Etude de la succession secondaire dans le cadre de la pratique des cultures sur brûlis au Menabe central, Madagascar

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Etude de la succession secondaire dans le cadre de la pratique des cultures sur brûlis au Menabe central, Madagascar

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A Dieu seul revient la gloire !

Abréviations

ANGAP : Association Nationale pour la Gestion des Aires Protégées

CEL : Central Environmental Laboratory

CFPF: Centre de Formation Professionnelle Forestière

CIREEF : Circonscription Inter-régional de l'Environnement, des Eaux et Forêts

CNFEREF : Centre National de Recherche et de Formation en Environnement et Foresterie

ESSA : Ecole Supérieure des Sciences Agronomiques

FAO: Food and Agriculture Organization

SAHA: *Sahan'Asa Hampandrosoana ny Ambanivohitra* - Programme de Développement Rural (par Intercoopération Suisse)

USAID: United States Agency for International Development

WRB: World Reference base for soil resources

Résumé

Madagascar est connu pour ses richesses en biodiversité et ses écosystèmes uniques. Une forte pression d'origine anthropique entraîne pourtant une destruction rapide des habitats naturels et une perte massive de cette biodiversité. La culture sur brûlis est une des causes de cette pression. Il s’agit d’une pratique traditionnelle et prédominante dans plusieurs régions à Madagascar et notamment dans le Sud-Ouest. La végétation secondaire qui s’installe sur les parcelles anciennement brûlées puis abandonnées présente des intérêts économiques pour la population locale, soit sous forme de bois de feu, plantes à tubercules, pâturage ou plantes médicinales, pour n’en nommer que quelques usages commerciaux potentiels. Pour limiter les atteintes aux forêts intactes, une réutilisation des surfaces anciennement brûlées s’avère nécessaire. Le but de cette thèse est d’étudier les potentialités des successions secondaires pour la pratique des cultures sur brulis en vue de l’optimisation de leur réutilisation. Différents âges d’abandon de parcelles ont été étudiés, allant de 1 an d’abandon de culture jusqu’à plus de 40 ans, et classés en 6 catégories (1 à 5 ans, 6 à 10 ans, 11 à 20 ans, 21 à 30 ans, 31 à 40 ans et plus de 40 ans).

Tant qu’ils ont le choix, les paysans préfèrent utiliser les sols jaunes (nomination fréquemment utilisée à cause de la couleur du sol) plutôt que les sols rouges parce que les sols jaunes présentent un pH légèrement basique et un rapport C/N plus élevé. La richesse spécifique de la végétation augmente avec la durée de la période d’abandon de culture et se stabilise à partir de 40 ans. Les espèces ligneuses augmentent à partir de 10 ans d’abandon de culture et les espèces herbacées diminuent légèrement à partir de 30 ans.

Concernant la biomasse, nos mesures ont montré que celle des herbacées augmente jusqu’à 20 ans d’abandon de culture et peut atteindre 2.1 t/ha (de biomasse sèche, c-à-d. biomasse fraîche séché à l’air libre pendant 3 semaines), puis cette quantité diminue jusqu’à 1.2 t/ha (de biomasse sèche) après 40 ans d’abandon de culture. Cette diminution est due à la baisse de la luminosité liée à l’apparition des grands arbres. Pour les espèces ligneuses, la biomasse sèche augmente avec l’âge d’abandon de culture. La quantité de biomasse sèche (c-à-d. biomasse fraîche séchée au four après avoir été séchée à l’air libre) passe de 0.43 t/ha pour la période de 1 à 5 ans à 66.9 t/ha après 40 ans d’abandon de culture.

Concernant la concentration de nutriments apportés par les cendres, elle est plus élevée pour les feuilles que pour le tronc et les branches. D’autre part, la quantité de nutriments libérés par les cendres augmente en fonction de l’âge d’abandon de culture compte-tenu des biomasses sur pied. Neuf espèces atteignent la biomasse sèche de plus de 1 t/ha, après 30 à 40 ans, *Poupartia sylvatica* et *Tarenna sericea* contribuent non seulement à la plus grande quantité de biomasse mais aussi de nutriments libérés au sol.

En ce qui concerne la fertilité des sols, il y a une augmentation des éléments chimiques à partir de 6 à 10 ans d'abandon de culture. Après cette période, les concentrations de nitrate et d'ammonium augmentent progressivement. Quant au magnésium, au calcium et au potassium, les concentrations augmentent puis diminuent légèrement, alors que les concentrations restent constantes pour le Ctot et Ntot, et diminuent pour le pH et le CEC.

Nous concluons qu'une réutilisation avant dix ans conduirait à une pratique agricole non durable et recommandons en conséquence une rotation de 11 à 30 ans, de manière à permettre au sol de régénérer suffisamment sa fertilité avant un nouveau cycle de culture.

Mots clés : Culture sur brûlis - végétation secondaire – biomasse – minéralomasse – inflammabilité – fertilité - Menabe central - Madagascar

Abstract

Madagascar forests are among the most biologically rich and unique ecosystems. Strong pressure from human activities causes, however, a rapid destruction of natural habitats and a massive loss of biodiversity. Slash and burn is one of the causes of this pressure. This is a traditional practice in many areas and predominantly in Madagascar, particularly in the South-West. Secondary vegetation that has developed on surfaces formerly burned and abandoned has an economic value for the local population, either as firewood, root crops, pasture or medicinal plants, or potential commercial uses. To limit the pressure on natural forest, re-use of previously burned and abandoned surfaces is necessary. The aim of this thesis is to study the potential of secondary succession for the practice of slash and burn in order to optimize its use. Different ages of culture abandonment were studied in plots ranging from 1 year of culture abandonment to more than 40 years, and classified into six classes (1-5 years, 6-10 years, 11-20 years, 21-30, 31-40 years and more than 40 years). In this region, farmers prefer to use yellow soils (name used because of their color) rather than red soils because pH is slightly basic in the yellow and the ratio C/N higher. The species richness increases with the age of abandonment and stabilizes at more than 40 years. Woody species increased from 10 years of culture abandonment and herbaceous species decreased slightly after 30 years.

With respect to biomass, our measures showed that herbaceous biomass increases up to 20 years of abandonment and can reach up to 2.1 t/ha (dry biomass, i.e. air dryed biomass during three weeks), then this quantity decreases to 1.2 t/ha (dry biomass) after 40 years of abandonment. This decrease is due to the growth of large trees and bushes and the decrease of luminosity. For woody species, the oven dry biomass increases with the age of abandonment. The amount of oven dry biomass increases from 0.43 t/ha for the class 1 to 5 years, to 66.9 t/ha after 40 years of abandonment.
The nutrients concentrations released by ashes are higher for the leaves as compared to the trunk and the branches. The amount of nutrients released increases with the age of abandonment because of overal increase of biomass. Nine species reach a dry biomass of over 1 t/ha after 30 to 40 years. *Poupartia sylvatica* and *Tarena sericea* contribute not only to the largest amount of biomass but also of nutrients released to the soil
With respect to soil fertility, for most chemical variables, a significant increase is observed between six and ten years after abandonment. After this period, nitrate and ammonium concentrations increase steadily. As for magnesium, calcium and potassium, they show a tendency for hump-shaped patterns, whereas the concentration remains constant for Ctot and N tot, and decreases for pH and CEC.
We conclude that a fallow period shorter than 10 years would lead to an unsustainable agricultural system and recommend a turn-over period of 11 to 30 years since last cultivation to permit soil recovery to a sufficient fertility level to start a new cycle of cultivation.

Key words : Slash and burn - secondary succession – biomass – nutrient – inflammability – fertility- Central Menabe - Madagascar

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1.1. Contexte et problématique

Madagascar, qui s'est détachée de l'Afrique il y a 165 millions d'années et de l'Inde il y a 70 millions d'années (Rakotosamimanana 2003), est l'île la plus vaste de l'Océan Indien et la 4ème plus grande île du monde. Madagascar se présente comme l'un des pays ayant une des plus grandes diversités floristiques et faunistiques dans le monde et constitue un véritable laboratoire vivant (Ganzhorn et al 2001; Dufils, 2003; Harper et al 2007).

La forêt dense sèche du sud-ouest de Madagascar couvre moins de 20% de la surface de la région. Elle est parmi les écosystèmes les plus fragiles en raison de la déforestation et des cultures sur brûlis. Dans la région de Menabe, entre 1991 et 2000, une perte de forêts de 0.70 à 1.1% a été enregistrée avec une légère diminution de 0.35 à 0.53% entre 2000 et 2005 (USAID, Conservation International, 2007).

La culture sur brûlis est la pratique traditionnelle et prédominante dans beaucoup de régions à Madagascar (Brand et Pfund 1998 ; Styger *et al.* 2009) et dans le monde (ex : en Indonésie (Varma 2003), en Afrique (FAO soils bulletin 1974), en Amérique du Sud (Uhl 1987 ; Fujiska et White 1998). Selon Genini 1996, la pratique consiste à couper la forêt naturelle à la fin de la saison sèche (juin à septembre), à empiler le bois coupé autour des grands arbres, à le sécher pendant un certain temps (1 à 3 mois), et à le brûler. En général, le feu détruit toute la végétation à part les grands arbres comme le baobab. Les cendres obtenues de la biomasse brûlée sont utilisées pour la culture de maïs dans les premières années (1 à 3 ans) et des arachides ou du manioc pour les autres années. Cette pratique ne nécessite pas des travaux d'entretien difficiles des cultures. Après quelques années, le rendement de la culture diminue et les paysans abandonnent leurs champs et recommencent la même pratique dans d'autres parcelles de forêt. La perte de fertilité du sol, le surpâturage, l'érosion du sol et l'envahissement par des plantes invasives sont les conséquences directes de cette culture sur brûlis (Brady 1996; Kotto-Same 1997; Harper *et al.* 2007). Les parcelles issues de cette pratique deviennent des formations secondaires (forêt secondaire ou végétation secondaire) qui datent de une ou de plusieurs années selon l'âge d'abandon de culture. Dirac Ramohavelo 2009 a relevé l'intérêt économique de ces formations secondaires qui sont des sources de bois de feu, zones de pâturage, réservoirs de plantes médicinales et fournisseurs de bois d'intérêt commercial.

Comme dans les autres pays en développement, l'agriculture est la principale activité de la population locale (Calderoni 1999; Dirac Ramohavelo 2009). Le maïs, le manioc et les arachides sont les principales cultures dans la zone d'étude. Les produits sont consommés sur place ou vendus au marché local. Quelques fois, des collecteurs achètent la production sur place à la fin de la récolte. En ce qui concerne le riz, même s'il est l'aliment principal des Malgaches, notre zone d'étude ne contient pas de rizières. Les paysans achètent le riz pour leur besoin quotidien au marché de Beroboka (environ à 5 km du village).

La pratique continue de la culture sur brulis entraîne la diminution de la biodiversité floristique et faunistique par le surpâturage, l'érosion des sols et leur envahissement par des plantes invasives (*Ocimum cannum)*. La perte des nutriments conduit à l'appauvrissement des sols.

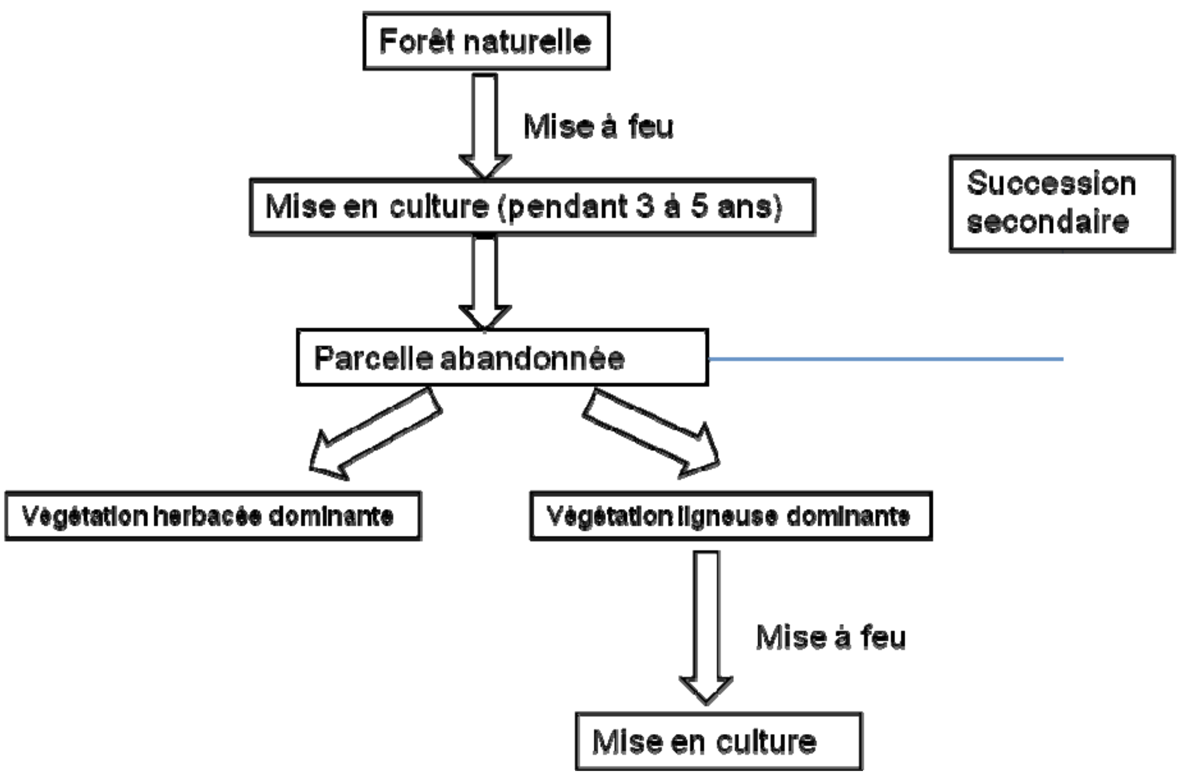

Figure 1 : Schéma générale de la culture sur brûlis et son optimisation

1.2. Milieu humain et ses activités

La région du Menabe, située le long de la côte ouest de Madagascar, est dominée par l'ethnie Sakalava, caractérisée par le respect des ancêtres, une forte puissance de la lignée et des systèmes de gestion de village qui sont dominés par la tradition (Cabalzar 1996). L'élevage (bovin) est son activité principale. Le rôle du cheptel - autant économique qu'indispensable pour tous les rituels d'une certaine importance - a même changé depuis (Cabalzar, 1996). Au 19ème siècle, l'arrivée d'étrangers (Européens et Comoriens), la domination du royaume Sakalava par les Merina et l'arrivée d'immigrés Indo-Pakistanais, apportent leur lot de multi-ethnisme dans la région. Le Menabe offre alors un tableau très varié de populations vivant côte à côte, en échange et en se mélangeant (Andriambelo 2010, Cabalzar 1996, Fauroux 2002). Une autre immigration de populations originaires du sud (Antandroy) et du sud-est de l'île (Korao) a été observée en raison de la dégradation de leur milieu d'origine et par le fait que le Menabe offrait des terres cultivables et certains pôles d'attraction avec des emplois (culture de sisal de la concession De Heaulme, sucrerie de Siranala). Mais, la dégradation du système de culture de riz irrigué, accompagnée d'une hausse des prix aux producteurs pour le maïs ainsi que les non interventions des structures responsables (Eaux et Forêts et administration publique) ont favorisé la destruction de la forêt naturelle par le biais de culture sur brûlis. Dans notre zone d'étude, l'absence de rizière a poussé les agriculteurs à d'autres types de cultures (maïs, manioc, arachide).

Dans le Menabe, le milieu paysan favorise des comportements défavorables au développement. En effet, le niveau de vie est bas, les moyens technologiques sont simples, les techniques et les méthodes culturales sont très limitées. Ce qui fait qu'au niveau du comportement par rapport aux ressources naturelles, on constate un état d'esprit plutôt prédateur que cultivateur (Cabalzar, 1996). L'exemple type est celui du défrichement où une ressource inestimable et non renouvelable part littéralement en fumée sans considération des conséquences à moyen et long terme. Migration et transhumance (migration saisonnière) sont fréquentes et dues à la précarité de certaines ressources naturelles ainsi qu'aux déplacements imposés par le système de culture itinérante sur brûlis (Cabalzar 1996, Réau 2003).

Pour la gestion forestière de la région, Andriambelo (2010) a proposé comme solution (1) l'appropriation du processus par les communautés villageoises ; (2) la participation effective de tous les acteurs concernés (communauté villageoise, administration forestière, commune, organismes d'appui) dès son élaboration, la signature du contrat et sa mise en œuvre ; (3)

l'existence et l'application d'un système de contrôle et de suivi intra- et inter-acteurs, surtout pour les contractants ; (4) la mise en œuvre de mesures de compensations dans les cadre des activités principales des paysans (AGR, appui au développement) ; et (5) le développement de filières commerciales porteuses pour les paysans (pour les produits agricoles, mais également pour les produits forestiers comme le miel).

Le projet de recherche PFM (Paysages Forestiers du Menabe) vise à approfondir les connaissances scientifiques de l'interface homme-forêt au Menabe Central et à établir des bases scientifiques pour un aménagement durable, multifonctionnel et participatif des paysages forestiers du Menabe Central. Ce projet a été réalisé dans le cadre de deux thèses de doctorat par Dirac Ramohavelo 2010 et Andriambelo 2010. De l'autre côté, un autre travail, celui de Razafitsalama, thèse en cours à l'ESSA forêts d'Antananarivo, vise à approfondir les connaissances de la formation secondaire du point de vue social et économique dans le Menabe. Concernant notre travail, il vise plutôt les aspects purement écologiques de la formation secondaire. L'ensemble de ces travaux offre une vue d'ensemble unique des formations secondaires du Menabe.

1.3. Objectif général

Ce projet vise à acquérir des informations scientifiques sur la succession secondaire dans le cadre de la pratique des cultures sur brûlis au Menabe central. Un but appliqué consiste à pouvoir optimiser les cultures sur brûlis afin d'élaborer des recommandations pour la préservation de la biodiversité dans le cadre d'un développement durable. Pour ce faire, nous allons déterminer la valeur potentielle de la végétation secondaire du point de vue écologique et les potentialités d'utilisation des sols compte tenu des différents types d'âge d'abandon de parcelles après la culture sur brûlis.

En d'autres termes, nous cherchons la réponse à la question combien de temps après le premier brûlis (âge d'abandon de culture) la végétation secondaire fournira les nutriments nécessaires à la biomasse des plantes cultivées.

1.4. Objectifs spécifiques

Pour atteindre cet objectif général, plusieurs objectifs spécifiques ont été visés :

- Caractérisation du site d'étude du point de vue sols et végétation,
- Mesure et quantification de la biomasse ligneuse et herbacée,

- Analyse des éléments nutritifs des espèces et quantification des éléments nutritifs après la combustion,
- Etude de la fertilité du sol,
- Test d'inflammabilité et propriétés des espèces les plus fréquentes,
- Optimisation de la culture sur brûlis et recommandations.

1.5. Structure de la thèse

1.5.1. Langues de travail

Les langues de travail sont le français et l'anglais. Le français est utilisé dans la généralité, et la synthèse générale. Ceci en vue de la distribution à Madagascar auprès des institutions académiques (universités) et administratives (ministères) et les organismes non gouvernementaux nationaux et internationaux travaillant dans la région.
L'anglais a été utilisé pour la rédaction des articles à l'intention de journaux et revues spécialisés.

1.5.2. Structure de la thèse

La présente thèse s'organise autour de 5 articles scientifiques dont un travail de diplôme et se divise en 7 chapitres. Cette structure a pour conséquence que certains paragraphes se répètent dans l'introduction et les parties sur les matériels et méthodes dans chaque chapitre comme dans le site d'étude et la sélection des points d'échantillonnage. Mais ceci est inévitable vu le système choisi.

Chapitre I : Généralités sur la région, où on a situé notre étude par rapport au contexte et à la problématique générale, où on a présenté les objectifs suivis ainsi que les sols et la végétation.

Chapitre II : "Soil vegetation patterns in secondary slash and burn successions in Central Menabe, Madagascar", Raharimalala et al, 2010 in Agriculture, Ecosystems and Environment (139): 150-158.

Ce chapitre II fournit le contexte général de la région concernant les sols et la végétation des formations secondaires de la région, de la zone de culture à plus de 40 ans d'abandon de culture sur les sols jaunes et rouges. Il présente aussi les méthodes que nous avons adoptées pour la sélection des sites dans les sols jaunes et sols rouges.

Chapitre III : “Quantifying biomass of secondary forest after slash and burn cultivation in Central Menabe, Madagascar” (2ème publication, soumise au Journal of Tropical Forest Science)

Nous avons ici quantifié la biomasse herbacée et ligneuse dans les sols jaunes que les paysans préfèrent pour leurs cultures habituelles.

Chapitre IV : “Nutrients released from ligneous vegetation in secondary forest after slash and burn cultivation in Central Menabe, Madagascar”(publication, en préparation)

Nous avons ici analysé et quantifié les minéralomasses (C, N, P, K, Na, Ca, Mg). Chapitre V : « A handy methodology for testing wood flammability with application to fire risk assessment and optimization of slash-and burn cultivation » (publication, en préparation)

A l’aide d’un système développé à l’EPFL, nous avons effectué le test d’inflammabilité des 27 espèces tropicales et 6 espèces européennes, dans le but d’obtenir des valeurs de référence afin de prédire les potentialités d’inflammabilité des principales espèces et d’identifier les espèces qui présentent une grande potentialité pour l’optimisation de la culture sur brûlis. Nous avons classé aussi les espèces selon leur degré d’inflammabilité.

Chapitre VI : “Soil fertility in secondary slash and burn successions in Central Menabe, Madagascar” (publication soumise à Agricultural Systems)

Ce chapitre reprenant un travail de diplôme (Schneider 2011) consistait à effectuer des analyses physico-chimiques des sols, des mesures du taux de respiration et fertilité acquise après incubations pour différencier les nitrates et les phosphates entre sols secs et sols incubés dans les parcelles d’étude.

Chapitre VII : L’optimisation et la synthèse contiennent la récapitulation des principaux résultats obtenus dans chaque chapitre et une discussion des scenarios possibles pour les besoins nutritifs des plantes en vue d’une optimisation.

1.6. Végétation

1.6.1. Localisation géographique

La région d’étude se trouve dans le Sud-Ouest de Madagascar, dans la région du Menabe central, commune de Bemanonga. Andranolava se trouve à 70 km de Morondava (Chef lieu de la région), à 15 km à l’est de la forêt de Kirindy. Elle est limitée au nord par la fleuve Tsiribihina, au sud par la rivière Andranolava et à l’ouest par le littoral du canal de Mozambique. Le climat est de type tropical sec, avec 791 mm de précipitations annuelles, divisé en deux saisons, l'une sèche très accusée (avril à octobre), l'autre humide (novembre à mars). La température moyenne annuelle est de 24.8°C.

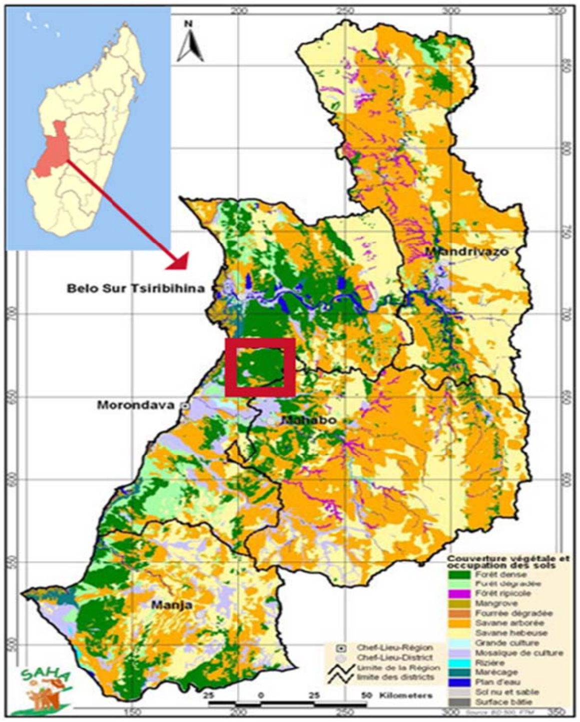

Figure 1b

Figure 2 : Site d'étude dans le Sud-Ouest de Madagascar avec végétation et occupation du sol (Sources: Wikipedia et SAHA, Antananarivo, Madagascar; Dirac Ramohavelo, 2009)**.**

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1.6.2. Végétation

Forêt naturelle

Notre zone d'étude se trouve dans la zone classifiée par Koechlin *et al.* (1997) comme forêt dense sèche caducifoliée sur sols arénacés. En général, la forêt comprend 3 strates de plantes lignifiées qui se distinguent par leur hauteur et leur diamètre (Rakotovao et *al* 1988):

- Le sous-bois de 1 à 5 m de hauteur, comprenant 4'000 à 8'000 tiges à l'hectare avec un diamètre inférieur à 10 cm. Les houppiers des espèces sont relativement petits et peu développés.
- La strate intermédiaire de 6 à 12 m de hauteur, comptant entre 600 et 1'500 tiges par hectare de 10 à 25 cm de diamètre. Les houppiers s'entrecroisent et s'entremêlent de manière à constituer une couche dense et souvent fermée.

