency in the CF was probably exacerbated due to plant absorption and erosion processes (Da Silva Neto et al., 2019), even though the CF was established only one year before the soil sampling. In Oxisols, the richness of Fe-oxyhydroxides promotes a strong immobilization of phosphates (Lü et al., 2017; Markovic et al., 2019), and the plant absorption in absence of fertilizer application can rapidly decline the amount of AvP (Shen et al., 2011). Considering the small chemical differences between CF and FF soils within locations, it appeared that the effect of reforestation on the recovery of soil fertility was irrelevant.

4.2.3 Soluble anions and cations in soils

Only at Vanduzi the soil under CF appeared enriched with chloride and nitrate compared with that under FF. In general, possible vectors of chloride and nitrate are irrigation water, fertilizers, and/or other human activities (e.g., Geilfus 2019; Martinez Uribe et al., 2020; Oberhelman and Peterson, 2020). In this case, manual irrigation is practiced taking advantage of the water of a nearby stream that, in the previous five km, crosses an area devoted to industrial poultry production, an urban area at four km NW from the city of Chimoio, and a nearby industrial area. Concerning fertilization, Geilfus (2019) mentioned as possible sources of chlorides animal wastes like cattle manure, pig slurries, and chicken or pigeon manures. Both manure and sewage are possible sources of nitrates (Jin et al., 2018; Wakida and Lerner, 2005; Torres-Martínez et al., 2021). Because of this, in the absence of information about the water quality of the stream over the years, it is reasonable that the relatively high content of chloride and nitrate in the CF soil of Vanduzi is mostly derived from the irrigation water collected from the near stream. However, the CF is located in an educational institution where, in addition to agriculture, extensive free-range cattle livestock is practiced during the offseason, and cattle manure could be an additional source of nitrate and chloride.

Therefore, also for cations and anions distribution, soil management rather than the length of the forest-fallow period appeared to exert some effect.

5 Conclusions

The CF and FF soils of the studied slash and burn system showed low physicochemical fertility, with small differences depending mainly on the parent rock and soil management. Even if detailed information about agroecological settings was impossible to obtain for this region, it was possible to assess that FF soils were not in better conditions than those under CF and that the recovery of soil fertility appeared inconsistent at least for a maximum of 50 years old forest-fallow, which represented the longest forest-fallow period considered in this paper. Based on soil organic matter, TN, nitrate, and ammonium contents, it seems that soil management such as mulching, irrigation, and reduced fire application foster the recovery of the soils. It is therefore beneficial to adopt these agronomic practices aimed at maintaining (or increasing) crop yields, but also at reducing the pressure on forest land due to the frequent cuts and fires, with consequent improvement for macro- and micro- fauna and flora biodiversity, at least in the first phase of the forest-fallow period.

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