- La strate dominante avec les grands arbres, ne constitue pas une couche de houppiers fermée sauf certaines exceptions sur les meilleures stations. La base du houppier se situe entre 10 et 14 m et ne dépasse pas 20 m. Cette strate est la plus importante du point de vue exploitation, avec une répartition de 10 à 60 tiges à l'hectare. La végétation herbacée en forêt dense fermée est plus ou moins inexistante.

Dans la forêt dense sèche, on observe des caractères biologiques particuliers :

- La caducité des feuillages de la plupart des essences de la strate dominante ;
- Plusieurs formes de xérophyllie : réduction de la taille des feuilles, aphyllie, pachycalie, spinescence ;
- Floraison fréquente en saison sèche, en l'absence de feuillage ou peu avant l'apparition des feuilles;
- Enracinement profond par des racines pivotantes.

Formation secondaire et situation dans la région

Selon la FAO, les forêts secondaires (ou végétations secondaires ou successions secondaires ou formations secondaires) ou « monka » (appellation locale) sont définies comme des forêts dont la régénération se fait en grande partie par des processus naturels après d'importantes perturbations, d'origine humaine ou naturelle. La structure et la composition des espèces de la végétation secondaire sont très différentes de celles de forêts primaires ou naturelles existantes à proximité sur des sites aux conditions comparables.

(http://www.fao.org/DOCREP/006/J0628E/J0628E64.htm)

Dans la zone d'étude, la perturbation est due essentiellement aux activités humaines en particulier la culture sur brûlis.

Cette végétation secondaire a déjà été étudiée par Schulthess 1990. Cet auteur a effectué des inventaires de l'évolution des formations secondaires. Il a étudié dans une vallée dont la population s'est vue contrainte de passer de la culture du riz à celle du maïs lorsque les rivières se sont taries. Cet auteur a classé, par la suite, les formations secondaires selon les inventaires floristiques en 5 catégories :

- Surfaces de culture et de défrichements : il s'agit de zones encore cultivées ou abandonnées depuis peu. L'âge de la surface choisie était d'entre 1 à 6 ans après la culture sur brûlis.

- Surfaces de friche : il s'agit de surfaces à proximité des villages, à dominance de jujubiers dont les graines ont été disséminées par les troupeaux de zébus. Ces surfaces ont été désignées par la suite de friches à jujubiers. L'âge d'abandon après le défrichement sur brûlis se situait entre 9 et 29 ans.
- Brousse ouverte : il s'agit de zones présentant des trouées irrégulières où hommes et animaux peuvent circuler facilement. Ces trouées sont dominées par la végétation herbacée et des termitières. L'âge d'abandon après le défrichement sur brûlis était inférieur à 41 ans.
- Brousse fermée : il s'agit de zones où les trouées n'existent plus et la végétation herbacée a disparue. L'âge d'abandon après le défrichement sur brûlis était supérieur à 41 ans.
- Surfaces de forêt secondaire : il s'agit de zones caractérisées par la fermeture des houppiers, appelées surfaces fermées. L'âge d'abandon après le défrichement sur brûlis était supérieur à 41 ans.

De son côté, Ravoavy 1998 a effectué une évaluation et un suivi de l'évolution de la dégradation de la forêt primaire en utilisant des images satellites (1987, 1989, et 1994). Il a classé les formations secondaires en 5 catégories fondées sur le dynamisme et la physionomie de la végétation (description du peuplement) dans le Menabe central:

- Nouveau défrichement : ce sont des zones jonchées d'arbres abattus par les paysans lors du défrichement ;
- Jeune friche : c'est un terrain défriché et abandonné récemment. Il est caractérisé par l'installation de la végétation herbacée ;
- Vieille friche ou savane arbustive : c'est une zone irrégulière dominée par les arbustes, pourvue d'une strate graminéenne et pouvant évoluer en forêt secondaire en absence de facteurs extérieurs, ou en friche si elle est utilisée comme pâturage;
- Forêt secondaire au stade de couvert pionnier: c'est une formation peu dense favorisant les essences héliophiles. Elle est constituée par l'association des essences sempervirentes et caduques ;
- Forêt secondaire au stade de couvert secondaire tardif : zone où le degré de fermeture est assez élevé en fonction du développement des houppiers et des branches.

Cet auteur a conclu que l'évolution du défrichement est en étroite relation avec l'évolution démographique, notamment l'immigration en fonction du contexte local, régional voire national. La reconstitution de la forêt est difficile après les défrichements, principalement en raison de facteurs d'ordre anthropique.

Une autre étude dans le Menabe, conduite par Razafiarisoa 1999, dans 3 sites différents, a révélé la composition floristique, la stratification et sa répartition spatiale, et a déterminé les types de successions secondaires possibles. Razafiarisoa a divisé les formations secondaires en :

- Savane herbeuse : monka 3 - 5 ans. C'est une formation secondaire à dominance herbacée ;
- Savane arbustive : monka 7 - 10 ans. C'est une formation secondaire dominée essentiellement par les *Zizyphus mauritiana* et aussi par des formations herbacées.
- Savane arborée : monka 10 - 20 ans. C'est une formation secondaire dominée par des espèces arbustives peu exigeantes comme *Zizyphus mauritiana* ou *Poupartia caffra* et aussi des formations herbacées.
- Couvert pionnier : monka 20 - 30 ans. C'est une formation secondaire avec présence d'espèces pionnières comme *Harungana madagascariensis* ou *Capparis chrysomeia.*
- Couvert secondaire initial : monka 30 - 50 ans. Ce sont des formations secondaires dominées par des espèces sciaphiles comme *Hymenodyctium decaryanum, Baudouinia rouxevellei, Noronhia leandriana*, *Dalbergia sp*. ;
- Couvert secondaire tardif : monka de plus de 50 ans. C'est une formation secondaire dont la richesse floristique est la plus élevée par rapport aux autres formations de transition.

De notre côté, notre classification des « monka » est basée sur des visites sur place avec les encadreurs et des enquêtes auprès des paysans et des guides locaux. Ces derniers ont connu les historiques des parcelles choisies, raison pour laquelle nous n'avons pas besoin d'utiliser des images satellites. Nous avons choisi cette zone d'Andranolava, Morondava car:

- elle présente une large superficie (environ 1000 ha) ;
- elle comporte plusieurs stades de formations secondaires ;
- elle permet la comparaison avec d'autres études de formations secondaires dans la région et dans le monde.

Par la suite, nous avons établi 7 différentes classes de formations secondaires après l'abandon de la culture :

- Culture en cours
- Monka 1-5 ans
- Monka 6-10 ans
- Monka 11-20 ans

- Monka 21-30 ans
- Monka 31-40 ans
- Monka 40 ans et plus

1.7. Description du sol

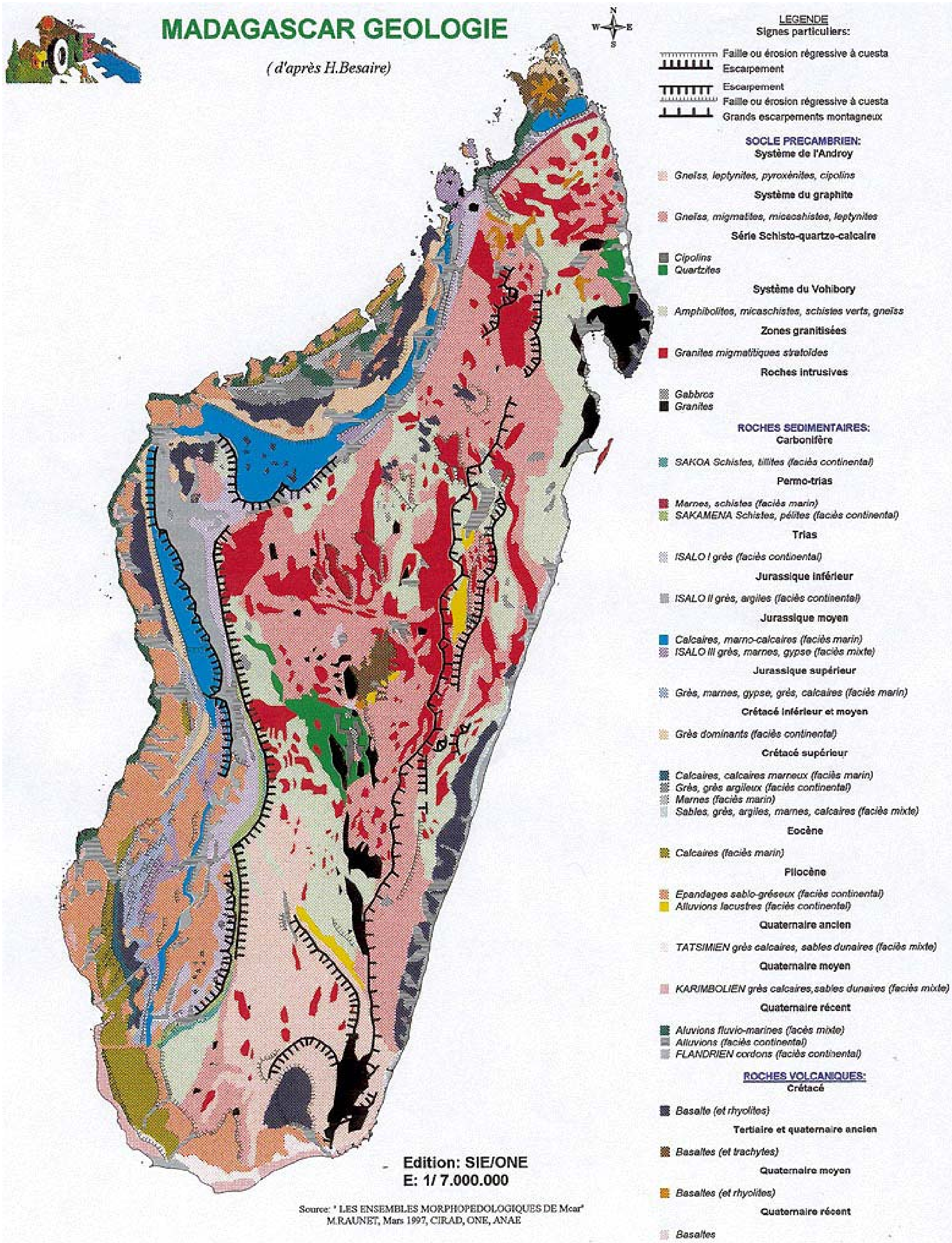
Sur le versant occidental de Madagascar, les formations sédimentaires couvrent une superficie importante (figure 3). Par suite de l'instabilité du socle cristallin, affecté par des mouvements orogéniques successifs, ces formations correspondent à des alternances de dépôts marins, représentés essentiellement par des calcaires, et de dépôts continentaux où les grès sont largement prédominants (Bourgeat 1996). La série s'étale depuis le carbonifère jusqu'à la période actuelle. La forêt dense caducifoliée subsiste encore sous forme de lambeaux, sur quelques plateaux calcaires, mais les plus beaux témoins couvrent les glacis formés à partir des grès et auxquels les géologues ont donné le nom de « sable roux » ou de carapace « argilo-sableuse » (Bourgeat 1996). Notre zone d'étude se trouve dans une zone de glacis conservés. Felber 1984, Randriamboavonjy 1996 avaient distingué 2 types de sols selon la couleur : les sols jaunes et les sols rouges. Ces 2 types de sols ont de faibles capacités de rétention cationique (Randriamboavonjy 1996) et nécessitent dans l'idéal l'utilisation recurrente d'engrais et/ou de chaux. Pourtant, le terrassement en courbe, le paillage et l'utilisation de cultures de couverture peuvent contribuer à préserver les sols (Felber 1984).

Durant les campagnes de terrain, nous avons effectué 2 profils pédologiques dans les sols jaunes, dont une dans une zone abandonnée depuis 5 ans et l'autre dans une zone à l'abandon depuis 40 ans.

Selon le Référentiel pédologique-2008, AFES 2009, les ferruginosols sont des sols de régions intertropicales ayant une saison sèche de 4 à 5 mois et une saison des pluies avec des précipitations annuelles de 400 à 1400 mm. Ils sont riches en fer, par accumulation relative ou absolue, ce qui peut conduire à une induration. Ils présentent des structures peu développées et des taux de saturation (S/CEC) très variables. Les textures sont très marquées par les sables grossiers, car les matériaux parentaux sont le plus souvent des altérations très anciennes dépourvues de limons grossiers. Les termites ont une action importante sur ces sols. L'activité microbiologique est faible voire très faible en rapport avec les faibles teneurs en matières organiques de ces sols.

L'analyse effectuée dans ces 2 types de sols (**Annexe Chapitre I**) a montré que nous sommes en présence d'un **FERRUGINOSOL LUVIQUE peu prononcé.** La séquence d'horizons référence est A/FE/Ea/BT/IIC.

C'est un **FERRUGINOSOL** caractérisé par la concentration en hydroxydes de fer aux 3è et 4è horizons. La couleur est 5YR 4/8, la texture sablo-argileuse (Richard de Forges et al 2008), le pH varie entre 5,0 et 6,2 et la concentration du Fe diminue vers le bas de l'horizon. Le sol subit une **illuviation peu prononcée :** la couleur de l'horizon Ea n'est pas plus claire que les horizons sous-jacents, le pH est peu acide (6,2) ; il s'agit dès lors d'un **début de Ea**. Sous le début de Ea, on a un **début de BT** car on n'a pas encore une accumulation d'argile et de fer nette à la base du solum. Dans le système WRB, c'est un « Lixisol ».



(Auteur : GAF AG, R. Dahl, Version: 1.0 Date: Nov. 2005)

Figure 3 : Carte géologique générale de Madagascar d'après Besairie (1972)

(Source : Les ensembles morphologiques de M/car par M. Raunet, 1997)

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CHAPTER II

Soil vegetation patterns in secondary slash and burn successions in Central Menabe, Madagascar

Chapitre II : Soil vegetation patterns in secondary slash and burn successions in Central Menabe, Madagascar

Soil–vegetation patterns in secondary slash and burn successions in Central Menabe, Madagascar

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ABSTRACT

Slash and burn agriculture is a traditional and predominant land use practice in Madagascar and its relevance in the context of forest preservation is significant. At the end of a cycle of culture, the fields become mostly weed covered and the soil fertility starts to drop. As a consequence, these fields are abandoned (they are called "monka") and the farmers, in the best case, re-use old surfaces where the vegetation has recovered to some extent. Nevertheless, some of the farmers continue to extend part of their cultures into the natural forest. In order to decrease deforestation, the paper focuses on the potential for agricultural re-use of monkas. To do so, we present the soil–vegetation pattern along a slash and burn successional gradient from newly cultivated surfaces to surfaces abandoned for 40 years. Vegetation relevés were carried out on 61 plots sampled on yellow and red soils, and soil variables such as loss of ignition, pH, total carbon content and total nitrogen content were measured. Results show that: (1) by Vegetation successionındonment woody species are increasing, and after 21–30 years herbaceous plants become less dominant, (2) the species richness increases with age of abandonment, but flattens out by 40 years, (3) by 20 years of fallow, the loss of ignition, total carbon and total nitrogen show similar values or even higher values than in cultivated surfaces, (4) the yellow soils are related to higher pH more than the red soils and are preferred for cultivation, but the higher pH of yellow soils is not associated with higher species richness. Given these results, we conclude that fields older than 20 years have recovered sufficient fertility to be re-used as agricultural land. This re-use would decrease impacts on natural forests. But beyond the nutrient perspective, critical problems remain, including the growing demand for arable land and the need for cultivation to control invasive weeds.

Keywords: Fire, Deforestation, Cultivation, Dry tropical forests, Vegetation succession, Soil fertility

1. Introduction

Madagascar's forests are among the most biologically rich and unique ecosystems in the world but, despite longstanding concern about their destruction, estimates of past forest cover and deforestation have varied widely (Ganzhorn et al., 2001; Dufils, 2003; Harper et al., 2007). Slash and burn agriculture is the traditional and predominant land use practice in all forested regions of Madagascar and its relevance in the context of forest preservation is significant. In Madagascar (see Dirac Ramohavelo, 2009) as well as in West and Central Africa (Lubini, 2003), secondary successions resulting mainly from slash and burn are of economic interest because they provide various resources: firewood, food plants, pastures for cattle, caterpillars, medicinal plants, etc. Moreover, several commercial timber species can be found in secondary forest.

Cultivation is the principal activity of the villagers in Central Menabe (south-western coast of Madagascar) and the villagers themselves consider agriculture as their most important activity (Calderoni, 1999; Dirac Ramohavelo, 2009). Forest soils are extremely important to the villagers, providing land for cultivation and pastures. Nevertheless, wherever possible, villagers prefer to cultivate rice, as rice is the staple foodstuff for Malagasies (Rakotovao et al., 2000: in Dirac 2009). However, over the past 50 years, fields that were adequately flooded to grow rice have become

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rare because of the drying out of some rivers (Tache, 1994). Farmers are thus forced to cultivate products whose growth depends on rainfall, e.g. shifting slash and burn cultivation of maize, cassava or groundnuts (République de Madagascar, 2006). In this region, the agricultural products are consumed, sold or exchanged; they are the basis of the local commerce (Dirac Ramohavelo, 2009; Dirac Ramohavelo et al., submitted for publication).

According to modern law, all forests in Madagascar belong to the State. The cleared forests and fallows, which become secondary forests, are considered as freehold and belong to those who cleared the land, accordingly to common law (Réau, 2003). The difference between land-owner and land-holder is that the first can sell the land, the second cannot, but his land can be inherited. Recently, the situation in the study area became more complicated because of the devolution of rights and duties within the CGF (Gestion contractualisée des forêts) initiative, which moves towards land holding and not land property, and because of the creation of protected areas (aires protégées) with delineation of land for multi-usage.

Genini (1996) described how natural and secondary forests are cleared during the cold and dry season (June–September) with consecutive gathering of logs and branches in piles around larger trees. The wood is dried during several weeks and finally burnt at the end of the dry season (in October). The following year, remaining vegetation and new sprouts are cut and burnt again. After three or four passages, fire has usually destroyed all the vegetation, except the large baobab trees and the tall crowned trees, which have not been felled and give the typical landscape feature to these openings. Villagers gather the remaining wood that they find in the secondary forests and on newly cleared parcels of land, because it is dry and burns well. As a consequence, not much dead wood remains on the soil to rot. Although certain useful wood species can be found in both natural and secondary forests, the villagers prefer to take wood for construction from the natural forest because the trees grow in more regular forms.

On the cleared plots (called "hatsake"), the farmers mainly grow maize in the first few years and then cassava and groundnuts (République de Madagascar, 2006). On a new cleared surface, the maize cultivation unfolds the following way (Genini, 1996): small holes are dug out with a spade every 80–100 cm between the remaining tree trunks. When it starts to rain, three to five corn seeds are buried in each hole. On a new cleared plot, this type of culture does not need farming maintenance until harvest; seedlings benefit from the fertilizing effect of the ash and the yield reaches 2 tons per hectare (Genini, 1996). At the end of a cycle of culture, the fields get mostly weed covered and the soil fertility begins to decline. The maize production decreases by 80% after four years of culture on the same plot (Réau, 2002). As a consequence, these plots are cultivated with cassava or groundnuts, and then abandoned (and called "monka"). After a few years of abandonment and vegetation re-growth, the land can be burnt again and cultivated in the same way, but weeds become problematic (Cabalzard, 1990; Genini, 1996). Some farmers limit their cyclic activities to secondary surfaces, re-using plots of various ages of abandonment, but others extend part of their cultivation into the natural forest. Each family clears between 0 and 2 ha per year (including virgin and secondary forests) and the average cultivated surface is about 0.86 ha (Dirac Ramohavelo, 2009). Fire is also applied on cultivated lands between harvests, and not only in forested vegetation.

Forest also serves as pasturages for livestock, and they represent a livestock refuge to protect them from cattle thieves (Réau, 2003). During the day, the oxen roam in the forests, wooded areas of the savannah and monkas. The savannahs and monkas are maintained as pastures by means of fires that also favour the regeneration of herbs on which zebus feed. Oxen are only supervised in the forest in the dry season; in the humid periods, they are left to roam in the forested areas without surveillance (Raharinomenjanahary, 1998). Herds are kept in enclosures at night to prevent theft. According to Randriamahaleo (1989), the use of oxen in agricultural production is limited to stamping in the rice fields (which adds a non-voluntary supply of organic faecal material to the fields) and the haulage of carts and ploughs. Manure is collected only occasionally (to fertilise enclosed gardens or, more rarely, the rice fields), and milk exploitation is not a local custom (République de Madagascar, 2006).

This slash and burn method leads to significant losses of nutritive elements in the soil and changes the flora composition (Genini, 1996; Milleville et al., 2000). According to FAO (2003), the secondary vegetation succession results from a significant disturbance induced either naturally or by humans, and the principal factors of differentiation are climate, altitude, soil type, human actions and natural disasters (land slides, volcanic eruptions, etc.). Milleville et al. (2000) discovered in their study, that repeated use of fire initiates a predictable vegetation succession, which can lead to a grass savannah in its ultimate stage of degradation. Moreover, they explained that the soil impoverishment is characterized by increased erosion, soil compaction and higher evapotranspiration.

In eastern Madagascar Pfund (2000) highlighted the importance of soil–vegetation patterns in slash and burn cultivation systems and found some correlations between the elements (nitrogen, phosphorus and potassium) contained in soil and in vegetation. Generally, the fewer elements found in the soil, the higher their content in the vegetation. Furthermore, he found that the amount of biomass produced by fallow land contributed significantly to soil fertility and was thus a determinant of the farming cycles.

The paper's hypothesis is that the cultivation of secondary forests could be optimized in such a way that the incursion into natural forests could be significantly reduced; indeed, after some years, the soil and vegetation should recover enough for allowing a profitable re-cultivation of abandoned surfaces. We aim at discovering the age at which an abandoned surface recovers the necessary nutrients to allow re-cultivation. We compare the soil and vegetation patterns of cultivated surfaces at different ages of abandonment (newly cultivated up to surfaces abandoned for 40 years) on red and yellow soils.

2. Materials and methods

2.1. Description of the study area

The study area is located in Andranolava in south-western Madagascar, at 75 km north of Morondava (Central Menabe) near the well-known Kirindy forest (Sorg et al., 2003). The ecosystem is dominated by dry deciduous forests of various types as described in Koechlin et al. (1997). In the northern part, the land is characterized by old sisal plantations; the southern part is delimited by the Andranolava river, the eastern part by the Kirindy forest, and the western part by littoral forest.

The local climate is characterized by two distinct periods (Sorg and Rohner, 1996): a rainy season (November–March) and a dry season (April–October). Average annual temperature is 24.7 °C, with a relatively cool period from May to August. Total precipitation average is 767 mm/year.

According to the geomorphologic description of Besairie (1969), the region of Morondava is composed of sedimentary deposits of the Pliocene, mainly sandstone and shale-dominated continental materials containing also lagoon or marine deposits. The rock layers are several hundred meters thick and are normally covered by sandy or silt alluvial deposits from rivers flowing from east to west (Brenon, 1972). Bourgeat (1996) distinguished two geomorphologic units: (i) preserved glacis, with interfluves represented by wide areas crossing the main valleys with very gentle slopes (3–5 per thousand) and sometimes showing small depressions that can form closed cups, and (ii) located below the former, a layer slightly deeper with the presence of numerous small gullies, occupied by wadis (temporary oueds or vavarano). The sandstone outcrops quite frequently in the deep valleys and on the slopes.

The study area of Andranolava was chosen because it offered a large area (about 1000 ha) with many different stages of secondary succession after slash and burn cultivation, and thus allowed comparisons of some ecosystem and soil properties.

The population in the study area is essentially constituted of immigrants from the south of Madagascar, mainly Antandroy, Mahafaly and Antesaka ethnics. Many of them arrived in the 60s to cultivate sisal, bringing along good knowledge of agriculture and extensive domestic breeding.

2.2. Selection of plots

The age of the monkas was estimated by a local guide who has already worked with many scientists in the area and in the Kirindy forest, and this information was cross-checked by consulting also local farmers. We selected 61 sites classified according to two criteria, the age of the monkas and the soil type (Table 1). Seven age classes were considered, from surfaces that were still in cultivation, up to surfaces that had been abandoned about 40 years ago. Considering the concentric expansion of deforestation around the village, and because the sampling of plots was done along a line from younger plots near the virgin forest to the older plots near to the village, we can reasonably assume that the history of the plots is rather similar. We considered this time series for both red soils and yellow soils, because they are the predominant soils in the area (Randriamboavonjy and Bourgeat, 1993). Whenever possible, five replications in each category were targeted.

The red and yellow soils were classified by Felber (1984) and Rohner and Sorg (1986) as "red and yellow soils" of the "luvisols ferric" category, and can be named according to the French classification "ferruginous tropical leached soils" (Rakotovao et al., 1988) and Lixisols after the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). Several hypotheses have been formulated to explain differences between the red and yellow soils including (i) a different kind of original material, (ii) different ages of the initial materials, (iii) a difference in microclimate and (iv) the influence of local climate (Bourgeat, 1996). Indeed, it was found that the yellow soils lie under red soils or in areas where the sandstone is close to the surface. Sourdat (1977) also reported the occurrence of yellow soils in confined areas in the south west of Madagascar, and Randriamboavonjy (1995) indicated that yellow soils can be found among red soils also in slightly more humid locations.

2.3. Vegetation

In all sites, vegetation inventories were performed according to the Braun-Blanquet (1964) method. Observations at the plot scale were recorded within areas of apparently homogenous physical features, vegetation structure and species dominance (Gounot, 1969). To determine the minimal area, we used multiple relevés of increasing area arranged along a transect-line. Starting at 1 m^2, the stopping rule was set at five newly recorded species. An additional rule was applied to patchy shrubby vegetation. In this case, the explored distance along the transect-line had to be at least equal to the mean distance between individual shrubs. Depending on the vegetation, plot sizes ranged from 1 m^2 to 256 m^2 (up to 16 m × 16 m). Cover/abundance data for all vascular plants were recorded using the Braun-Blanquet scale. Whenever possible, plants were identified in the field, otherwise specimens were collected for subsequent identification with the essential help of a local botanist (Armand Rakotozafy). All the plots were situated close to sea-level on flat surfaces.

Table 1
Investigated plots according to the two criteria, age of abandonment after cultivation (monkas) and soil type.

Age classes	Age of monkas	Number of plots on soil types		pH		LOI (%)		C_{tot} (%)		N_{tot} (%)	
		Red	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red	Yellow
I	Culture	1	4	6.6	6.5 (0.213)	4.8	5.5 (0.955)	1.4	1.6 (0.307)	0.1	0.2 (0.026)
II	1–5	2	4	6.7 (1.202)	6.2 (0.349)	5.7 (1.047)	4.2 (0.082)	1.7 (0.233)	0.9 (0.102)	0.2 (0.019)	0.1 (0.007)
III	6–10	5	4	5.9 (0.310)	6.3 (0.275)	4.7 (0.332)	4.1 (0.883)	0.9 (0.194)	1.0 (0.059)	0.1 (0.011)	0.1 (0.014)
IV	11–20	5	7	6.4 (0.769)	6.1 (0.263)	4.9 (0.437)	5.2 (0.513)	1.2 (0.294)	1.6 (0.493)	0.1 (0.022)	0.2 (0.047)
V	21–30	5	5	5.7 (0.203)	6.1 (0.475)	5.4 (1.410)	4.9 (1.222)	1.5 (0.771)	1.6 (0.391)	0.1 (0.044)	0.2 (0.027)
VI	31–40	5	4	6.0 (0.579)	6.1 (0.563)	5.3 (0.619)	5.5 (1.421)	1.5 (0.260)	1.5 (0.799)	0.1 (0.020)	0.2 (0.096)
VII	>40	5	5	6.0 (0.236)	6.2 (0.967)	5.0 (0.506)	5.8 (1.403)	1.5 (0.371)	1.8 (0.709)	0.1 (0.031)	0.2 (0.046)

Age classes are: (I) culture; (II) 1–5 years; (III) 6–10 years; (IV) 11–20 years; (V) 21–30 years; (VI) 31–40 years; (VII) more than 40 years. Means and standard deviations are given for pH, loss of ignition (LOI), total carbon (C_{tot}) and total nitrogen (N_{tot}) of soil samples.

2.4. Soil analyses

Soil samples were collected on all sites at depths 0–10 and 10–20 cm. A brief qualitative soil description was made, including colour and texture, to classify the plots into red and yellow soil categories. A pooled sample of about 250 g for the depth 0–10 cm (where most plants were rooted) was used for laboratory analyses. The following analyses were done, using standard procedures (Baize, 2000) on 2 mm sieved soil: loss of ignition (LOI, % dry weight^{-1}) after burning the samples in a furnace at 450 °C and pH in water (pH_{water}). The dried ground samples were used for the analysis of total carbon content (C_{tot}, % dry weight^{-1}) by means of 1000 °C combustion under oxygen flow using a carbon analyzer (Casumat 8-Adge; Wösthöff, Bochum, Germany), and of total nitrogen content (N_{tot}, % dry weight^{-1}) with the Kjeldahl method using the digestion procedure in sulphuric acid with a catalyser, followed by distillation and titration.

2.5. Statistical analysis

Redundancy analysis (RDA) was used to detect the pattern of plant assemblages in relation to environmental explanatory variables using the R statistical program (R version 2.7.1). Data were log transformed prior to analyses. Differences in mean species richness and in environmental variables according to soil type and age of monkas were tested with ANOVA after testing that assumptions were met, or Kruskal–Wallis ANOVA when these were not fulfilled.

3. Results

3.1. Vegetation succession

Overall, 114 species belonging to 50 families were identified in the studied plots (see Appendix A). Some important or frequent species can be classified into trees or shrubs (*Capurodendron perrieri, Chadsia grevei, Dalbergia sp., Diospyros perrieri, Fernandoa madagascariensis, Poupartia silvatica* and *Tarenna sericea*), lianas (*Mussaenda arcuata*), herbs (*Breweria sp. Commiphora lamii, Mundulea ambatoana, Ocimum canum, Sida grevioides, Sida rhombifolia* and *Triumfetta sp.*), graminoids (*Cyrtococcum bosseri* and *Heteropogon contortus*), plant's with edible tubers or roots (*Arachis sp., Dioscorea acuminata, Dioscorea trichopoda, Ipomoea pes caprae, Manihot esculenta* and *Tacca pinnatifida*), plants with edible fruits or seeds (*Phylloctenium decaryanum, Zea mays* and *Ziziphus mauritiana*), medicinal plants (*F. madagascariensis, S. rhombifolia* and *Zanthoxylum decaryi*) and ornamental plants (*Terminalia sp.*). After 5 years of abandonment, pioneer woody species already appeared, such as *Albizia bernieri, D. perrieri, F. madagascariensis* and *Z. mauritiana* (Appendix A). Fig. 1 shows that species richness (relative to the area surveyed) increased significantly with age of abandonment ($P < 0.001$) and flatted out in the oldest age class. Overall, diversity was not significantly different on the two soil types. Herbs and grasses appeared more often in early successions, and after 21–30 years (class V), these species became less dominating (Table 2), as for example *Breweria* sp., *Commelina ramulosa* and *C. lamii* (Figs. 2 and 3, Appendix A).

3.2. Soil–vegetation relationship

The RDA analysis presents the overall gradient in species assemblages with respect to the constrained model using 6 explanatory variables (Fig. 2). Along axis 1, which is significant with 14.2% of variance ($P = 0.001$), the age of abandonment appears very clearly. Total nitrogen, total carbon and loss of ignition are highly correlated, and by 20 years of fallow, these variables show similar values or even higher values than in cultivated plots (Table 1). The

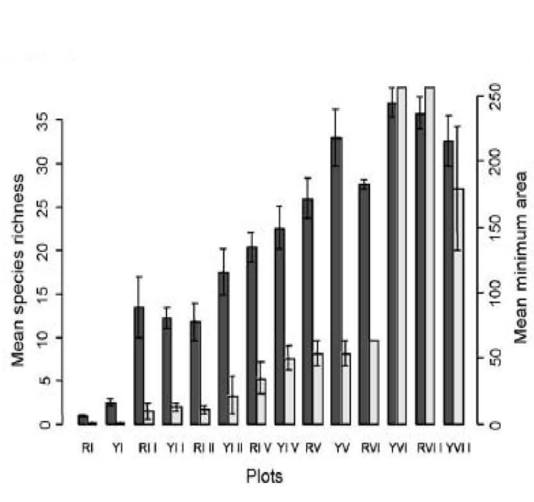

Fig. a. Mean minimal area (m^2) and mean species richness in the plots. Grey bars are mean minimal areas considered for the vegetation relevés, dark bars are mean species richness, both indicated with standard errors. Letter R denotes red soils, letter Y denotes yellow soils and numbers indicate the age classes (see also Table 1).

Table 2
Total number of species recorded in the different growth forms and in the seven age classes of abandonment.

Species	Age classes of abandonment						
	I	II	III	IV	V	VI	VII
Herbaceous species	3	21	22	27	30	21	21
Shrub species	0	4	5	13	13	11	10
Tree species	0	4	12	20	31	37	29
Liana species	0	3	6	9	12	12	13

Age classes of abandonment are: (I) culture; (II) 1–5 years; (III) 6–10 years; (IV) 11–20 years; (V) 21–30 years; (VI) 31–40 years; (VII) more than 40 years.

opposed soil type centroids (qualitative variable) along axis 2 (4.5%, $P = 0.021$) indicate that yellow soils are related to higher pH, but this was only marginally significant when tested ($P < 0.100$). According to the sampling design, age of monkas is independent (orthogonal)

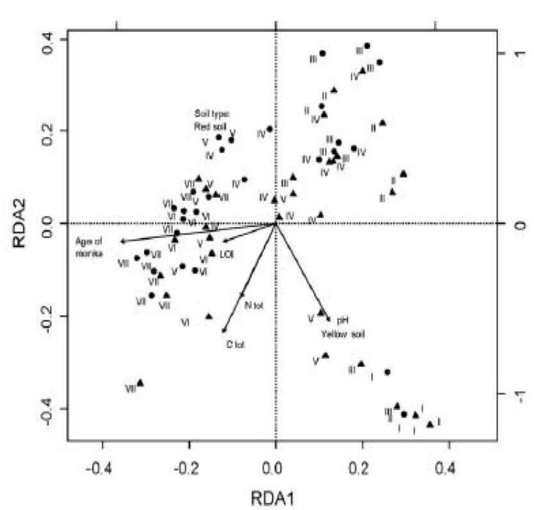

Fig. b. Scatter plot of the redundancy analysis of the vegetation relevés in 61 plots. Symbols indicate soil type; black circles: red soils; triangles: yellow soils. Numbers indicate the classes of age after abandonment. Classes are: (I) culture; (II) 1–5 years; (III) 6–10 years; (IV) 11–20 years; (V) 21–30 years; (VI) 31–40 years; (VII) more than 40 years. Arrows show the quantitative explanatory variables; position of centroids of qualitative explanatory variables are indicated without arrows. Axis 1 represents 14.2% of the variance ($P < 0.001$) and axis 2 represents 4.5% ($P < 0.021$).

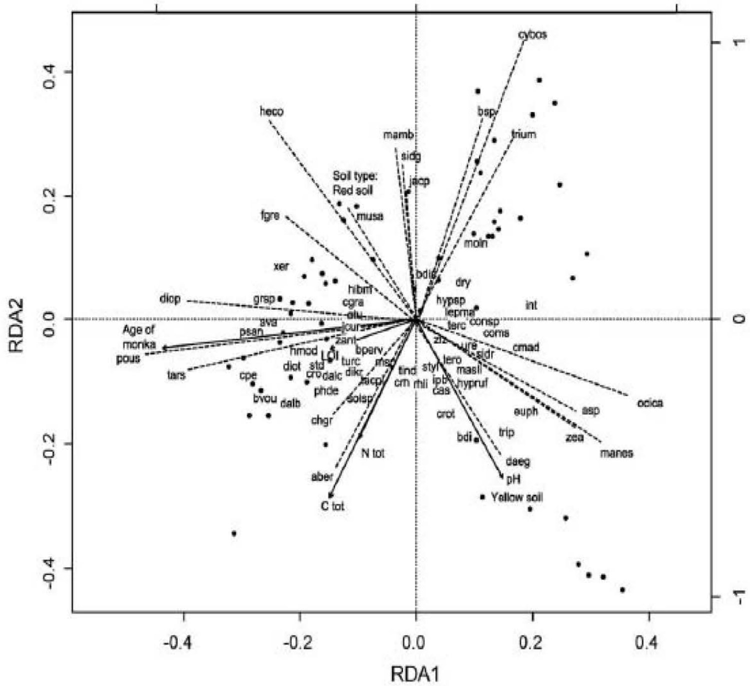

Fig. 3. Scatter plot of the redundancy analysis as in Fig. 2, but with representation of the species (see abbreviation of species names in Appendix A). Arrows are drawn only for species that were far from the scatter plot centre. Species that were near the centre have been removed and are: lsmd, penp, aex, tris, terf, clsp, casp, deid, crac, cgr, aac, cfal, poc, cbos, cvul, orav, abe, lepmu, neob, aau, csat, cedu, marc, prh, rotr, ape, ahi, gsq, homsp, aas, gcyc, secs, icam, diac, tur, comsp, ses, lpsp, opg, bperr, clea, asc, bpu, cgr.1, steu, bmi, steu, corm.

of soil type and pH. It appears that older plots have more mature soil, in particular with higher carbon contents. Both total carbon and C/N ratios were significantly different (respectively $P<0.011$ and $P<0.018$) across the age classes. Cultivated plots take an excentric position, due to their distinct floristic assemblages.

The position of species in the scatter plot (Fig. 3) shows some of them being strongly linked to soil parameters. The cultivated species *Z. mays* (zea), *M. esculenta* (manes) and *Arachis* sp. (asp) prefer a higher pH and yellow soils. The higher pH in yellow soils was not associated with higher species richness ($P>0.05$). Species such as *A. bernieri* (aber) and *Cryptostegia grandiflora* (chgr) are related to soils rich in carbon and nitrogen, whereas *C. bosseri* (cybos), *Breweria sp.* (bsp) and *Triumfetta sp.* (trium) are related to poor soils. Considering the age of monkas, *D. perrieri* (diop), *P. silvatica* (pous) and *T. sericea* (tars) are characteristic trees of older secondary formations. In addition, *H. contortus* (heco), *M. arcuata* (Musa), *S. grevioides* (sidg), *M. ambatoana* (mamb), *C. lamii* (jacp) and *F. madagascariensis* (fgre) are more typical of red acid soils.

4. Discussion

4.1. Cultivation on yellow soils

Slash and burn cultivation aims at producing ash on cleared land and recycling the mineral wealth for crop growth. Furthermore, the subsequent decomposition of unburned residues, if any, that are left behind also constitutes a potential mineral input after decomposition. As a consequence of the release of alkaline bases, the pH increases. We observed that farmers tend to prefer yellow soils for their traditional cultures, which is in accordance with the higher pH that we measured (Table 1). On one hand, this may be because red soils are poor in nutrients and rich in sand or gravel, with low clay content (5–10%), whereas yellow soils have a normal permeability with a clay content of 10–15% (Felber, 1984). In the Colombian hillsides, cassava (*M. esculenta*) is cultivated because of its ability to produce higher yields on acidic soils poor in nutrients (Anderson et al., 2004; Daellenbach et al., 2005; Perez et al., 2005), while maize (*Z. mays*) and groundnuts (*Arachis sp.*) require basic soils. But on the other hand, it is also on the richer yellow soils that weeds are more abundant, which in turn requires greater cultivation effort to control competitive wild species. Von Schulthess (1990) found that red soils have a reduced humus layer and are poorer than yellow soils. Furthermore, the natural regeneration of trees is low on red soils and their use by farmers is irregular. The higher pH of cultivated yellow soils was not associated with higher species richness. More importantly, fire modifies species composition and dominance in the early successional stages with concomitant ecological impact (Messerli, 2000; Pfund, 2000). Indeed, we observed that with increasing duration after abandonment, species richness becomes higher (on average 13 species by 5 years to 35 species after 40 years – Fig. 1, overall a total of 32 species by 5 years and 73 species after 40 years – Table 2).

Cultivation has been shown to result in a significant increase in soil C and N mineralization rate, as well as an increase in microbial activity (Raiesi, 2006). Henig-Sever et al. (2001) suggested that the pH of the ash layer and the composition of the microarthropod community may offer a wider understanding of the impact of fire on ecosystems. The total number of microarthropods decreased in plots which had received the most drastic treatments with high ash content and intensive burning (Haimi et al., 2000).

4.2. Post-cultural cycle

The successional pattern on post-cultural surfaces is characterized by the following species, either woody or herbaceous (Table 2):

pioneer herbaceous plants emerge in the first five years after cultural abandonment and include mostly *C. bosseri* and *O. canum* (a very dominant invasive species), and in many sites also *Breweria sp., C. lamii, Euphorbia hirta, M. ambatoana, S. rhombifolia, S. grevioides* and *Triumfetta sp.*; from the fifth year, several woody tree species (*A. bernieri, Boerhavia diffusa, D. perrieri, F. madagascariensis, P. decaryanum* and *Z. mauritiana*) begin to emerge and *C. bosseri* or *H. contortus* are dominant; by the tenth year after abandonment, more forest trees and shrubs are present (*Calopyxis grandidieri, C. grevei, Cordyla madagascariensis, Dalbergia sp., D. tropophylla, Pourpartia silvatica, Psorospermum androsaemifolium* and *Strychnos decussata*); after 21–30 years trees become dominant and shrubs and herbaceous plants less abundant (Table 2, Appendix A). Together with the increase of soil carbon and nitrogen contents, this could indicate that adequate ecosystem maturation has been achieved after about 20 years, and that a new cultivation cycle might be possible. Indeed, the few soil chemical properties that have been investigated show similar values or even higher values than in cultivated surfaces already after 11–20 years (Table 1). In other regions of the world, a time lag of about 40 years was observed (Topoliantz, 2002). If re-cultivation commenced before this recovering stage, soil amendments and fertilizers would be needed. Several experiments showed that satisfactory maize and groundnut yields can be obtained in fertilized re-cultivated wastelands (Blanc-Pamard et al., 2005). In eastern rain forests and western dry forests agroforestry systems have been recommended in order to reduce nutrient losses during the cropping phase since this combined use allows matching plant requirements with adequate nutrient supplies despite the losses caused by burning (Brand and Pfund, 1998; Milleville et al., 2000). Styger et al. (2007) described the cultural cycle in the rainforest region of eastern Madagascar as follows: the first treeless fallows after deforestation are best suited for rice yields; the second and following stages are shrub fallows (6 months to 2 years) characterized by herbaceous plants; up to 10 years, there is a progressive replacement of the herbaceous species by woody species; by 10–20 years, the wood biomass is well developed, with trees of large stem diameters, and surfaces are ready to be re-cultivated ("savoka"). By comparison, in the western part of Madagascar Von Schulthess (1990) found that after 25–30 years the vegetation is only a mature shrub fallow. Development of secondary forest takes at least 50–60 years and includes trees of sufficient diameters to permit extraction of timber boards from soft wood species. The post-cultural vegetation cycles we observed are similar to those described in western Madagascar (Milleville et al., 2000) and west Africa regions such as in Cameroon and Mali (Donfack, 1993; Yossi et al., 1993).

5. Conclusion

Productive woody species appear rapidly following abandonment and start to suppress the herbaceous field layer after 20 years. This indicates good potential for biomass and ash production, and indeed, is paralleled by soil maturation and recovery after approximately 20 years with respect to soil total nitrogen and organic matter content. Thus, a rotation time of about 20 years seems to be ecologically feasible but is still a long period considering the constant need for new arable land due to population growth. Nevertheless, this would reduce pressure on the virgin forests and allow for the reconstitution of some forest patches to close-to-natural conditions. A serious gap remains between scientific knowledge and farmers's know-how. In order to increase local acceptance of new land-uses and technologies such as agri-ecological and socio-economical alternatives, participatory research needs to be carried out and the results disseminated appropriately to the local people. This is the way paved recently by Sorg (2004), Andriambelo (2010) and Dirac Ramohavelo (2009).

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Appendix A.

Species recorded in the 61 plots and their abundance in the seven age classes of abandonment. Age classes of abandonment are: (I) culture; (II) 1–5 years; (III) 6–10 years; (IV) 11–20 years; (V) 21–30 years; (VI) 31–40 years; (VII) more than 40 years. Growth forms are T: trees, S: shrubs, H: herbaceous species, L: lianas. Species are in alphabetic order of the abbreviation.

Species	Family	Vernacular name	Abbreviation	Growth form	Abundance in the age classes of abandonment						
					I	II	III	IV	V	VI	VII
Aristolochia acuminata	Aristolochiaceae	Totonga	Aac	H	–	1	1	2	4	1	4
Achyranthes aspera	Amaranthaceae	Tsipotika	Aas	H	–	–	–	–	1	–	1
Abrus precatorius	Fabaceae	Voamaintilany	Aau	L	–	–	–	1	–	–	–
Acacia bellula	Fabaceae	Betratra	Abe	T	–	–	–	–	–	1	–
Albizia bernieri	Fabaceae	Alim-boro	Aber	T	–	1	1	–	6	8	5
Acridocarpus excelsus	Malpighiaceae	mantalazo	Aex	S	–	–	–	3	–	–	–
Acanthospermum hispidum	Asteraceae	Bakakely	Ahi	H	–	–	–	–	1	–	–
Agelaea pentagyna	Connaraceae	Vahimainty	Ape	L	–	–	–	1	6	1	1
Acacia sp.	Fabaceae	Rohy mena	Asc	L	–	–	–	1	1	–	–
Arachis sp.	Fabaceae	Voanjo	Asp	H	15	–	–	–	–	–	–
Apaloxylon tuberosum	Fabaceae	Talamena	Atu	T	–	1	–	1	4	4	4
Asparagus vaginellatus	Liliaceae	Rohim-boalavo	Ava	L	–	–	1	5	9	6	8
Boerhavia diffusa	Nyctaginaceae	Biamena	Bdi	H	–	1	3	1	3	–	1
Berchemia discolor	Rhamnaceae	Tsiandala	Bdis	T	–	–	–	–	–	1	–
Brachylaena microphylla	Asteraceae	Mangily an-kelika	Bmi	T	–	–	–	–	2	5	4
Breonia perrieri	Rubiaceae	Valo	Bperr	T	–	–	–	–	–	–	3
Bridelia pervilleana	Euphorbiaceae	Kitata	Bperv	T	–	–	–	–	2	2	4
Baudouinia spp.	Fabaceae	Banaka	Bpu	T	–	–	–	–	–	1	1

Appendix A (*Continued*)

Brewerta sp.	Convolvulaceae	Tsidai-posa	Bsp	H	–	8	11	19	12	9	6
Byttnerta voulily	Sterculiaceae	Volily	Bvou	L	–	–	–	3	4	8	9
Centella asiatica	Apiaceae	Talapetraka	Cas	H	–	–	1	–	1	–	–
Calopyxis sphaeroides	Combretaceae	Voanjonala	Casp	L	–	–	–	1	3	–	–
Cissus bussei	Vitaceae	Lela tandraka	Cbos	H	–	–	–	1	1	–	–
Crataeva sp.	Capparaceae	Kabokala	Cedu	T	–	–	–	2	–	–	–
Chloroxylon falcatum	Rutaceae	Mandakolahy	Cfal	T	–	–	–	–	–	2	3
Calopyxis grandidieri	Combretaceae	Boramena	Cgr	T	–	–	1	2	3	2	2
Cedrelopsis grevei	Meliaceae	Katrafay	Cgr.1	T	–	–	–	–	2	–	–
Chadsia grevei	Fabaceae	Remoty	Cgra	T	–	–	1	7	11	9	1
Cryptostegia grandiflora	Asclepedaliaceae	Lombiry	Chgr	L	–	–	–	1	2	6	7
Piptadenia chrysostachys	Fabaceae	Fany	Clea	T	–	–	–	–	–	1	–
Clerodendron sp.	Verbenaceae	Tsivakinampy	Clsp	T	–	–	–	4	3	3	1
Commelina ramulosa	Commelinaceae	Sofin'akanga	Cmad	H	–	3	2	6	3	–	–
Commiphora sp.	Burseraceae	Arofy	Coms	T	–	–	–	–	1	–	–
Commiphora simplicifolia	Burseraceae	Sekatsy	Comsp	T	–	–	–	–	1	3	3
Convolvulus sp.	Convolvulaceae		Consp	H	–	1	–	1	–	1	–
Cordyla madagascariensis	Fabaceae	Anakaraka	Corm	T	–	–	1	1	1	6	3
Capurodendron perrieri	Sapotaceae	Nato	Cpe	T	–	–	–	2	2	10	10
Colvillea racemosa	Fabaceae	Saron–gaza	Crac	T	–	–	–	–	–	1	1
Cissus rhodotricha	Vitaceae	Vahy rano	Crh	L	–	–	–	–	–	1	2
Croton	Euphorbiaceae	Poapoaky	Cro	S	–	–	–	1	3	5	7
Cyperus rotundus	Cyperaceae	tsingetsetsy	Crot	H	–	–	1	2	2	–	–
Cucumis sativus	Cucurbitaceae	Voatsaky	Csat	L	–	–	–	–	1	–	–
Citrullus vulgaris	Cucurbitaceae	Giseny	Cvul	H	–	–	–	–	2	–	–
Cyrtococcum bosseri	Poaceae	Ahi-daly	Cybos	H	–	14	20	39	19	22	7
Dactyloctenium aegyptium	Poaceae	Dematsy	Daeg	H	–	3	3	3	2	–	–
Dalbergia sp.	Fabaceae	Manary	Dalb	T	–	–	2	7	8	15	7
Dalechampia clematidifolia	Euphorbiaceae	Vahy teloravy	Dalc	L	–	1	2	1	3	5	8
Deidamia sp.	Passifloraceae	Papain'ala	Deid	L	–	–	1	1	–	1	1
Dioscorea acuminata	Dioscoreaceae	Ovy	Diac	H	–	1	2	2	3	4	6
Dioscorea trichopoda	Dioscoreaceae	Babo	Dikr	H	–	–	–	–	–	1	5
Diospyros perrieri	Ebenaceae	Mainty fototra	Diop	T	–	1	2	14	18	24	18
Diospyros tropophylla	Ebenaceae	Hazom-boenga	Diot	T	–	–	1	–	5	11	6
Noronhia	Oleaceae	Hazon-tsifaka	Dry	T	–	–	–	–	–	2	–
Euphorbia hirta	Euphorbiaceae	Kimenamena	Euph	H	–	5	3	6	3	4	1
Fernandoa madagascariensis	Bignoniaceae	Somtsoy	Fgre	S	–	5	9	8	17	8	17
Grewia cyclea	Tiliaceae	Latabarika	Gcyc	T	–	–	–	–	–	3	–
Grewia sp.	Tiliaceae	Sely	Grsp	T	–	–	–	5	9	9	7
Gardenia squamifera	Rubiaceae	Mahabibo ala	Gsq	S	–	–	–	–	1	–	2
Heteropogon contortus	Poaceae	Ahi-dambo	Heco	H	–	4	17	28	23	22	26
Hibiscus macrogonus	Malvaceae	Halampo	Hibm	S	–	–	–	–	–	4	3
Bivinia jalbertii	Flacourtiaceae	Sary goavy	Homsp	T	–	–	–	–	–	3	–
Hyparrhenia rufa	Poaceae	Tongolo akata	Hypruf	H	–	1	2	2	1	–	–
Cynodon dactylon	Poaceae	Kidresy	Hypsp	H	–	–	2	2	–	3	2
Indigofera tritoides	Fabaceae	Sary voanjo	Int	H	–	4	4	5	1	2	–
Ipomoea pes caprae	Convolvulaceae	Vomanga	Ipb	H	–	1	–	–	–	–	–
Isolona madagascariensis	Annonaceae	Kililo	Ismd	L	–	–	–	–	1	6	2
Commiphora lamii	Burseraceae	Milà	Jacp	H	–	5	8	13	11	10	8
Jatropha curcas	Euphorbiaceae	Boy	Jcur	S	–	–	–	–	2	2	5
Lantana camara	Verbenaceae	Radriaka	Lcam	S	–	–	–	–	5	3	1
Leptadenia reticulata	Asclepiadaceae	Vahy ronto	Lepma	L	–	1	1	1	1	1	–
Leptolaena multiflora	Sarcolenaceae	Madiorano	Lepmu	T	–	–	–	1	2	1	–
Mundulea ambatoana	Fabaceae	Tsindi-dritsy	Mamb	H	–	4	5	13	8	7	6
Manihot esculenta	Euphorbiaceae	Mangahazo	Manes	H	16	–	–	–	–	–	–
Macrorhamnus sp.	Rhamnaceae	Mamy aho	Marc	S	–	–	–	–	1	1	2
Marsdenia cordifolia	Asclepiadaceae	Bokabe	Masli	L	–	–	–	1	2	–	–
Mascarenhasia lisianthiflora	Apocynaceae	Kidroa	Moln	T	–	2	1	5	–	2	–
Mollugo nudicaulis	Aizoaceae	Aferom-bohitra	Msp	H	–	–	–	2	1	4	2
Mussaenda arcuata	Rubiaceae	Lengo	Musa	L	–	4	6	17	9	14	10
Neobeguea mahafaliensis	Meliaceae	Handy	Neob	T	–	–	–	–	1	–	2
Ocimum canum	Lamiaceae	Akata maimbo	Ocica	H	–	12	17	15	8	3	2
Poupartia minor	Anacardiaceae	Sarisakoambanditsy	Opg	T	–	–	–	1	3	–	–
Phoenix reclinata	Arecaceae	Kalalo	Orav	T	–	–	–	–	1	–	–
Pennisetum polystachion	Poaceae	Andravala	Penp	H	–	–	–	–	1	–	–
Phylloctenium decaryanum	Bignoniaceae	Pitik'ala	Phde	S	–	1	1	7	3	9	7
Poivrea coccinea	Combretaceae	Tamenaka	Poc	S	–	–	3	5	4	5	3
Pourpartia silvatica	Anacardiaceae	Sakoam-banditsy	Pous	T	–	–	2	6	10	23	22
Protorhus humbertii	Anacardiaceae	Tokam-bakatra	Prh	S	–	–	1	1	1	1	2
Psorospermum androsaemifolium	Clusiaceae	Harongam-panihy	Psan	T	–	–	2	3	9	7	9
Rhopalocarpus lucidus	Sphaerosepalaceae	Talafotsy	Rhli	T	–	–	–	–	1	1	–
Rothmannia tropophylla	Rubiaceae	Piropitsok'ala	Rotr	S	–	–	1	1	1	3	3
Securinega seyrigii	Euphorbiaceae	Anatsioky	Secs	T	–	–	–	–	2	5	1
Sesbania punctata	Fabaceae	Katsakatsa	Ses	H	–	–	–	1	–	–	–
Sida grevioides	Malvaceae	Tsilavon-drivotra	Sidg	H	–	7	7	11	11	14	10
Sida rhombifolia	Malvaceae	Mandrava sarotra	Sidr	H	–	6	5	13	12	8	8
Solanum sp.	Solanaceae	Masaboa tsy fihany	Solsp	S	–	–	–	1	3	2	4
Stereospermum euphorioides	Bignoniaceae	Mangarahara	Std	T	–	–	–	3	3	5	7

Appendix A (*Continued*)

Strychnos decussata	Loganiaceae	Hazom-by	Steu	T	–	–	1	1	4	3	4
Stylosanthes sp.	Legumineuses	Vazan'ombilahy	Styl	H	–	–	–	–	1	–	–
Tacca pinnatifida	Taccaceae	Kabija	Tacpi	H	–	–	–	1	5	4	3
Tarenna sericea	Apocynaceae	Papolahy	Tars	T	–	–	1	2	14	13	14
Terminalia calcicola	Combretaceae	Taly	Terf	T	–	–	–	–	2	1	1
Terminalia boivinii	Combretaceae	Amanin'omby	Tero	T	–	–	–	–	–	1	–
Tamarindus indica	Caesalpiniaceae	Kily	Tind	T	–	–	–	1	2	4	1
Tridax procumbens	Asteraceae	Sary kimalao	Trip	H	–	2	4	1	2	2	–
Loesenertella rubiginosa	Hippocrateaceae	Vahipindy	Tris	L	–	1	–	3	1	2	1
Triumfetta sp.	Tiliaceae	Sakaviron'ala	Trium	H	–	5	6	8	4	3	1
Terminalia sp.	Combretaceae	Taly	Tsp	T	–	–	–	1	–	–	–
Turraea sp.	Meliaceae	Tsirara-posa	Turc	H	–	–	–	1	–	4	4
Urena sp.	Malvaceae	Kisalenjo	Ure	H	–	–	2	–	2	–	1
Xeromphis sp.	Rubiaceae	Iamotim-boay	Xer	T	–	–	–	–	4	5	8
Zanthoxylum decaryi	Rutaceae	Monongo	Zant	T	–	–	–	–	3	4	5
Zea mays	Poaceae	Tsako	Zea	H	12	–	–	–	–	–	–
Ziziphus mauritiana	Rhamnaceae	Konazy	Ziz	S	–	1	6	12	11	5	2
Unknown scientific name		Tandrok'osy	hmod	H	–	1	–	7	4	8	8

Species names are given according to Tropicos: www.tropicos.org, except for *Rothmannia tropophylla*, whose name is given after Lebigre and Petignat (1998).

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Chapter III

Quantifying biomass of secondary forest after slash and burn cultivation in Central Menabe, Madagascar

Chapter III : Quantifying biomass of secondary forest after slash and burn cultivation in Central Menabe, Madagascar

(submitted to Journal of Tropical Forest Science, July 2011)

Abstract

Biomass is the principal input of nutrients in slash and burn cultivation of tropical dry deciduous forest. In this paper, we report the above ground biomass of ligneous and herbaceous vegetation as a function of the age of abandonment in order to analyze the potential amount of nutrients released into the soil. To estimate biomass, we used dendrometric classes based on height and circumference breast height of all individual ligneous plants inventoried in plots, and harvested for biomass measures representative trees in each defined dendrometric class. The paper focuses on the method to estimate the biomass according to the age of abandonment (1 to 5 year, 6 to 10 year, 11 to 20 year, 21 to 30 year, 31 to 40 year and up to 40 year), and growth type in ligneous species. In addition, we measured the biomass of the herbaceous field layer and litter. Fresh biomass (FB), air-dried biomass (ADB) and oven-dried biomass (ODB) were recorded. In total 1101 individual trees and lianas were measured in 30 plots amounting a surveyed surface of 3360 m^2. The quantity of total biomass increased with age of abandonment, reaching 72 t/ha after 40 years of abandonment. The species that contributed most to biomass (more than 10 t/ha in any one of the age classes) were *Fernandoa madagascariensis, Diospyros perrieri, Dalbergia sp., Poupartia silvatica, Tarenna sericea, Xeromphis sp, Phylloctenium decaryanum, Stereospermum euphorioides* and *Croton greveanum. Diospyros* increased regularly already after 10 years of abandonment. Biomass of *Dalbergia* increased also with the age of abandonment, but after 30 years, this quantity decreased because of selective harvest by farmers. *Fernandoa* increased after 30 years, as did *Poupartia,* but the latter became a key player as it was, comparatively, the species with the highest biomass shortly after 30 years of abandonment.

Keywords: fire; cultivation; biomass; tropical dry forest; vegetation succession; soil fertility; wood drying; Madagascar.

3.1. Introduction

Madagascar's isolation from the African continent and India dates back respectively to the late Jurassic and the end of the cretaceous (Rakotosamimanana 2003). Its evolution has since occurred in isolation and favored the emergence of various types of plants and animals and a multitude of forms not seen anywhere else (Goodman and Benstead 2003; Raherison and Grouzis 2005). In addition, Madagascar has both high biodiversity and a high rate of endemism (Langrand and Wilme 1997). In the South West of Madagascar, slash and burn agriculture is the traditional and predominant land use practice and its relevance in the context of forest and biodiversity preservation is significant (Ganzhorn et al. 2001; Dufils 2003; Harper et al. 2007). Secondary successions resulting mainly from slash and burn cultivation have an economic interest because they provide various resources: firewood, food plants, pastures for cattle, caterpillars, medicinal plants or commercial timber species (Dirac Ramohavelo 2009; Raharimalala et al 2010). In this region, the agricultural products are the basis of the local commerce and are consumed, sold or exchanged (Dirac Ramohavelo 2009). Genini (1996) described how natural and secondary forests are cleared during the cold and dry season (June–September) with consecutive gathering of logs and branches in piles around larger trees. The wood is dried during several weeks and finally burnt at the end of the dry season (in October). Fire destroys practically all vegetation except big baobabs and tall crowned trees. For two to three years, people plant maize on areas cleared this way (called: *hatsake*) and then cassava and groundnuts (République de Madagascar 2006). This type of farming does not require any maintenance until harvesting. It benefits from fertilization by the burnt vegetation and yields about two tons of maize per hectare. Only a small fraction of the dead unburnt wood is used for fencing or firewood, the majority is left to rot.

The maize production decreases by 80% after four years of culture on the same plot (Réau 2003). After 2 to 5 years, the plots are abandoned (called "*monka*") because of declining fertility (losses of nutritive elements in the soil) but also because of the increasing need for weeding and changing the floristic composition (Genini 1996; Milleville et al. 2000). Some farmers limit their cyclic activities to secondary surfaces, re-using plots of various ages of abandonment, but others extend part of their cultivation into the natural forest. Each family clears between 0 and 2 ha per year (including natural and secondary forests) and the average cultivated surface is about 0.86 ha (Dirac Ramohavelo 2009). Fire is also applied on cultivated lands between harvests, and not only in forested vegetation. In eastern Madagascar, Pfund (2000) highlighted the importance of soil–vegetation patterns in slash and burn cultivation systems and found some correlations between the elements (nitrogen, phosphorus and potassium) contained in soil and in vegetation. Generally, the less elements found in the soil, the higher their content in the vegetation. Furthermore, he found that the biomass produced by fallow land contributed significantly to soil fertility and was thus a determinant of the farming cycles. In the primary dry deciduous forest of south–western Madagascar, Raherison et al. (2005) determined the composition and quantities of nutrients in biomass to verify whether this dry forest had similar physiological characteristics as other dry ecosystems of the world.

This paper is part of a more general project the aim of which was to study the amount of nutrients released into the soil after slashing and burning of aboveground biomass. In a previous paper (Raharimalala et al. 2010) we presented the soil vegetation patterns using basic soil properties and concluded that fields older than 20 years have recovered sufficiently to be re-used as agricultural land. In this paper, we report the above ground biomass of ligneous and herbaceous vegetation as a function of the age of abandonment in order to analyze the potential amount of nutrients which could be made available for cultivation in secondary vegetation. The different questions studied in this paper are: (i) how is biomass of herbaceous and ligneous vegetation related to the age of abandonment? (ii) how is the biomass of dominant species related to age of abandonment? (iii) how are the different tree parts (stem, branches, leaves) contributing to the biomass? (iv) can we validate the biomass obtained indirectly with biometric measurements and selective sampling for biomass weighting with the measure of the total biomass after clear cut?

3.2. Materials and methods

3.2.1. Study site

The study site (about 1000 ha) is located in Andranolava in south-western Madagascar, 75 km north of Morondava (Central Menabe) near the well-known Kirindy forest (Sorg et al 2003) and the village of Beroboka. In the northern part, the area is characterized by old sisal plantations; the southern part is delimited by the Andranolava river, the eastern part by the Kirindy forest, and the western part by littoral forest.

The climate of Central Menabe is classified as tropical dry with 2 distinct seasons: a rainy season (November to March) and a dry season (April to October) (Sorg & Rohner 1996). Data from meteorological office (2000-2006) (Rakotondrabe 2007), show that the average annual temperature is 26°C, with a relatively cool period from June to August. Average total precipitation is 791 mm per year. The study area can be classified into the world's tropical dry forest (Murphy & Lugo, 1986a). Vegetation is dominated by dry deciduous forests of various types as described in Koechlin et al. (1997).

Red and yellow soils were classified by Felber (1984) and Rohner & Sorg (1986) as "red and yellow soils of the luvisols ferric" category, and can be named according to the French classification "ferruginous tropical leached soils" (Rakotovao et al. 1988). For this study the yellow soils were chosen. They are preferred by farmers for cultivation (Raharimalala et al. 2010).

3.2.2 Plot selection

We selected 30 plots across 6 age classes on yellow soils according to the age of the culture abandonment. These plots were chosen in homogenous vegetation patches (see also Raharimalala et al. 2010). Each class of age had five replicated plots taken randomly across the entire area of study. Age classes 1 to 5 years and 6 to 10 years were surveyed on plots of 16 m^2, age classes 11 to 20 and 21 to 30 years on plots of 64 m^2, and age classes of 31 to 40 and more than 40 years on plots of 256 m^2. The age of the "*monka*" (abandoned surface) was estimated by a local guide who has already worked with many scientists in the area and who was a former guide in the Kirindy forest. This information was cross-checked by consulting local farmers. The minimal area was defined according to Barkman (1989) and Hopkins (1957).

3.2.3 Biometric measures on trees and tree selection for biomass measurements

We numbered all individual trees having reached breast height and wood climbers in the plot. We measured circumference at breast height (or girth breast height) according to Hashimoto et al (2004) and Kale et al (2004) and visually estimated the height after training with a clinometer on isolated trees. We separated 4 growth types: single stem, fork on trunk, fork from the base, which can be considered multi-stemmed, and small bush which is similar to fork from the base but has a height smaller than 1.3m (**Figure 4**). The latter comprises true bushes and young sprouting trees that will ultimately become multi-stemmed. Each individual was registered by a unique identification number, with its species name, its growth type as well as the plot number and the age of abandonment.

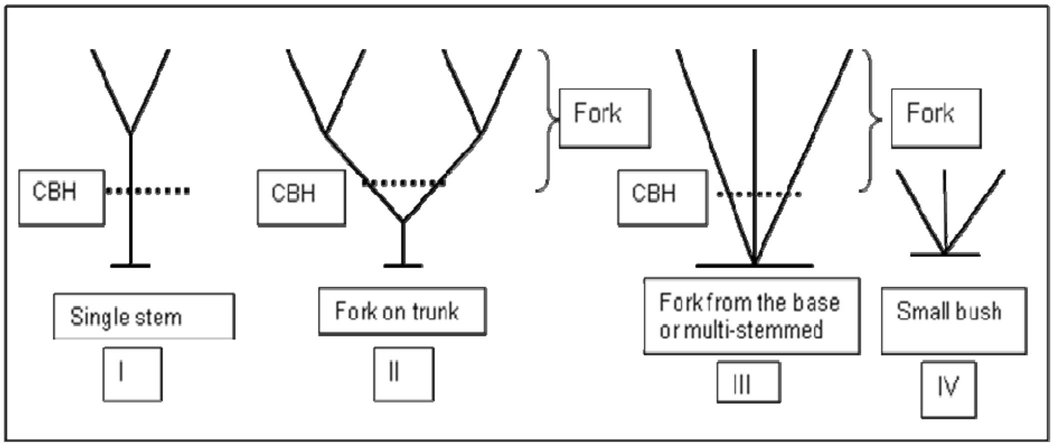

Figure 4 : Growth type considered for biometric measurements. CBH: Circumference breast height (1.3m).

For fresh biomass measurement, the aim was to select a certain number of trees in order to have a representative sample. Whenever possible, we tried to have for each species individuals in all represented growth types, and in all represented classes of abandonment. Nevertheless, our sample remained unbalanced for growth types and classes of abandonment. For all recorded species in all growth types and all 5 classes of age of abandonment (class I was not used since plots were treeless), we ranked the individual trees according to the calculated variable circumference*height. For the growth types “fork on trunk” or “fork from the base (multi-stemmed)”, we took as circumference the sum of the circumferences of each fork. For growth type “small bush”, we ranked the individuals only according to the height. We then defined a certain number of classes and took for biomass harvest and measurements an individual tree in the median of each class (see example in **Figure 5**).

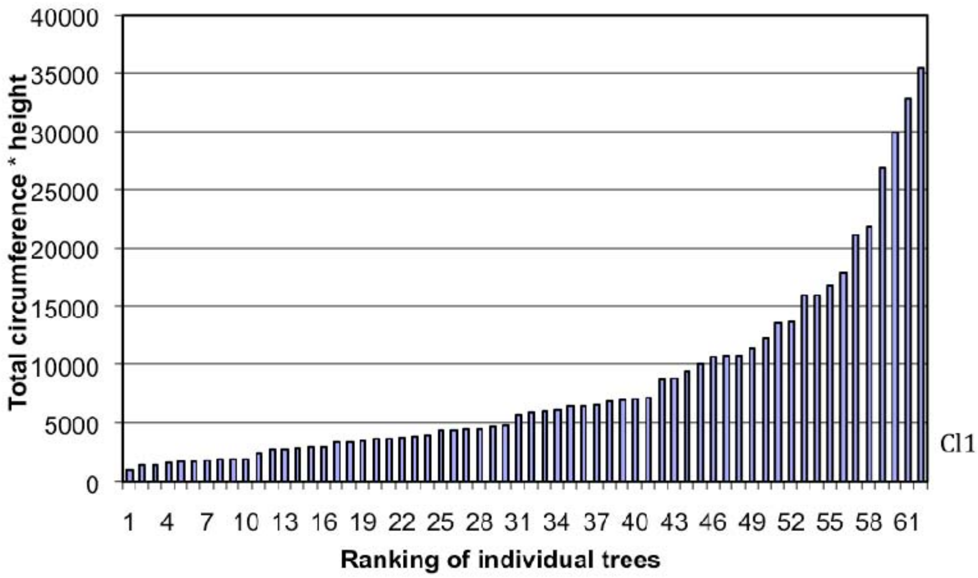

Figure 5 : Example of class determination for *Diospyros perrieri* in the growth form fork from the base (multi-stemmed) and age class 31 to 40 years. Individual trees are ranked according to the variable total circumference at breast height*height. In this example, we defined 7 classes of "total circumference*height" (Cl 1 to 7): <5000; 5-10000; 10000–15000; 15000-20000; 20000-25000; 25000-30000; >30000, and we took the median individual of each class for harvesting and measuring its biomass

The sampling effort in the different categories for biomass measurement can be seen in **Table III**. For a total of 433 trees representing 61 species, there are 100 individuals in growth type I, 41 individuals in growth type II, 208 individuals in growth type III, and 84 in growth type IV. The distribution in the age of abandonment classes shows that the number of trees increases with the age. This is partly because the area is increasing with age too.

Table I : Sampling effort (number of measured trees) for tree biomass estimation according to the age of abandonment and growth types

Age of abandonment	Growth types				**Total**
	I	II	III	IV	
1 - 5 years	0	0	0	2	**2**
6 -10 years	0	0	1	5	**6**
11 -20 years	7	0	5	14	**26**
21 -30 years	31	8	25	16	**80**
31 - 40 yeras	28	16	83	23	**150**
More than 40 years	34	17	94	24	**169**
Total	100	41	208	84	**433**

The selected trees were cut at ground level. The above ground fresh biomass was weighed separetly for branches, which where piled according to 3 size classes (small, median or large), leaves and stems. When there were several branches in each branch class, we weighed one branch which we considered as average, as well as leaves from this branch, and multiplied their weight by the number of branches. This was done for the three classes of branches and, adding the three values, this gave the total fresh weight of branches and leaves. We used two types of scales: Kern EMB 5.2K1 for leaves and small branches (precision: 0.01 g), and Kern CH 50K50 for stems and large branches (precision: 0.050 Kg)

3.2.4 Biomass of herbaceous vegetation

Depending on the spatial pattern of herbaceous vegetation, we sampled subplots in two different manners. When the green biomass and litter were covering the ground homogeneously, we took randomly one square of 2 mx2 m. We cut all herbaceous vegetation at the ground level and weighed its biomass. The litter was weighed separately. All measures were taken with a precision of 0.01 g and expressed as Kg ha^{-1} of fresh weight. When there was a clear ground cover heterogeneity, we sampled according to two strata: one subplot of 2 mx2 m was taken in the surface where green herbaceous vegetation was dominating, and another subplot was taken where the litter was dominant. We then weighed the biomass and litter according to the proportion occupied by each strata in the plot so as to have an average biomass and litter value per plot, again expressed as Kg ha^{-1} of fresh weight.

3.2.5 Dry biomass estimation

Our assumption is that, for a given tree species, the relative water loss during the drying process is the same irrespective of size, growth type and age of abandonment. We selected 28 tree species with the highest relative frequencies in the inventory of all plots (see **Appendix Chapter III.1**). For each species, we selected 3 trees (replications) from the plot with the highest numbers of trees of the considered species. Whenever possible we took these 3 trees from growth type I (single stem), otherwise we took growth type II, III or IV. At the end of the dry season, we cut each tree and from these 84 individuals we selected 5 morphological parts: part 1 corresponding to a piece of wood (roughly 400 g) at the bottom of the stem, part 2 corresponding to the top of the stem, part 3 corresponding to a piece of wood (roughly 100 g) at the bottom of an average fork, part 4 corresponding to the top of an average fork (roughly 50-100 g), and part 5 corresponding to the leaves stripped form the branche taken in part 4. When growth types III or IV had to be used, we got only parts 3, 4, and 5. For the other species (32), we applied the mean values obtained for each part of these 28 species.

The 5 parts of the trees were weighed fresh, then again after air-drying for 45 days (ADW), and drying in the oven for 30 days at 60°C (ODW) (**Appendix Chapter III.1**). This oven temperature was chosen because samples were further used for chemical content. For each part, the water loss was obtained and expressed as percent of the fresh weight. The relative water loss of the stem is calculated as the average of the relative water loss of parts 1, 2 and 3 (bottom of stem, top of stem and bottom of the fork). The relative water loss for branches results from part 4 and the one of leaves from part 5. We obtained the dry biomass of the trunk, the branches and the leaves of each tree by multiplying the fresh biomass by their respective dry matter content, calculated as the complement to 1 of the relative water loss.

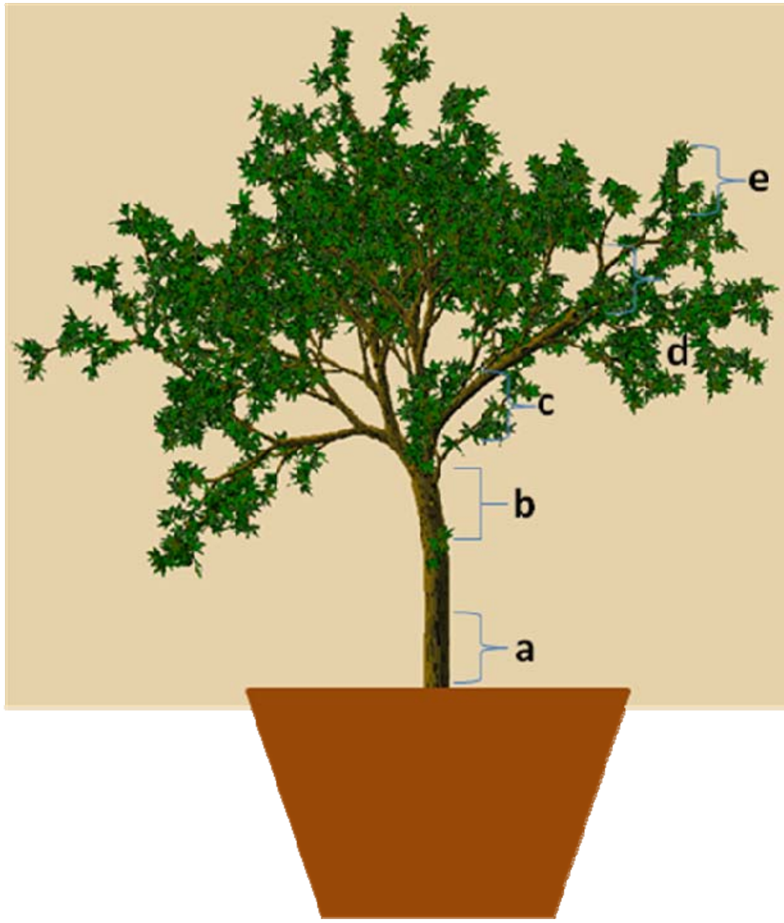

Figure 6 : The different parts of the tree for estimating dry biomass

a- Bottom of the stem, b: top of the stem, c: bottom of the fork, d: top of the fork, e: leaves

For the dry biomass of herbaceous vegetation, we took in each 2 mx2 m subplot one bunch of vegetation. We measured its fresh biomass and air-dried it during 3 weeks. We obtained the dry biomass of the herbaceous layer by multiplying the fresh biomass by its respective dry matter content, calculated as the complement to 1 of the relative water loss.

3.2.6 Biomass at plot scale

For the ligneous vegetation, we identified the class (circumference*height) of each individual tree in the plot and attributed to it the biomass of the corresponding cut and measured tree with respect to species, growth type and age class. The total biomass of each plot was obtained by adding the biomasses of ligneous vegetation (growth types I to IV), herbaceous vegetation and litter. All dead branches lying on the soil were identified and weighed. They were added to the quantity of dry biomass of branches. Finally the result for each plot is presented as fresh and dry (air and oven) biomass of stem, branches, leaves, and herbaceous vegetation, as well as the total fresh and dry biomass.

3.2.7 Bulk biomass

In order to validate the biomass values obtained with the above described biometric method, we chose one plot within each class of abandonment, based on the vegetation surveys (centroïd surveys in Raharimalala et al. 2010). We cut every tree and air-dried the wood during one month on the soil, similarly to common practice among farmers at the end of the dry season. We then weighed all the wood. The herbaceous vegetation and the litter were collected in five 1 m^2 subplots. This allowed us to calculate the bulk biomass of these plots.

3.3. Results

3.3.1 Species richness and stand structure

Overall, 1101 individual trees and lianas were measured in 30 plots (total of surveyed surface of 3360 m^2) (**Appendix Chapter III.2**). They belonged to 27 families, 57 scientifically known and 3 species only known with their vernacular name. Among these species, we had plants with edible tubers, e.g *Dioscorea acuminata*, plants with edible fruits or seeds, e.g *Ziziphus mauritiana*, *Tamarindus indica* and *Phylloctenium decaryanum*, medicinal plants, e.g *Fernandoa madagascariensis* and *Cryptostegia grandiflora*, and plants for economic use such as *Jatropha curcas*, and especially *Dalbergia sp* and *Diospyros perrieri*, wich are used for their wood quality.

Appendix 2 shows that two species (*Tarenna sericea*, *Ziziphus mauriatiana*) were observed in plots between 1 to 5 years of abandonment, 4 (*Dalbergia sp, Mussaenda arcuata, Stereospermum euphorioides, Albizia bernieri*) between 6 and 10 years, 10 (e.g. *Fernandoa madagascariensis, Diospyros perrieri, Poupartia silvatica, Phylloctenium decaryanum*) between 11 and 20 years, 18 (e.g. *Apaloxylon tuberosum*, *Ripikala*, *Grewia sp*, *Strychnos decussata, Xeromphis sp*, *Brachylaena microphylla*) between 21 and 30, 20 (e.g. *Isolona madagascariensis*) between 31 and 40 years and 6 (e.g. *Croton greveanum*, *Clerodendron sp*) after 40 years. Most species (23, e.g. *Diospyros, Acalypha diminuata, Poupartia*) had the highest frequency in the class of abandonment 31 to 40 years, 15 (e.g. *Fernandoa, Croton, Xeromphis*) in the class over 40 years, 17 (e.g. *Dalbergia*, *Tarenna*, *Mussaenda*, *Apaloxylon*) in the class 21 to 30 years and 5 in the class 11 to 20 years (*Ziziphus*, which was not observed after 30 years, and *Phylloctenium*). Only one species (*Albizia*) had its maximum in the class 6 to 10 years and none in the class 1 to 5 years.

Appendix 2 and Table I show that during the first 5 years, only two species (*Ziziphus* and *Tarenna)* were observed as small bushes (growth type IV). After 5 years, single stems (type I) and multi-stemmed (type III) appeared (e.g *Ziziphus)*, and some additional bushes grew (e.g. *Dalbergia, Tarenna, Stereospermum* and *Albizia)*, and some lianas (e.g. *Mussaenda)*. Trees with fork on trunk (type II) appeared only after 20 years. Their density was the highest in the class 21 to 30 years and decreased after 30 years. The density of inventoried trees, lianas and bushes (**Table IV**) was the most important in the age class 21 to 30, except for growth type III, which had highest density in the class 31 to 40 years. Several species had high density and their maximum by about 30 years or soon after (e.g. *Fernandoa, Diospyros, Acalypha, Dalbergia, Poupartia, Tarenna, Mussaenda and Apoxylon)*. Some dominant species such as *Fernandoa* increased their density with age of abandonment, whereas some others such as *Dalbergia* and *Diospyros* decreased it after 30 or 40 years.

Table II : Density of the inventoried trees and bushes in function of the age of abandonment and growth types (number of individuals per ha).

Age of abandonment	Growth type				**Total**
	I	II	III	IV	
1 - 5 years	0	0	0	250	**250**
6 - 10 years	125	0	250	750	**1125**
11 - 20 years	1063	0	344	1156	**2563**
21 - 30 years	2563	281	1281	1156	**5281**
31 - 40 years	742	188	1836	742	**3508**
More than 40 years	766	188	1430	664	**3048**

The mean circumference at breast height (CBH) and the mean height (H) in any growth type increased generally with the age of abandonment (**Table V**), e.g the mean circumference of breast height for the single stem varied from 2.2±0.2 cm in the class 11 to 20 years to 9.6±0.9 cm after 40 years, and the height varied from 169±17 cm in the class 11 to 20 years to 328±14 cm after 40 years. Inconsistent values (in the class 6 to 10 years) in growth types I, III, and IV are due to small sample sizes.

With respect to herbaceous plants, 40 species (26 scientifically known and 14 species known with their vernacular name) in 20 families were found in our study area (Appendix 3).

The number of species present in all age classes varied between 15 and 18. A maximum of 18 species was observed between 11 and 30 years, but we noted a slight decrease in older plots. Three species were present in all age classes *(Commiphora lamii*, *Kidranta* and *mamaky hoho)*.

Table III : Mean of circumference breast height (CBH) and height (H) with standard error of the inventoried trees in function of age of abandonment and growth type in 30 plots. The number of individuals is given in parentheses.

Age of abandonment		Growth type			
		I	II	III	IV
1 - 5 years	mean CBH (cm)				
	mean H(cm)				65±15 (n=2)
6 - 10 years	mean CBH (cm)	5.0 (n=1)		21.2±9 (n=2)	
	mean H(cm)	190 (n=1)		200±25 (n=2)	177±30 (n=6)
11- 20 years	mean CBH (cm)	2.2±0.2 (n=34)		15.4±2.6(n=11)	
	mean H(cm)	169±17 (n=34)		199±9 (n=11)	153±11 (n=37)
21 - 30 years	mean CBH (cm)	3.6±0.5 (n=81)	14.8±2.5 (n=9)	44.8±6.7(n=41)	
	mean H(cm)	206±14 (n=81)	294±22 (n=9)	171±14 (n=41)	219±17 (n=38)
31 - 40 years	mean CBH (cm)	8.5±0.9 (n=95)	60.3±8.9 (n=24)	39.3±3.0 (n=224)	
	mean H(cm)	260±11 (n=95)	537±59 (n=24)	316±7(n=224)	191±12 (n=106)
More than 40 years	mean CBH (cm)	9.6±0.9 (n=98)	101±21 (n=24)	65.0±4.0 (n=183)	
	mean H(cm)	328±14 (n=98)	562±33 (n=24)	418±10 (n=183)	242±18 (n=85)

3.3.2 Plant biomass

Herbaceous biomass was decreasing with age of abandonment, after having reached a maximum in the age class 6 to10 years (**Table VI**). The tendency for litter biomass was the inverse to herbaceous biomass, increasing over time to reach 3.5±1.1 t/ha (ODB) in the age class beyond 40 years. However, taken together herbaceous biomass and litter was highest in the early stage (6 to 10 years). For trees and lianas, the biomass increased with age of abandonment (**Table IV**).

Table IV : Mean of fresh biomass (FB), and oven dry biomass (ODB) (t/ha) of trees, lianas and herbaceous vegetation and litter per age of abandonment with standard error (n=5 plots per age of abandonment).

Age of abandonment	Trees + lianas		Herbaceous		Litter		**Trees + lianas + herbaceous + litter**	
	FB	ODB	FB	ODB*	FB	ODB*	**FB**	**ODB**
1- 5 years	0.79±0.78	0.403±0.401	4.4±1.0	2.0±0.5	1.0±0.5	0.4±0.2	**6.19±1.35**	**2.8±0.7**
5 - 10 years	2.3±1.3	1.2±0.7	5.3±0.4	2.4±0.2	3.2±1.1	1.5±0.5	**10.8±1.7**	**6.1±0.9**
11 - 20 years	5.5±0.7	2.5±0.3	4.8±1.8	2.1±0.8	4.1±1.2	1.9±0.5	**14.4±2.3**	**6.5±0.9**
21 - 30 years	35.3±9.5	17.4±4.2	2.5±0.5	1.2±0.2	4.5±1.3	2.0±0.6	**42.3±9.6**	**20.6±4.2**
31 - 40 years	78.7±15.8	41.1±8.4	2.1±0.5	1.0±0.2	4.4±1.1	2.0±0.5	**85.2±15.8**	**44.1±8.4**
More than 40 years	128.8±23.0	66.9±9.5	2.7±0.6	1.2±0.3	7.8±1.0	3.5±0.5	**139.3±24.0**	**71.6±9.5**

* The values for oven-dried herbaceous vegetation and litter were taken over from air-dryed values because the drying process was already reached with the air drying.

The water loss during the drying process was highest for the branches, ranging from 58.7 to 63% in the different age classes, and lower for leaves (54.1 to 58.2%) and stem (38.5 to 44%).

The distribution of dry biomass in trees showed that, irrespective of the age class, more than half of the biomass was in stems (**Table VII**). It is noteworthy to see that the youngest stage (1-5 years) had proportionally much of its biomass in stems and leaves, and that with age of abandonment, the relative contribution of stems increased again, whereas those of leaves decreased.

Table V : Distribution of dry biomass (oven-dried, ODB) between stem, branches and leaves, in function of age of abandonment.

Age of abandonment	Stem		Branches		Leaves		**Total**
	t/ha	%	t/ha	%	t/ha	%	
1- 5 years	0.26	65	0.081	20	0.059	15	**0.4**
6 - 10 years	0.79	66	0.3	25	0.11	9	**1.19**
11 - 20 years	1.18	48	0.95	38	0.36	14	**2.49**
21 - 30 years	11.02	63	4.98	29	1.38	8	**17.38**
31 - 40 years	27.01	66	11.3	27	2.79	7	**41.1**
More than 40 years	48.4	72	15.68	23	2.86	4	**66.94**

The species that contribute most to biomass (more than 1 t/ha in any one of the age classes) are represented in **figure 7**. *Diospyros perrieri* increased regularly already after 10 years of abandonment. Biomass of *Dalbergia sp* increased also with the age of abandonment, but after 30 years, this quantity decreased. *Fernandoa madagascariensis* increased after 30 years. Other major biomass contributors were *Poupartia sylvatica*, which increased drastically after 30 years, and *Tarenna sericea*. *Croton greveanum* was a late arrived species that contributed importantly to biomass in the highest age class.

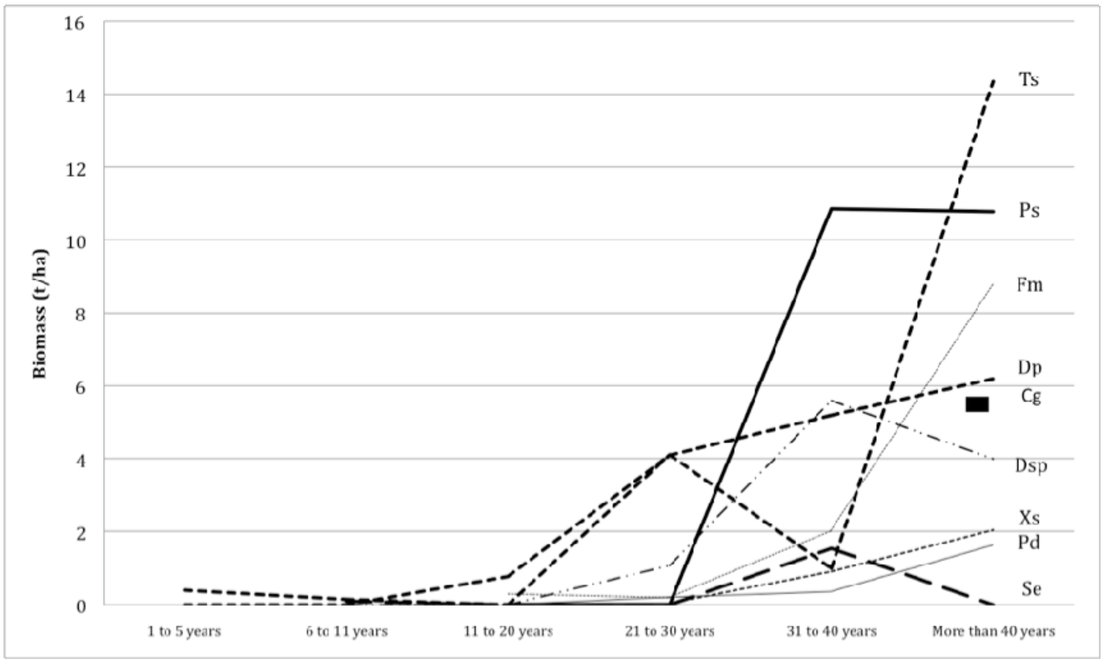

Figure 7 : Mean total biomass (stem, branches, leaves) per age of abandonment (N=5) of trees that have dry biomass (ODB) >1 t/ha in any one of the age class. Ts: *Tarenna sericea*, Ps: *Poupartia sylvatica*, Fm: *Fernandoa madagascariensis*, Dp: *Diospyros perrieri*, Cg: *Croton greveanum*, Dsp: *Dalbergia sp*, Xs: *Xeromphis sp*, Pd: *Phylloctenium decaryanum*, Se: *Stereospermum euphorioides.*

3.4. Discussion

3.4.1. Regeneration and tree growth types

Regeneration is an important process for forest sustainability and restoration. In exploited forests, regeneration can be achieved by planting, or naturally by sprouting or seed dispersal. Sprouting is the consequence of felling trees and leads to the multi-stemmed growth type, and indeed, in our study area, this is the most common growth type after 30 years. The high frequency of both multi-stemmed trees and small bushes is typical of exploited forests. Sprouting ability is more common and more important as a mechanism of regeneration in dry tropical forest than in rainforests (Ewel 1980; Murphy & Lugo 1986b; Russell-Smith 1996; Kennard 2002; McLaren & McDonald 2003c, Vieira & Scariot 2006). The growth types single stem and fork on trunk appear as a sign of another form of regeneration using seed.

Resprouting after disturbances such as slash and burn is a shortcut for forest recovery because it bypasses the most vulnerable life stages and the new plants start with vigorous shoots (Miller and Kauffman 1998; Kammesheidt 1998; Bond & Midgley 2001; Kennard et al. 2002). However, species can lose their resprouting ability after sequential cutting, burning, and as a consequence of intensive tractor use (Uhl et al. 1988; de Rouw 1993; Sampaio et al. 1993; Nepstad et al. 1996).

3.4.2 Herbaceous biomass in regenerating stands

After abandonment of culture, herbaceous plants in the field layer grow rapidly as shown by the quantities of dry biomass in the first 5 years (herbaceous ADB of 2.0 t/ha), and decrease after 20 years. This trend is due to the development of ligneous species, which allows less light to reach the soil, and increases coverage by litter.

Soumit & Malaya (2006) studied dry deciduous forests in India and the impact of varying periods of protection of degraded forest stands on species composition, phytosociological type and biomass of herbaceous vegetation. After the beginning of stand regeneration, they found herbaceous biomasses of 83.2 (after 2 years), 62.2 (after 4 years), 58.0 (after 6 years) and 64.0 g/m^2 (after 10 years) (respectively 0.83, 0.62, 0.58 and 0.64 t/ha), which is less than in our study site (2.0 t/ha in the first 5 year, and 2.4 t/ha between 6 to 10 years). In their study site the annual rainfall was much higher (1407 mm) than in our study (707 mm). Soumit & Malaya (2006) dried the herbaceous vegetation at a temperature of 90°C. Our herbaceous vegetation was air-dried at ambient field temperature but the samples did not significantly lose more water when oven-dried at 65°C. Therefore, this cannot explain why our values of herbaceous biomass are higher. Another explanation is the age old practice of shifting cultivation and the anthropogenic activities such as clear felling of trees for timber and fuel wood, overgrazing and surface burning, which were the causes of the destruction of the climax tropical dry deciduous forest in India and thus might have degraded soils more severely.

3.4.3 Comparison with other studied forests

In the dry forest of Yucatan, Mexico, Read & Lawrence (2003) obtained a dry biomass of 21 t/ha after 2 to 5 years in forest recovering following shifting cultivation of maize. In the same age class (1-5 year after culture abandonment), we had 0.4 t/ha. The high precipitation (900-1400mm), the type of soils (shallow, calcareous and highly permeable due to organic matter content and underlying limestone bedrock) are presumably the main cause of this biomass difference.

Saldarriaga et al. (1988) studied the above-ground biomass of rain forest in the upper Rio Negro of Columbia and Venezuela slash and burn cultivation. Their surfaces were clear-felled, burned and used for crops 2-4 years and abandoned, allowing regrowth of forest. Their soils like ours were poor in nutrients (oxisols and ultisols). They found 44 t/ha in the first 10 years following slash and burn agriculture. Their above-ground biomass was much higher than in our case (1.2 t/ha in 6-10 years after culture abandonment and 2.5 t/ha after 11 to 20 years). The equatorial climate with yearly rainfall of 3500 mm is the reason of this contrast of biomass yield.

Raherison et al. (2005) studied dense primary deciduous dry forests of *Dalbergia, Commiphora* and *Hildegardia* (described by Humbert & Cours-Darne 1965) in the south West of Madagascar (about 400 km south of our study site). Despite similar climate and soil types, their above ground dry biomass was roughly two times higher (113 t/ha) than in our case (66.9 t/ha after more than 40 years after culture abandonment) and this shows the contrast between virgin dry forest and secondary forests of 40 years.

In the East of Madagascar, the traditional slash and burn agricultural system (*tavy*) is the dominant land use (Styger et al. 2009). Forests or fallows are cut, burned and upland rice is usually cultivated for 1 year. The land soon becomes unsuitable for cropping, and is finally abandoned. Styger et al. (2009) observed after a fallow period of three years, a biomass of 11t/ha for the shrub species *Psiadia alitissima,* and of 8.5 t/ha for *Trema orientalis*. This is considerably larger than our value of total above ground biomass of trees and lianas after 5 years of abandonment (0.4 t/ha). Again, the difference might be due to the contrasted climate between the east and the west cost of Madagascar (2000 and 3500 mm per year, only 791 mm in our study site).

The above mentioned studies used allometric equations based on dendrometric variables. In our case we used a direct method (cutting and weighing), which is probably more suited for secondary vegetation with various growth-types and lower statured trees. The exhaustive measures of biomass by means of a total harvest in one selected plot of each age class gives a validation of the calculated values with biometric measures. It appeared that the calculated biomasses were generally lower than the measured ones (between 68 and 87 %, except for age class 31 to 40 years, where they were higher with 110%). This discrepancy can partly be explained by selective harvests by local farmers in the period between biometric and biomass measurements and the total harvest of biomass.

Martinez-Yrizar et al. (1992) studied the above ground biomass of dry undisturbed dense tropical forest in Mexico. They found for these forests 77.7 t/ha of dry biomass. This value is comparable to our tree biomass (ODB 66.9 t/ha) measured after 40 years. This result is surprising given the fact that the forest studied by Martinez-Yrizar et al. (1992) had an average height of 6.9 m, which is more than in our forest (3.3 - 5.6 m). It is possible that our relatively high biomass value is due to the drying process (60°C in our case and 105°C for Martinez –Yrizar et al, 1992) and to the slightly higher precipitation (797 mm against 707 mm in Mexico). On the other hand, because of shifting cultivation, the multi-stemmed trees were very dense in our older sites and this contributed much to the biomass.

3.4.4 Common species and biomass contribution

After 30 years, we were able to identify the species used by the local population. *Dalbergia sp* and *Diospyros perrieri*, which produce heavy and hard wood, are widely used for cabinet making and construction, and this explains the biomass decrease after 30 years for one of them. By contrast, *Fernandoa madagascariensis* is a species that the local populations use only for cattle fences and this does not affect the biomass over time. Poupartia, which settles lately, becomes a key player as it is, comparatively, the species with the highest biomass shortly after 30 years of abandonment.

3.5. Conclusion

Considering the biomass reconstitution after slash and burn cultivation, it becomes clear that the overall ligneous biomass is continuously increasing up to 40 years. Furthermore, comparisons with virgin forest in similar climates in the same region indicate the potential for biomass to double. Early in the succession, stems represent more than 50% of the total above-ground biomass, and this increases up to 72% after 40 years. This contribution is largely due to ligneous species such as *Fernandoa madagascariensis, Diospyros perrieri, Dalbergia sp., Poupartia sylvatica ,Tarenna sericea* and *Croton greveanum.* Since *Dalbergia* and *Diospyros* are targeted by local farmers, it is important to have other species able to contribute significantly to biomass. *Pourpartia* has a good potential as a major biomass contributor after 30 years. Nutrient content of the biomass of these different species is then critical for quantifying the overall inputs and benefit for slash and burn cultivation, but this knowledge is required for optimizing this traditional practice.

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Chapter IV

Nutrients released from ligneous vegetation in secondary forest after slash and burn cultivation in Central Menabe, Madagascar

Chapter IV: Nutrients released from ligneous vegetation in secondary forest after slash and burn cultivation in Central Menabe, Madagascar (will be submitted)

Abstract

Nutrients stocks play a significant role in the agricultural productivity. In tropical regions where slash and burn agriculture is practiced, most of the nutrients required for the crops are derived from the ashes of the burned vegetation (Karimuna 2000). In this study, we report that the concentration of nutrient is higher in leaves than stems and branches. The amount of nutrients released increased with the age of abandonment. Some quantities of C and N contributed to greenhouse gases during burning and the most of nutrients required for crops are derived from ashes of burned vegetation. Some species such as *Poupartia sylvatica* and *Tarenna sericea* constitute good candidates for a target forest management which would promote a rapid rebuilding of biomass and nutrient pool.

4.1. Introduction

Madagascar's forests are among the most biologically rich and unique ecosystems in the world but, despite longstanding concern about their destruction, estimates of past forest cover and deforestation have varied widely (Ganzhorn et al. 2001; Dufils 2003; Harper et al. 2007). According to USAID, Conservation International (2007), yearly forest loss between 1999 and 2000 was 0.70-1.1 %, and after 2000 it was between 0.35-0.53 %. Slash and burn agriculture is the traditional and predominant land use practice in all forested regions of Madagascar and its relevance in the context of forest preservation is significant. In Madagascar (Dirac Ramohavelo 2009) as well as in West and Central Africa (Lubini 2003), secondary successions resulting mainly from slash and burn cultivation have some economic interest because they provide various resources: firewood, food plants, pastures for cattle, caterpillars, medicinal plants and some commercial timber species that regenerated after abandonment. Cultivation is the principal activity of villagers in Central Menabe (south-western coast of Madagascar) and the villagers themselves consider agriculture as their most important activity (Calderoni 1999; Dirac Ramohavelo 2009). Farmers cultivate products whose growth depends on rainfall, e.g. maize, cassava or groundnuts (République de Madagascar 2006). In this region, agricultural products are the basis of the local commerce and are consumed, sold or exchanged (Dirac Ramohavelo 2009). According to the modern law (Dirac ramohavelo, 2009), all forests in Madagascar belong to the State but farmers are allowed to use the forests. The cleared forests and fallows, which become secondary forests, are considered as freehold and belong to those who cleared the land, according to common law (Réau 2003). Genini (1996) described how natural and secondary forests are cleared during the cold and dry season (June–September) with consecutive gathering of logs and branches in piles around larger trees. The wood is dried during several weeks and finally burnt at the end of the dry season (in October). Fire destroys practically all vegetation except big baobabs and tall crowned trees. For two to three years, people plant maize on areas cleared this way (called: *hatsake*) and then cassava and groundnuts (République de Madagascar 2006). This type of farming does not require any maintenance until harvesting. It benefits from fertilization by the burnt vegetation and yields about two tons of maize per hectare. Only a small fraction of the dead un-burnt wood is used for fencing or firewood, the majority is left to rot.

The maize production decreases by 80% after four years of culture on the same plot (Réau 2002). As a consequence, these plots are cultivated with cassava or groundnuts, and then abandoned (called "*monka*") because of declining fertility, but also because of the increasing need for weeding. Some farmers limit their cyclic activities to secondary surfaces, re-using plots of various ages of abandonment, but others extend part of their cultivation into the natural forest. Each family clears between 0 and 2 ha per year (including natural and secondary forests) and the average cultivated surface is about 0.86 ha (Dirac Ramohavelo 2009). Fire is also applied on cultivated lands between harvests, and not only in forested vegetation. These slash and burn methods lead to significant losses of nutritive elements in the soil and change the floristic composition (Genini 1996; Milleville et al. 2000). In eastern Madagascar, Pfund (2000) highlighted the importance of soil–vegetation patterns in slash and burn cultivation systems and found some correlations between the elements (nitrogen, phosphorus and potassium) contained in soil and in vegetation. Generally, the fewer elements found in the soil, the higher their content in the vegetation. Furthermore, he found that the biomass produced by fallow land contributed significantly to soil fertility and was thus a determinant of the farming cycles. The elements nitrogen, phosphorus, potassium, calcium and magnesium in the above ground living biomass increased linearly with the age of the fallow (Toky 1983). In the primary dry deciduous forest of south-western Madagascar, Raherison et al. (2005) determined the composition and quantities of nutrients in biomass to verify whether the dry forest had similar physiological characteristics as other dry ecosystems of the world despite its unique biodiversity and endemism.

During slash and burn, C and N transfer into the atmosphere and contribute as greenhouse gases as CO_2 and NO_2 (Palm et al 2000). Minerals such as Ca, Mg, K, Na, P remain as ashes on the soil surface and are incorporated into soil by rainfall and cultivation (Giardina 2000).

Our general aim was to study the amount of minerals released into the soil after slashing and burning of aboveground biomass and thus the potential contribution to soil fertility. In a previous paper (Raharimalala et al. 2010) we presented the soil vegetation patterns using basic soil properties and concluded that fields older than 20 years have recovered sufficiently to be re-used as agricultural land. We reported in another paper (Raharimalala et al. 2011, submitted) the pattern of above ground biomass of ligneous and herbaceous vegetation in function of age of abandonment. We found that the quantity of total biomass increased with age of abandonment, reaching 72 t/ha after 40 years of abandonment and that some species such as *Fernandoa madagascariensis*, *Diospyros perrieri*, *Dalbergia sp.*, *Poupartia sylvatica*, *Tarenna sericea*, *Xeromphis sp*, *Phylloctenium decaryanum*, *Stereospermum euphorioides and Croton greveanum* contributed mostly to biomass. *Poupartia sylvatica* appeared to be a key player in the secondary vegetation since it had the highest biomass shortly after 30 years of abandonment.

The goal of the paper is to quantify the amount of nutrients potentially entering the soil in the form of Ca, Mg, K, Na and P after biomass burning, and the C and N released to the atmosphere. The questions are: (i) what are the nutrient concentrations in the different parts of the trees (stem, branches, leaves)? (ii) How do the different tree species differ with respect to nutrient release in the ashes? (iii) How is the pattern of potential nutrient release in plots of different age of abandonment? (iv) what are the carbon and nitrogen quantities released to the atmosphere during the burning process?

4.2. Materials and methods

4.2.1. Study site

The study site (about 1000 ha) is located in Andranolava in south-western Madagascar, 75 km north of Morondava (Central Menabe) near the well-known Kirindy forest (Sorg et al 2003) and the village of Beroboka. In the northern part, the area is characterized by old sisal plantations, the southern part is delimited by the Andranolava river, the eastern part by the Kirindy forest, and the western part by littoral forest.

The climate of Central Menabe is classified as tropical dry with 2 distinct seasons: a rainy season (November to March) and a dry season (April to October) (Sorg and Rohner 1996).

Data from metereological office (2000-2006) (Rakotondrabe 2007) show that the average annual temperature is 26°C, with a relatively cool period from June to August. Average total precipitation is 791 mm per year. The study area can be classified into the world's tropical dry forest (Murphy and Lugo 1986). Vegetation is dominated by dry deciduous forests of various types as described in Koechlin et al. (1997).

Red and yellow soils were classified by Felber (1984) and Rohner and Sorg (1986) as "red and yellow soils of the luvisols ferric" category, and can be named according to WRB: "lixisols" For this study the yellow soils were chosen. They have higher pH and C/N ratios and are preferred by farmers for cultivation (Raharimalala et al. 2010).

4.2.2 Biomass estimation

4.2.2.1 Plot selection

We selected 30 plots across 6 age classes on yellow soils according to the age of the culture abandonment. These plots were chosen in homogenous vegetation patches (see also Raharimalala et al. 2010). Each class of age had five replicated plots taken randomly across the entire area of study. Age classes 1 to 5 years and 6 to 10 years were surveyed on plots of 16 m^2, age classes 11 to 20 and 21 to 30 years on plots of 64 m^2, and age classes of 31 to 40 and more than 40 years on plots of 256 m^2. The age of the "*monka*" (abandoned surface) was estimated by a local guide who has already worked with many scientists in the area and who was a former guide in the Kirindy forest. This information was cross-checked by consulting local farmers.

4.2.2.2 Biomass measurements for tree species and plots

We numbered all individual trees (1101 trees in 60 species) which had reached breast height and wood climbers in the plots. We measured circumference at breast height (or girth breast height) and visually estimated the height after training with a clinometer on isolated trees, considering 4 growth types (see details in Raharimalala et al. 2011, submitted). For fresh biomass measurement, we used for tree selection of each species in each age of abandonment classes and growth type, a median individual in classes using height and circumference (see Raharimalala et al. 2011, submitted). We selected 433 trees representing 60 species which we cut at ground level. The above ground fresh biomass was weighed separately for stems, branches and leaves and the dry biomass calculated after correction for water content (see details in Raharimalala, et al. 2011, submitted). For calculating plot scale tree biomass, we identified the class constructed by means of circumference and height of each individual tree in the plot and attributed it the biomass of the corresponding cut. Then we measured the trees with respect to species, growth type and age class. Finally the results give for each plot the dry (oven dried, ODB) biomass of stem, branches and leaves of the different species, as well as the total biomass (see Raharimalala et al. 2011, submitted).

4.2.3. Estimation of nutrients

4.2.3.1. Tree sample selection for nutrient content and sample preparation

We selected the 28 tree species with the highest relative frequencies in the inventory of all plots. For each of the species, we selected 3 trees (replications) near the plot with the highest number of trees of the considered species and which had an average circumference. At the end of the dry season, we cut each tree and from these 84 individuals we selected 3 morphological parts: stem, branches and leaves stripped from the branches. The 3 parts were dried in the oven for 30 days at 60°C (ODB) prior to further processing.

Between 80 to 100 g of oven-dry stem and branches were grinded using “Broyeur Axt Rapid 2000” first, and then “Mortar grinder Pulverisette 2–Fritsch” to yield a powder of 0.2 mm. About 50g of air-dried leaves were grinded directly with the “Mortar grinder Pulverisette 2-Fritsch”. As the samples had been taken at the end of the dry season, some plants had already lost their leaves, so we had only 15 trees with leaves on. Overall, 71 samples were analysed.

4.2.3.2. Nutrient analysis

For carbon and nitrogen, we took 5 to 10 mg of plant material powder, which was analyzed by combustion with an “Eager 200” analyser. This method is based on the complete and instantaneous oxidation of the sample by “flash combustion”, which converts all organic and inorganic substances into combustion products. Results are expressed as percentages of C and N in the dry material.

For the analysis of calcium, magnesium, potassium, sodium and phosphorus in ashes, we took 1 to 5 g of plant material powder, which we burned in a crucible at 450°C during 3 hours. We then dissolved the residue with 20 ml HCl 1M and heated up the solution to 90°C for 1h. After the solution had cooled down, we completed to 100ml with H_2O milliQ. After decantation of a 50 ml sub-sample, we filtered 10 ml of the obtained solution. Elements were analyzed with an inductively coupled plasma-optical emission (ICP-OE-9000). The results are given in mg/l concentration. Conversion in percentage values was obtained by multiplying the concentration (mg/l) by the volume of the sample (50 ml) divided by the dry weight of the sample in grams.

4.2.4. Nutrient in the biomass and plot scale

The nutrient percentage concentration obtained for each species and for each part, stems, branches and leaves, was multiplied by the corresponding amount of oven dry biomass of each species (see above and Raharimalala et al. 2011, submitted). For species that were not sampled for nutrient content but for which biomass data were available (32 species with less biomass), we applied the mean concentration values obtained for stems, branches and leaves with the 28 analysed species.

Finally the results are the amount of the different chemical elements in kg/ha for the most frequent species, for stems, branches and leaves, and for the entire plots.

4.2.5. Statistical analyses

Principal component analysis (PCA) was used to explore the overall variability of samples of stems, branches and leaves of 28 species described by their chemical elements. Differences between mean concentrations of chemical elements between stems, branches and leaves and between classes of age of abandonment were tested with Tukey-tests

4.3. Results

4.3.1.Nutrient concentration in plant material and ashes

The PCA analysis (**figure 8**) shows that the 71 samples (28 species for stems and branches and 15 species for leaves) described by 8 chemical variables split in three distinct groups along the first axis, with a clear separation between stems, branches and leave. Concentration of Mg, K, Na, N and P are lowest for stems and highest for leaves. These variables are all highly correlated with the ash content. C and Ca are more so correlated with axis two, but the two variables are only weakly correlated. **Table VIII** shows that the concentration of all chemical elements (except C) is highest in the leaves. For stem and branches, the ranking of the elements is Ca>K>Mg>Na>P, for leaves it is K>Ca>Mg>P>Na. For P, K and Mg, the difference between stems, branches and leaves are significant ($p<0.001$). For Na, the difference between stems and leaves is significant ($p<0.006$), but the differences between stem and branches and between branches and leaves are not significant. For Ca, there are no significant differences between stems, branches and leaves**.**

Table IX gives the concentration of chemical elements in ashes for the 9 species that had a mean biomass in any one of the age classes higher than 1 t/ha and for each tree part (stem, branches and leaves). *Croton greveanum* has the highest Ca concentration in stem, *Dalbergia sp* has the highest P concentration in leaves, *Diospyros perrieri* has the highest Ca concentration in branches and leaves, *Fernandoa madagascariensis* has the highest Na, K and Mg concentration in leaves, *Phylloctenium decaryanum* has the highest P concentration in stems and branches, and the highest Mg concentration in branches, *Poupartia sylvatica* has the highest Na concentration in stem and branches, *Stereospermum euphorioides* has the highest K and Mg concentrations in stem, and *Xeromphis sp* has the highest K concentration in branches.

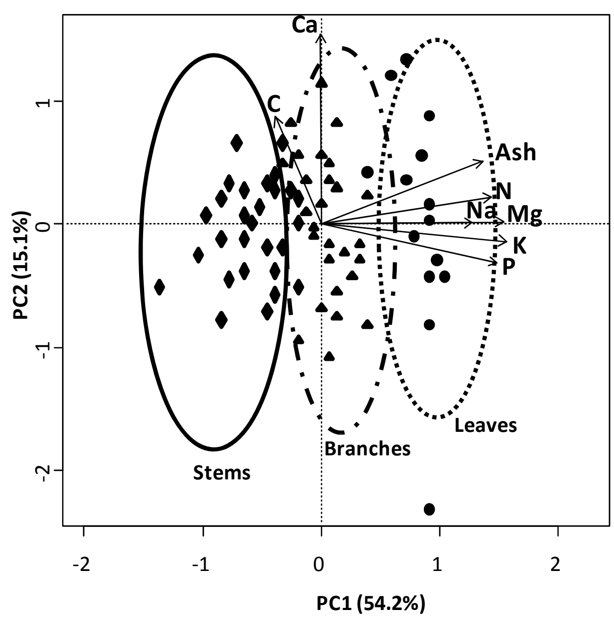

Figure 8 : Scatter plots of PCA analysis of all values (28 species, each for stem, branches and leaves) related to chemical variables (C, N, P, K, Ca, Na, Mg)**.**

Table VI : Overall concentration of chemical elements in ashes and plant material of stems, branches and leaves (%ODB). Mean, standard deviation and coefficient of variation are given.

	Parameters	Variables (% dw) for ashes					% dw for plant material	
		P	Na	Ca	K	Mg	N	C
Stem	Mean	0.019	0.055	0.747	0.280	0.065	0.558	46.284
n=27	CV	0.407	0.369	0.588	0.500	0.497	0.315	0.036
	Std error	0.002	0.004	0.085	0.027	0.006	0.034	0.322
Branches	Mean	0.038	0.075	1.059	0.533	0.116	0.861	46.303
n=27	CV	0.306	0.396	0.895	0.516	0.384	0.311	0.055
	Std error	0.002	0.006	0.183	0.053	0.009	0.052	0.495
Leaves	Mean	0.122	0.109	1.081	1.660	0.231	2.332	45.335
n=15	CV	0.481	0.310	0.771	0.409	0.225	0.312	0.188
	Std error	0.015	0.009	0.215	0.175	0.013	0.188	2.207

Table VII : Concentration of mineral elements in the ashes (% ODB) of the 9 species that have a mean dry biomass in any of the age of abandonment classes higher than 1t/ha and for their stem, branches and leaves. The mean values for all species (n=27) are given for comparison

Tree species	Part of tree	**P(%)**	**Na(%)**	**Ca(%)**	**K(%)**	**Mg(%)**
Croton greveanum						
	Stem	0.016	0.066	1.718	0.216	0.056
	Branches	0.027	0.120	0.956	0.450	0.052
	Leaves	nd	nd	nd	nd	nd
Dalbergia sp						
	Stem	0.018	0.044	1.162	0.185	0.102
	Branches	0.037	0.054	0.231	0.370	0.164
	Leaves	0.196	0.084	0.337	2.306	0.260
Diospyros perrieri						
	Stem	0.029	0.040	1.055	0.298	0.058
	Branches	0.040	0.051	1.219	0.302	0.099
	Leaves	0.042	0.112	2.232	2.172	0.193
Fernandoa madagascariensis						
	Stem	0.024	0.046	0.417	0.501	0.057
	Branches	0.023	0.059	0.645	0.768	0.105
	Leaves	0.158	0.118	0.506	2.343	0.272
Phylloctenium decaryanum						
	Stem	0.040	0.079	0.377	0.375	0.058
	Branches	0.058	0.106	0.596	0.820	0.201
	Leaves	nd	nd	nd	nd	nd
Poupartia sylvatica						
	Stem	0.023	0.110	0.400	0.514	0.088

	Branches	0.043	0.135	0.570	0.708	0.131
	Leaves	nd	nd	nd	nd	nd
Stereospermim euphorioides						
	Stem	0.025	0.066	0.191	0.529	0.166
	Branches	0.035	0.076	0.102	0.487	0.095
	Leaves	0.122	0.109	1.081	2.172	0.231
Tarenna sericea						
	Stem	0.022	0.046	0.413	0.251	0.043
	Branches	0.035	0.040	0.760	0.426	0.136
	Leaves	nd	nd	nd	nd	nd
Xeromphis sp						
	Stem	0.018	0.049	0.585	0.374	0.107
	Branches	0.038	0.072	0.167	1.292	0.176
	Leaves	nd	nd	nd	nd	nd
Mean of all species	stem (n=27)	0.019	0.055	0.747	0.280	0.065
	branches (n=27)	0.038	0.075	1.059	0.533	0.116
	leaves (n=15)	0.122	0.109	1.081	2.172	0.231
	nd: no data					

4.3.2.Nutrient amount in the ashes of burnt biomass in the different age classes of abandonment and for the most abundant species

The overall amount of chemical elements in the biomass is given in **Table X**. In the ashes, Ca and K show the largest quantities in all classes of age of abandonment. Ca has 2.34 kg/ha in plots of 1 to 5 years, up to 484.55 kg/ha after 40 years of abandonment. For K, these values are respectively 2.27 kg/ha and 296.37 kg/ha. After 40 years, P reaches 19.03 kg/ha, Na 43.20 kg/ha and Mg 54.67 kg/ha. For Ca and K, the increase is significant after 20 years ($p<0.00001$), for Mg, P and Na, it is significant after 30 years. For the 9 species that had a mean dry biomass higher than 1 t/ha in any of the classes of age of abandonment, the increase of nutrient content is given in **figure 9**. *Poupartia sylvatica*, *Tarenna sericea* and *Dalbergia sp* and *Diospyros perrieri* are the species that provide the highest amounts of minerals after some decades. *Poupartia sylvatica* has already after 30 years a high contribution for all elements. *Dalbergia* has an early contribution for Ca and K, followed by a slight decrease, whereas *Tarenna sericea* reaches levels of *Poupartia* after 40 years, except for P, which is then higher, and for Na, which is then lower. The N content of plant material increases from 2.81 kg/ha in the plots 1-5 years, up to 448.21 kg/ha in plots of more than 40 years. For C, these values are respectively 196.61 kg/ha and 31’506.78 kg/ha.

Table VIII : Mean amounts (kg/ha) of chemical elements contained in ligneous vegetation (stems, branches and leaves) in ashes and plant material in each class of age of abandonment (n=5 plots) with its standard error (60species)

Age of abandonment	Nutrients in the ashes (kg/ha)					In the plant material (kg/ha)	
	P	Na	Ca	K	Mg	N	C
1- 5 years	0.16±0.10	0.22±0.14	2.34±1.39	2.27±1.46	0.36±0.21	2.81±1.80	196.61±134.30
6 - 10 years	0.35±0.10	0.93±0.42	9.73±4.93	5.79±0.85	1.08±0.37	7.66±2.23	551.02±222.92
11 - 20 years	0.95±0.15	1.71±0.24	24.60±3.62	16.37±3.30	2.49±0.37	24.21±3.86	1’159.42±128.83
21 - 30 years	5.95±0.89	10.46±1.77	143.71±21.08	87.89±18.32	15.29±2.71	142.14±21.26	8'154.98±1'399.21
31 - 40 years	12.62±1.50	29.43±4.63	364.46±79.28	201.66±26.97	40.16±5.34	305.81±41.60	18'842.37±2'912.59
More than 40 years	19.03±1.83	43.20±4.78	484.55±59.31	296.37±23.44	54.67±5.18	448.21±41.38	31'506.78±3'443.49

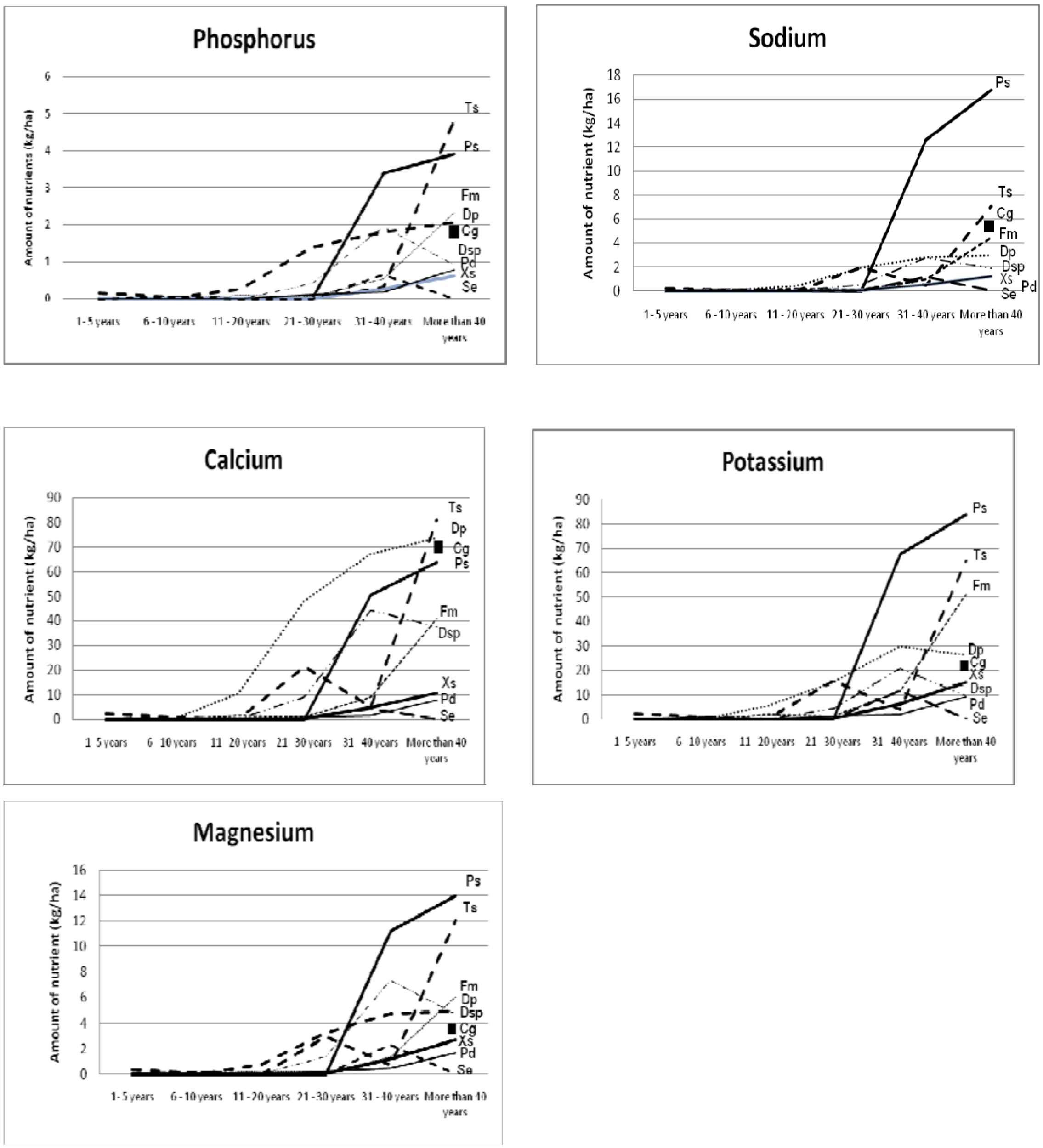

Figure 9 : Amounts (kg/ha) of mineral nutrients (P, Na, Ca, K and Mg) in the ligneous vegetation that have dry biomass (ODB) > 1 kg/ha in any one of the classes (Ts: *Tarenna sericea*, Ps: *Poupartia sylvatica*, Fm: *Fernandoa madagascariensis*, Dp: *Diospyros perrieri*, Cg: *Croton greveanum*, Dsp: *Dalbergia sp*, Xs: *Xeromphis sp*, Pd: *Phylloctenium decaryanum*, Se: *Stereospermum euphorioides)*

4.4. Discussion

4.4.1.Comparison of mineral concentration in above ground biomass of different tropical forests and in dominant tree species

Overall, the concentrations found in our study are comparable with data found in other tropical forests **(Table XI**). If one considers our values for stems, they are of the same order of magnitude as values found in the literature, except for Na, which was higher in our study (but only one other reference available). The references given by Brand and Pfund (1998) are noticeably higher for K and Mg, and lower for Ca. These concentrations might depend on annual rainfall (dry or rain forest) and on the type of forest (primary or secondary forest). It appears that in the rainforest of Madagascar studied by Brand and Pfund (1998), the nutrient concentration is much higher (about 3 times higher for P and Mg, 5 times higher for K). With respect to the ranking of elements, it appears to be similar everywhere, except that in the rain forest of Madagascar described by Brand and Pfund (1998), K is higher than Ca, whereas it is the reverse in the other forests.

The 9 species that have a mean dry aboveground biomass higher than 1 t/ha in any of the age classes have generally higher nutrient concentrations as compared to the average concentration of all analyzed trees (**Table XI**). Among these species, some have the highest concentration of P in stem and branches (*Phylloctenium decaryanum)*, of Na in stem and branches (*Poupartia sylvatica)*; of Ca in stem (*Croton greveanum)* and branches *(Diospyros perrieri)*, of K in stem (*Stereospermum euphorioides*) and branches (Xeromphis), and of Mg in stem *(Stereospermum euphorioides)* and branches (*Phylloctenium dacaryanum*)

Table IX : Mineral concentration in the above ground biomass (% ODB) for some tropical forests

Forest and Location	Annual rainfall	Stade	P	K	Ca	Na	Mg	Ranking (References)
Dry forest, Chamela	750mm	Secondary forest, >100 years	0.025	0.31	1.4	nd*	nd	Ca, K and P (Giardina et al 2000)
Pernambuco, Brazil	803 mm	Secondary forest, 16 years	0.044	nd	1.03	nd	nd	Ca and P (Kauffman et al 1993)

Dry forest, Madagascar	about 700 mm	Primary forest	0.04	0.33	1.21	0.006	0.09	Ca, K, Mg, P and Na (Raherison et al 2005)
Dry forest, Madagascar	**791mm**	**Secondary forest, 40 years**	**0.179**	**2.985**	**2.887**	**0.239**	**0.431**	**Ca, K, Mg, P and Na, our study***
Semi-deciduous forest, Ghana	1650 mm	Secondary forest, 30-50 years	0.02	0.25	0.68	nd	0.1	Ca, K, Mg and P (Greenland and Kowal 1960)
East Madagascar	2000-3500mm	Fallow, 5 years	0.052	1.42	0.37	nd	0.23	K, Ca, Mg and P, (Brand and Pfund 1998) (after calculation)

*nd: no data **First value is for stem, the second for branches and the third for leaves.

4.4.2.Comparison of amount of mineral released in ashes after above-ground biomass burning in some tropical regions

The amount of nutrients increased with the age of abandonment **(Figure 9**), accordingly to the increase of biomass (Raharimalala et al. 2011, submitted). The nutrient uptake increases generally linearly during the period of rapid growth and diminishes at maturity (Shanmughavel et al 2001; Pritchett 1979; Hilton 1987). In our study, this forest maturity has not yet been achieved after 40 years of abandonment.

Ca and K have the highest yield after 40 years of abandonment which corresponds with what was found by Raherison (2005) in another dry forest in Madagascar, which was considered as primary forest (**Figure 10).** In this primary dry forest, Ca was about 3 times higher as compared to our secondary vegetation, but Na was about 6 times lower. Compared to other tropical forests (all in wetter climates), our data appear to be of the same order of magnitude (e.g. primary forest in Brazil, Kauffmann et al. 1995) or higher (secondary forest in Côte d’Ivoire, Van Reuler and Janssen 1993, and in eastern Madagascar, Brand and Pfund, 1998).

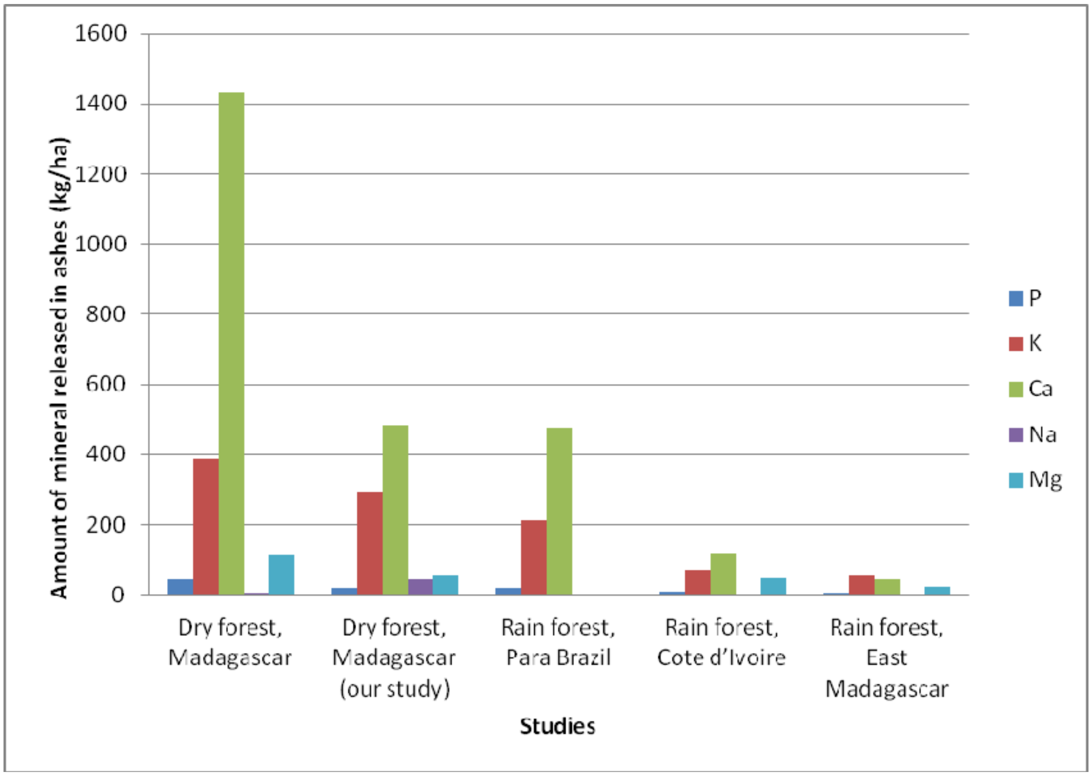

Figure 10 : Amount of minerals released in ashes (kg/ha) by above-ground biomass after burning

4.4.3.C and N stock in the dry aboveground biomass before burning and their quantity released to the atmosphere after burning

Compared to other tropical forests in wetter climates, our secondary dry forests have an order of magnitude lower carbon stock (31.5 t/ha compared to up to about 300 t/ha in Mexico and Cameroon) and this difference remains important even when comparing only secondary forests (**Table XII**). Less data are available for nitrogen, but they are better comparable in the different types of forests (e.g. 0.45 t/ha in our secondary dry forest, 0.55 t/ha in a 16 years old secondary dry forest in Brazil, 2 t/ha in a primary forest in wetter climate in Mexico).

Most of carbon and nitrogen are lost during the burning process. Some studies quantified C and N released to the atmosphere (**Table XIII**). The losses range from 89 to 98% for C and from 60 to 98% for N in the different forest types. These differences can be explained by the method of burning temperature. In Costa Rica (Mackensen et al, 1996), it was reported that the temperature ranged from 204 to 1371°C in different heights (0, 1, 2 and 3.5m) using temperature sensitive paints, and in Pernambuco, Para-Brazil (Kauffman et al, 1993), the measured temperature ranged from 38°C to 816°C of temperature sensitive paints in thin lines along 5*8 cm mica sheet. This aspect of slash and burn cultivation has a global impact since it has been shown that the carbon and nitrogen released into the atmosphere during forest fires contribute to CO_2 for 17.3% and to N_2O for 7.9%, whereas fossil fuel contributes to global anthropogenic greenhouse gases emissions for 56.6% (http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf).

Table X : Carbon and nitrogen stocks in un-burnt above-ground biomass (t/ha) in some tropical forests

Location	Annual rainfall	Stand (age)	quantity of C	Quantity of N	References
Chamela, Mexico	750mm	>100 years	nd*	0.944 t/ha	Giardina 2000
Pernambuco, Brazil	803mm	Secondary forest, 16 years	nd	0.551 t/ha	Kauffman et al 1993
South West Madagascar	791mm	Secondary forest, 40 years	31 tC/ha	0.448 tN/ha	Our study
Los Tuxtlas Region, Mexico	>4000mm	Primary forest	300 tC/ha	2 tN/ha	Hughes et al 1999
Los Tuxtlas Region, Mexico	>4000mm	Secondary forest (4-30 years)	20-200 tC/ha	0.072-1.167 t/ha	Hughes et al 1999
Cameroon	>1600mm	Primary forest	308 tC/ha	nd	Kotto –Samé et al 1997
SC of Brazil	2000-2250mm	Primary forest	200 tC/ha	nd	Fujisaka et al 1998
Cameroon	>1600mm	Secondary forest	130 tC/ha	nd	Kotto -Samé et al 1997

*nd:no data

Table XI : Percentages of carbon and nitrogen losses to atmosphere during the burning process in some tropical forests

Location	Annual rainfall	Stand (age)	Percentage of C released to the atmosphere	Percentage of N released to the atmosphere	References
Chamela, Mexico	750 mm	>100years	nd*	97%	Giardina 2000
Pernambuco, Brazil	803 mm	Secondary forest, 16 years	nd	97%	Kauffman et al 1993
Para, Brazil	2000-2250 mm	Secondary forest, 40 years	94-98%	95-98%	Mackenzen 1996
Cameroon	>1600 mm	Primary forest	89%	nd	Kotto –Samé et al 1997
Para-Brazil	2000-2250 mm	Secondary forest, 40 years	nd	60%	Hölscher 1996
East Madagascar	2000-3500 mm	Fallow , 5 years	98%	95%	Brand and Pfund 1998

*nd:no data

4.4.4. Potential nutrient release into the soil from ashes and plant uptake

In tropical regions where slash and burn is a common practice, most of the nutrients required for crops are derived from ashes of burned vegetation (Kalpage 1974; Pimentel and Heichel 1991; Ramakrishnan et al 1992). Furthermore, the large amount of ashes deposited after high intensity fires is likely to be the major cause of increased soil pH due to the acid neutralizing capacity of ash and to consumption of hydrogen ions during the combustion of organic acids in the soil and forest floor (Nye and Greenland, 1964). In acidic soils, the increasing pH may also increase the soil concentrations of extractable Ca, K, Mg and P and their availability, and induce microbial activity and nutrient mineralization rates (Giardina et al 2000; Pritchett and Fisher 1987 and Kennard and Gholz 2001). Both Matson et al. (1987) and Montagnini and

Buschbacher (1989) attributed increased nitrate concentrations to enhanced nitrification rates following slash and burn in Costa Rica and Venezuela.

The high amounts of minerals in the ashes have potentially the capacity to be taken up by the soil and accumulate (Shrivastava and Ulrich 1978), but a substantial amount of cations are generally leached out (Toky and Ramakrishnan, 1983). Burning converts slashed vegetation into ashes that are deposited onto the soil and incorporated into it by rainfall and cultivation (Nye and Greenland 1960, Sanchez et al 1991). In this best case, the nutrients contained in the ashes become fully available to plants and add to the soil nutrient pool (Nye and Greenland 1960; Seubert et al. 1977, Van Reuler and Janssen 1994). Nevertheless, ashes may be lost by wind and water erosion and nutrients partly leached. A loss of nutrients of 10 to 40% at driest sites, and of 40 to 60% in regions with 500-1200mm rainfall was observed by Chadwick et al (2003). In volcanic soils, and in dry and monsoonal climates, an average of 49% for P, 51% for Ca and 57% for K contained in the aboveground vegetation returned to the soil (Giardina et al 2000). If we assume a return of 50% of the elements to the soil, this would give about 10 kg/ha for P, 22 kg/ha for Na, 242 kg/ha for Ca, 148 kg/ha for K and 28 kg/ha for Mg in plots of more than 40 years of abandonment, which would add to the actual soil fertility. For C and N, Mackensen et al (1996) showed that 94 to 98% of C and 95% to 98% of N were lost by volatilization and by particle and leaching exports. Taking the median values, this would leave about 17 kg/ha of N and 1260 kg/ha of C in the soil. According to the plant needs (Lebot, 2009), manihot, sweet potatoes and maize would be adequate cultures if all nutrients could be re-used.

Despite the fact that the burning of biomass contributes to increase pH and soil fertility, a gradual decline in total nutrient stock over time was observed (Nye and Greenland, 1964) and this can be explained by invasive species, weeds, and overgrazing.

Using the assumptions of Chadwick et al 2003 and Giardina et al 2000, **Table XIV** indicates the quantity of nutrients returning into the soil after losses, supposed to be between 10 and 40 %, so that 60 % to 90% will return to the soil.

Table XII : Cation quantities returning to the soil by ashes after losses (leaching, erosion and wind) **(source : Tableau X)**

Age of abandonment	Na		Ca		K		Mg	
	40%	90%	40%	90%	40%	90%	40%	90%
1- 5 years	0,09	0,20	0,94	2,11	0,91	2,04	0,14	0,32
6 - 10 years	0,37	0,84	3,89	8,76	2,66	5,99	0,43	0,97
11 - 20 years	0,68	1,54	9,84	22,14	6,55	14,73	1,00	2,24
21 - 30 years	4,18	9,41	57,48	129,34	35,16	79,10	6,12	13,76
31 - 40 years	11,77	26,49	145,78	328,01	80,66	181,49	16,06	36,14
More than 40 years	17,28	38,88	193,82	436,10	118,55	266,73	21,87	49,20

4.4.5. Adaptive management

Some species have a higher potential than others for biomass production and nutrient release in their ashes after slashing and burning. *Poupartia sylvatica* and *Tarenna sericea* have already after respectively 30 and 40 years a high contribution for most of the chemical elements, and since these species are of no particular use to farmers, they represent good target species for promoting biomass and nutrient sequestration. Other species such as *Dalbergia sp.* or *Diopyros perrieri* would also constitute interesting species, but since they provide valuable wood to local farmers, they tend to be harvested in early stages.

4.5. Conclusion

The amount of chemical elements and in particular minerals released after slashing and burning of biomass increased with age of abandonment, and after 40 years, the secondary forest did not yet reach its maturity with respect to sequestration of these elements. Nevertheless, species such as *Poupartia sylvatica* and *Tarenna sericea* constitute good candidates for a targeted forest management, which would promote a rapid rebuilding of biomass and nutrient pool for optimizing slash and burn cultivation. It remains that the potential gain of nutrients after burning depends not only on the amount and quality of ashes but also on the capacity of soils to retain and store these nutrients in forms that are readily available to the plants (Juo 1996).

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Chapter V

A handy methodology for testing wood flammability with application to fire risk assessment and optimization of slash and burn cultivation

Chapter V: A handy methodology for testing wood flammability with application to fire risk assessment and optimization of slash and burn cultivation

Abstract

1. Assessing wood flammability is important, for predicting forest fire risk as well as for identifying species that have a high potential for optimization of secondary vegetation used for slash-and-burn cultivation.

2. We propose a handy device to test wood flammability by quantifying flame and temperature kinetics. Tests were made on 6 reference European tree species including angiosperms and gymnosperms and on 26 tropical tree species commonly found in slash-and-burn cultivation of the dry forest of southern Madagascar. The combustibility, sustainability and consumability of crushed wood chips of each species was characterized by means of 21 variables and analysed with a redundancy analysis.

3. Three main groups of species can be distinguished according to flammability, with reference to common European trees: *Fagus*–type woods, which have a high combustibility but a low sustainability, *Picea*-type woods that have low combustibility but high sustainability, and *Quercus*-type woods which have a very high sustainability. Some tropical tree species had typical features according to these types, others had intermediate characteristics.

4. Species such as *Poupartia silvatica* could play a key-role in slash-and-burn cultivation in Madagascar since they produce much biomass and high quality ashes for sustaining short-term cyclic cultures. Nevertheless, considering their flammability properties related to Quercus-type, an efficient burning and ash production requires complementary species that have long lasting burning with larger flames.

5.1. Introduction

Woody fuels are an important component of forests and wildlands, including live woods (i.e. tree stems, branches) and dead woods (i.e. dead trees, and debris) of various sizes (Pyne *et al.*, 1996a). If large and living woody fuels seldom burn in wildland fires and thus poorly participate to the spread of fire, they can nevertheless modify fire behaviour through wind velocity (Call and Albini, 1997), sustain fires of relatively high-intensity for a long time (Rothermel, 1993) and serve as potential source of spot fires (Pyne *et al.*, 1996a). They also provide ecosystems with postfire products such as ash and burned logs (Rothermel, 1993) and they contribute to the carbon cycling (Hollis *et al.*, 2010b). In comparison, dead woody fuels and woody debris can burn vigorously and constitute a potential threat for wildfires. Properties of woody debris such as size, water content, chemical composition and in particular contents in cellulose, lignin, and hemicelluloses, are important factors for flammability, fire spread, and ecosystems functioning (Pyne *et al.*, 1996b). Woody fuels are also sources of combustion products available to agriculture. In slash-and-burn agriculture, a practice commonly used in many poor countries of Africa and Asia, trees are felt and left on the soil for drying before being burnt for gaining ashes for short term cultures (Genini 1996, Raharimalala et al. 2010, Milleville et al. 2000, autre reference en Asie). In these regions optimization of cultivation is important and leads to the re-use of secondary vegetation, notably postfire vegetation. Some farmers limit their cyclic activities to secondary surfaces, re-using plots of various ages of abandonment, but others extend part of their cultivation into the natural forest, which represents an ongoing threat to biodiversity. With respect to the assessment of fire hazard, it is of interest to characterize the flammability of woody fuels. Forest managers would prefer low- or non-flammable species, i.e. species that ignite with difficulty, that burn slowly and incompletely while producing low-intensity fires (e.g. Liodakis *et al.*, 2011). Conversely, farmers in countries where slash-and-burn cultivation is common practice would favour woody species that produce much biomass, yield rich ashes and burn well and rapidly (Raharimalala et al. 2010, autre reference en Asie). In this latter case, flammability properties are important for management of secondary surfaces and selection of best-adapted trees for subsequent slashing and burning.

It is thus of major interest to assess the flammability of the main trees or woody shrub species in an ecosystem to better understand their potential impact on fire behaviour and on the potential post-fire uses such as agriculture or forestry. Flammability has been defined as having four components: ignitability, sustainability, combustibility, and consumability (Anderson 1970; Martin et al. 1994). Ignitability is the time to ignition once a material is put in contact with a source of ignition (Anderson 1970). Sustainability is the duration during which fuel particles will combust, with or without a constant ignition source (Anderson 1970). Combustibility refers to how rapidly or intensely a fuel burns (Anderson 1970; White and Zipperer, 2010), and consumability is the quantity of fuel that is consumed (Martin et al. 1994). Several combinations of these four components may arise from flammability experiments and allow distinguishing types of flammability among woody species (Dimitrakopoulos, 2001; Behm *et al.*, 2004). Some species have been proved to ignite and to sustain very high energy for a short time whereas others may ignite poorly but last for a long time (Dimitrakopoulos and Panov, 2001). In the past decades, research on wildland fuel flammability has focused on ignitability and combustion of forest litters and leaves with the search for ignition thresholds as a function of fuel moisture content (FMC) (Dimitrakopoulos and Panov, 2001; Liodakis *et al.*, 2002; Dimitrakopoulos *et al.*, 2010; Curt *et al.*, 2011). Three intrinsic characteristics of litter and leaves have been shown to influence flammability: the percent of cellulose, hemicelluloses and lignin, the volatile concentration, and the silica-free mineral content. The proportion of cellulose, hemicelluloses and lignin in woody tissues affect fuel flammability since each of these components has a specific temperature threshold for combustion and volatilization (Alessio *et al.*, 2008; De Lillis *et al.*, 2009; Ormeño *et al.*, 2009). The presence and the abundance of volatiles (flavonoids, waxes, terpens, oils, and resins) has been shown to increase ignitability and combustibility (Philpot, 1970; Dimitrakopoulos, 2001; Dimitrakopoulos and Panov, 2001). The mineral content of wood particles and especially the non-flammable silica portion is expected to decrease the maximum combustion rate and to increase post-fire ash residues (Philpot, 1970). In contrast, very few studies addressed the flammability of wood particles and no data exist for European and alpine tree species, nor for woody species in Madagascar. Woody fuel consumption has been studied for some ecosystems such as Australian eucalypts (Hollis *et al.*, 2010a). Some models have been developed to estimate the woody fuel consumption (e.g. CONSUME, Prichard *et al.*, 2005) or the postfire effects on the ecosystem (FOFEM, Reinhardt *et al.*, 1997).

In this paper we propose a simple and handy methodology to test wood flammability by quantifying flame and temperature kinetics. We use 6 European tree species as a reference to compare to 26 tropical tree species commonly found in slash-and-burn cultivation of the dry forest of southern Madagascar. The aim is to identify species that have a high potential for management and optimization of secondary vegetation for this traditional cultivation practice.

5.2. Materials and Methods

5.2.1.Wood sample preparation

Twenty seven tropical tree species from Central Menabe (Madagascar) and six common European tree species have been collected. The tropical species correspond to the most frequent species that were found in a vegetation survey on slash and burn cultivation plots that have been abandoned for some decades (see also Raharimalala et al. 2009). The European species were selected so as to provide a reference from common hardwoods or angiosperms (*Fagus sylvatica* L., *Quercus robur* L., *Malus communis* Poir., *Fraxinus excelsior* L., *Tilia europea* L.) and a softwood or gymnosperm (*Picea abies* (L.) Karst). Samples were taken from trunks or large branches in case of trees branching from the base. Sticks of section 12x18 mm were then prepared with a saw and oven dried at 60^0C till constant weight. The infra-density of the wood of each species was calculated from these samples. The wood sticks were then crushed in chips of standard size and samples of 130 g were prepared for the flammability tests.

5.2.2.Oven for flammability test

The flammability test device was made from an oil barrel of 200 liters (**figure 11**). At the bottom a door was cut for introducing the samples and an opening of diameter 20 cm was cut into the lid for acting as a chimney and preventing air turbulences in the oven. The wood samples were put on a metal basket made with a sieve of 20 cm diameter and 5 cm height with a mesh of 1mm fixed on a laboratory tripod cut to 15 cm height. For tests with wood chips samples of 130 grams, a metal ring of 12.3 cm diameter and 5 cm height (volume of about 0.6 l) was laid onto the sieve to reduce the container, but for larger samples (e.g. leaves or litter) the entire sieve could be filled (about 1.6 l).

The fire temperature was recorded at 5 cm and at 30 cm above the border of the sieve (which corresponds also to the height above the sample before burning), using at each level 4 high temperature thermocouples (Mantelthermoelement K, Inconel, Roth & Co AG, Oberuzwil).

The thermocouples were introduced horizontally through holes in the oven barrel and were placed in four different directions along two perpendicular axes. The tips of the thermocouples were placed at half the distance between the centre and the border of the basket.

An infra-red camera (Simtronics, MultiFlame DM-TV6x, Mod DM TU65EU00, ICAR UVIR6, F-13400 Aubagne, France) was placed at 140 cm above the sieve, centred on the opening in the lid and on the basket placed at the bottom of the barrel.

A fen flushing air (330 m^3/h) through 8 pipes of 4 cm diameter was placed at the bottom of the oven barrel. This insured regular ventilation in the oven.

A data logger (Papierlos Schreiber 18-Kanal, PHL LAN Communicator, Roth & Co AG, Oberuzwil) recorded continuously the data of the 8 temperature sensors and the fire signal of the IR-camera.

The device was conceived so as to be easily dismantled and shipped to remote field sites, except for the oven barrel and the poles for the IR camera, which can easily be acquired on spot.

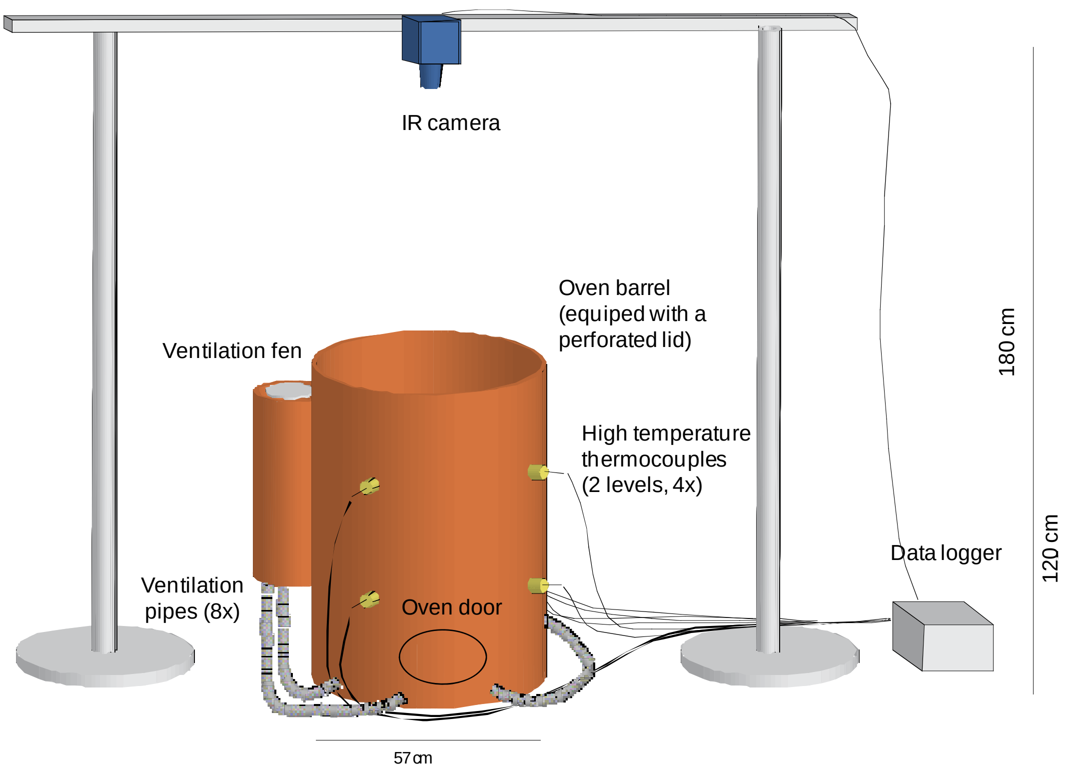

Figure 11 : Sketch of the flammability test device with oven, infrared camera and data logger

5.2.3.Flammability assessment

The wood chips were put in the basket and the basket slightly shacked for insuring regular packing. The basket and its tripod were placed in the centre of the oven, thus centred on the thermocouples and the IR-camera. We used 4 ml alcohol spilled cross-wise on the wood chips with a syringe to ignite woods. Tests with only alcohol showed that the temperature was hardly affected, neither was the IR-camera signal.

The data logger was turned on from the beginning and recorded continuously the sensors across all the burning sessions. The burning process was considered finished when the temperature dropped below 40 ^{0}C in all the thermocouples and when the IR-camera signal reached 0.88 (max. value = 4.3 volts). For most of the species, there were five replicated samples and burning trials.

After the burning process, the remaining un-burnt or partly burnt wood in the basket was sieved at 1 mm.

5.2.4.Burning curve

A software was written (available from the corresponding author) which reads the output file of the data logger and separates in different files each burning session using the minimum temperature as a cutting criterion. It generates for each burning trial a graphic with the temperature curves of each thermocouple, and another graph with the mean temperature curve for the lower (5 cm) and upper (30 cm) levels, as well as the IR-camera signal. The IR-camera signal is decomposed so as to give thresholds for large flames (4.3 volts), small flames (0.9 to 4.3 volts) and ember (0.6 to 0.9 volts). Based on this burning curve, the software calculates and writes into a file 20 variables describing the flame and temperature kinetics (**figure 12**): flame (total, large and small flames) and ember duration (minutes), time to reach the maximum temperature at lower and upper level (minutes), duration of temperature above 40^{0}C at lower and upper level (minutes), maximal temperatures and temperature at the end of flames at lower and upper level (^{0}C), slope of increase of temperature up to highest temperature (^{0}C mn^{-1}), slope of decrease of temperature after highest temperature till the threshold of 40^{0}C at lower and upper level (^{0}C mn^{-1}), slope of decrease of temperature after end of flames till the threshold of 40^{0}C at lower and upper level (^{0}C mn^{-1}), surface under the curve at lower and upper level, as a proxy for energy release

(^{0}C * min). The remaining un-burnt or badly burnt wood after sieving yields the variable ash>1mm.

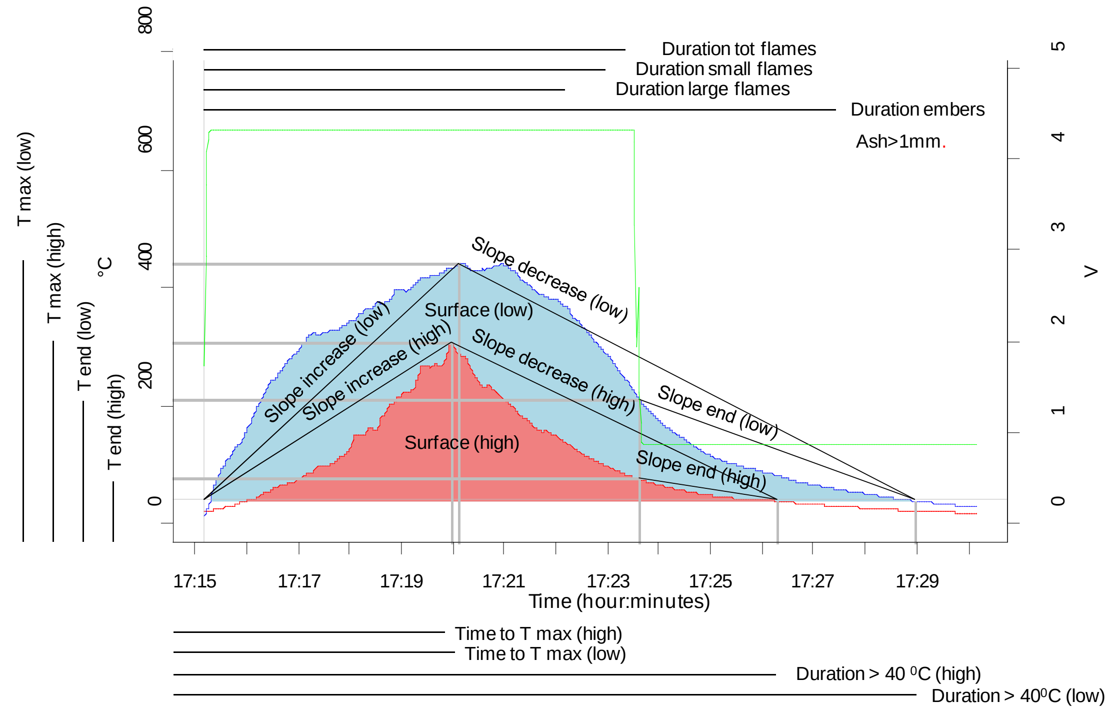

Figure 12 : Example of a burning curve (*Tilia europea*) with 21 variables describing the fire dynamics

5.2.5.Statistical methods

A file was created with the 27 tropical and 7 European trees, including the replicated samples, yielding 133 objects described by their 20 variables quantifying the flam and temperature kinetics. A Redundancy analysis (RDA) was applied after standardization of the variables. In order to remove the possible effect of ambient temperature, which could slightly vary between the burning trials, the minimum (at start) temperature was given as covariable and its effect removed before calculating the RDA. The scatter plot of axis 1 and 2 is given in **figure 13.**

5.3. Results

The flammability properties of the different tree species are graphically represented in the RDA scatter plot (**figure 13**) which gives a synthetic view of the multivariate data set composed of 21 variables of flames and temperature kinetics.

The scatter plots show a clear split of variables along axis one. Variables pointing towards the positive side of axis one indicate samples that increase temperature rapidly, that reach high maximum temperatures and have still high temperatures at the end of flames. These samples produce also temperature curves at the upper level with larger surfaces, therefore releasing much energy further away from the burning point. Variables pointing towards the negative side of axis one indicate samples that decrease slowly in temperature after their maximum and after end of flames (sharp decreasing slopes give more negative values then gentle slopes), that have a long duration of flames and in particular large flames, that sustain longer temperatures above 40^{o}C, and that leave more un-burnt particles. Axis 2 is characterized on the positive side by samples that need more time to reach their maximum temperature and which have a long duration of small flames and embers. These samples also tend to have a larger surface under the curve of the lower level, therefore much energy release near the burning point.

Some tree species are clearly linked with particular variables. Among the European species, *Fagus sylvatica* wood burns rapidly, heats up rapidly and reaches high temperatures, and then cools down rapidly (**figure 14**). The larger surface under the temperature curves indicates an important energy release. To a lesser extend *Malus communis*, *Fraxinus excelsior* and *Tilia europea* have similar properties as *Fagus*. *Picea abies* is characterized by woods that increase temperature slowly, with temperature remaining relatively low, but then decrease slowly in temperature because they sustain fires longer and with large flames. *Quercus robur* has a wood that also sustains longer fire with flames and thus has a slow decrease of temperature, but in addition it maintains temperatures above 40^{0}C for longer despite needing more time to reach maximum temperature. *Quercus* has also irregular flames with more small flames and long lasting embers, which provide more energy release near the burning point.

Tropical woods can be identified accordingly to the typical European species above. *Dalbergia sp*, *Albizia bernieri* and *Mascarenhasia lisianthiflora* show similar behaviour as

Fagus and *Malus*. *Zanthoxylum decaryi, Diospyros perrieri*, *Fernandoa madagascariensis* and *Calopyxis grandidieri* tend to burn similarly to *Picea*. *Poupartia sylvatica* has similar characteristics to *Quercus*, as do *Cordyla madagascariensis* and *Clerodendron sp*. *Xeromphis sp* and *Breonia perrieri* have intermediate characteristics between *Fagus* and *Quercus.*

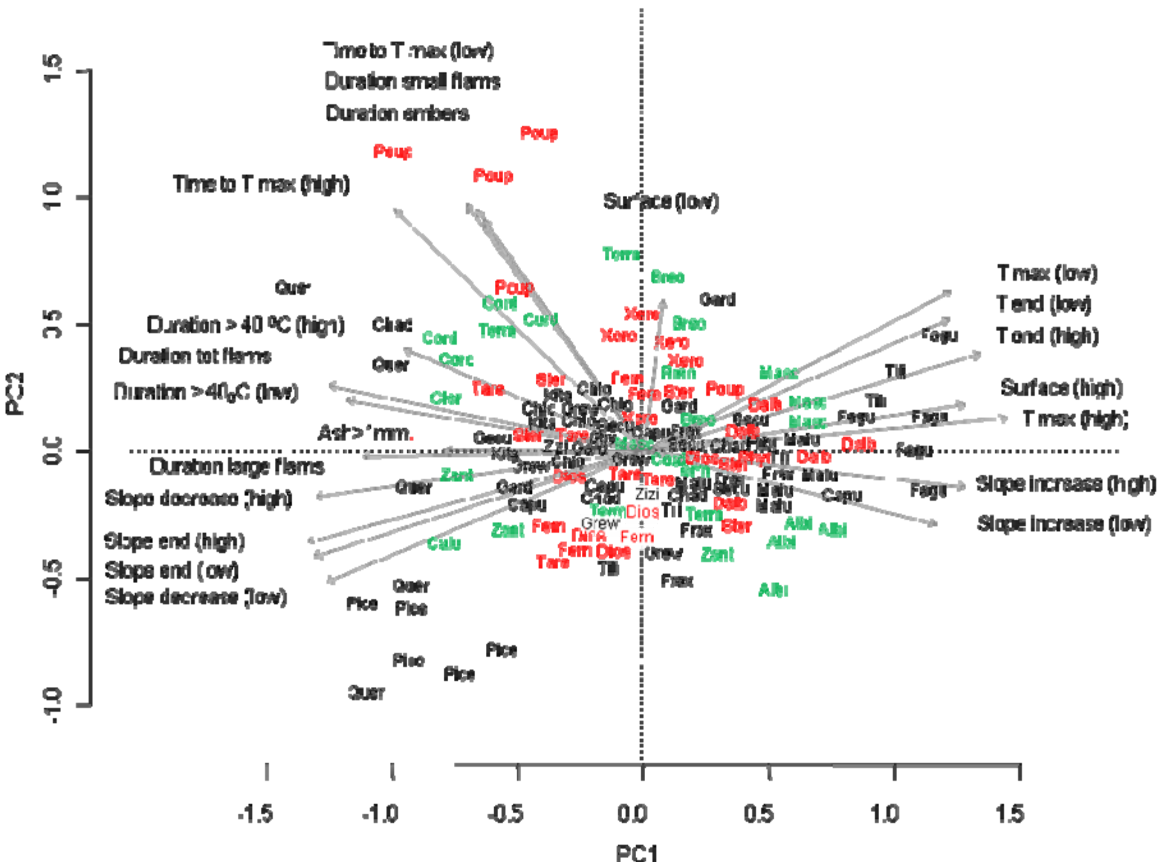

Figure 13 : Redundancy analysis (RDA) of 33 wood samples described by 20 flammability variables (see figure 3). Tests were made with 27 tropical woods of the dry forest of Madagascar and 6 common European forest species. Axis 1 (59.6%) and 2 (13%) are significant according to the Brocken stick model.

Species abbreviations are: Chlo: *Chloroxylon falcatum*, Grew: *Grewia sp*, Xero: *Xeromphis sp*, Ster: *Stereospermum euphorioides*, Breo: *Breonia perrieri*, Secu: *Securinega seyrigii*, Masc: *Mascarenhasia lisianthiflora*, Dalb; *Dalbergia sp*, Dios: *Diospyros perrieri*, Capu: *Capurodendron perrieri*, Gard: *Gardenia squamifera*, Zant: *Zanthoxylum decaryi*, Albi: *Albizia bernieri*, Tare: *Tarenna sericea*, Term: *Terminalia boivinii*, Cord: *Cordyla* *madagascariensis*, Chad: *Chadsia grevei*, Fern: *Fernandoa madagascariensis* , Kita: *Kitakitakala*, , Cler: *Clerodendron sp* , Zizi: *Ziziphus mauritiana*, Phyl: *Phylloctenium decaryanum*, Hibi: *Hibiscus macrogonus*, Stry: *Strychnos decussata*, Calo: *Calopyxis grandidieri*, Poup: *Poupartia sylvatica*, Psor: *Psorospemum androasaemifolium*, Frax: *Fraxinus excelsior*, Tili: *Tilia plathyphyllos*, Fagu: *Fagus sylvatica*, Malu: *Malus communis*, Pice: *Picea abies*, Quer: *Quercus robur***.**

Some tree species are clearly linked with particular variables. Among the European species, *Fagus sylvatica* wood burns rapidly, heats up rapidly reaching high temperatures, and then cools down rapidly (**figure 14**). The larger surface under the temperature curves indicates an important energy release. To a lesser extend *Malus communis*, *Fraxinus excelsior* and *Tilia europea* have similar properties as *Fagus*. *Picea abies* is characterized by woods that increase slowly in temperature which remains relatively low, but then decrease slowly in temperature because they sustain longer fires with large flames. *Quercus robur* wood also sustains longer fire with flames and thus has a slow decrease of temperature, but in addition it maintains temperatures above 40^0C for longer despite of needing more time to reach maximum temperature. *Quercus* has also irregular flames with more small flames and long lasting embers, which provide more energy release near the burning point (**figure 14**).

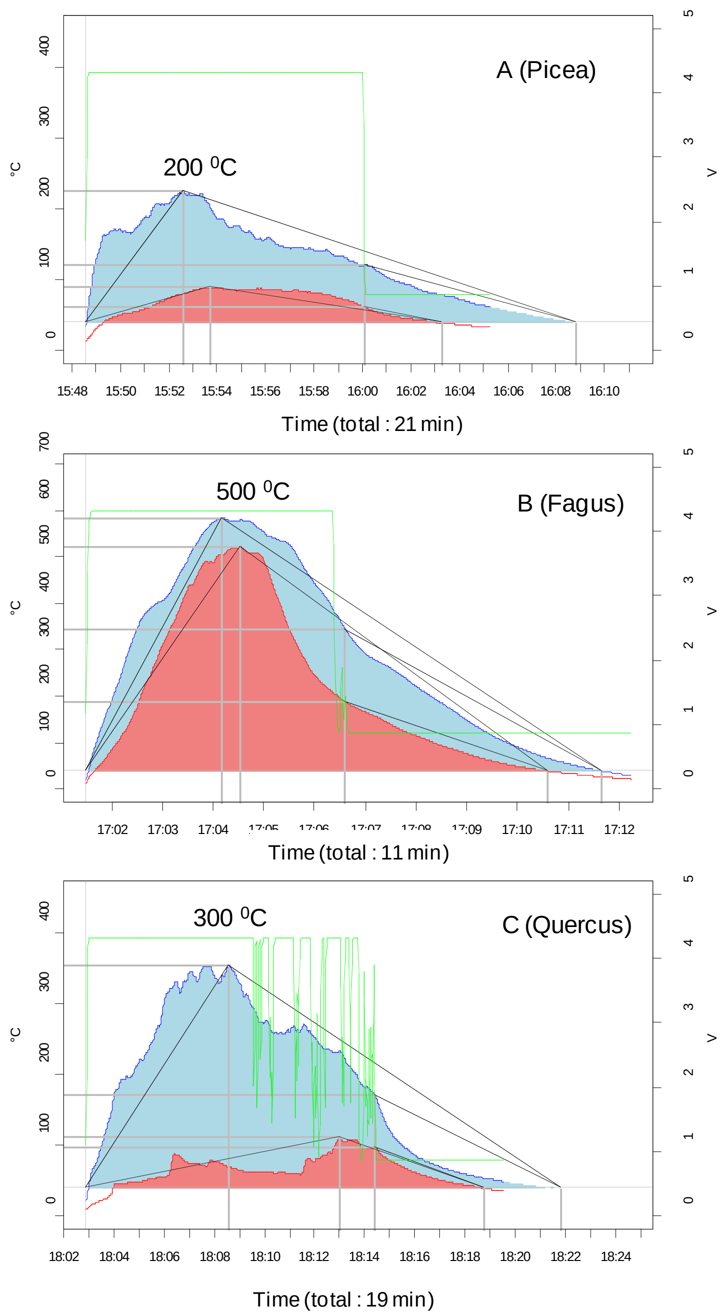

Figure 14 : Comparison of burning curves of three common European species (*Picea abies*, *Fagus sylvatica* and *Quercus robur*) (Black: area in the average of high sensor level, grey: area in the average of low sensor level)

5.4. Discussion

The simple and handy device for testing flammability has proved efficient for distinguishing burning properties of different woods. It can be used for other fuels, for example in ecological studies for testing flammability of leaves and litter, for testing fuel moisture, compaction, particle size, which are all main drivers of flammability.

Three main groups of species can be distinguished according to flammability, with reference to common European trees: *Fagus*–type woods, which have high combustibility but low sustainability, *Picea*-type woods that have low combustibility but high sustainability, and *Quercus*-type woods which have very high sustainability. In general, species with high wood density (e.g. *Quercus*) are expected to have higher sustainability than those having lower density (e.g. *Fagus*). Combustibility depends partly on lignin content and is thus expected to be lower for gymnosperms such as *Picea*. Cornwell *et al.* (2009) suggest that high-lignin woods may show less mass loss during combustion, since lignin has a higher volatilization temperature than cellulose, and a higher lignin content gives a slower pyrolysis rate (Gani & Naruse 2007).

With respect to the tropical woods, Raharimalala et al. 2011 (submitted) found that the quantity of total biomass increased with age of abandonment, reaching 72 t/ha after 40 years of abandonment and that some species such as *Fernandoa madagascariensis, Diospyros perrieri, Dalbergia sp., Poupartia sylvatica, Tarenna sericea, Xeromphis sp, Phylloctenium decaryanum, Stereospermum euphorioides and Croton greveanum* contributed mostly to biomass with more than 1 t/ha in any of the age classes considered up to 40 years after abandoment. *Poupartia sylvatica* appeared to be a key player in the secondary vegetation since it had the highest biomass shortly after 30 years of abandonment. Raharimalala et al. 2011 (submitted) showed that some species had a higher potential than others for biomass production and nutrient release in their ashes after slashing and burning. *Poupartia sylvatica* and *Tarenna sericea* had already after respectively 30 and 40 years a high contribution for most of the chemical elements, and since these species are of no particular use to farmers, they represent good target species for promoting biomass and nutrient sequestration. Other species such as *Dalbergia sp.* or *Diopyros perrieri* would also constitute interesting species, but since they provide valuable wood to local farmers, they tend to be harvested at early stages.

In our study we show that among these dominant species, *Poupartia* has a very excentric position in the RDA scatter plot, with the properties of a wood that produces irregular flames with more small flames and long lasting embers, and which needs more time to increase temperature and leaves more un-burnt particles. (**figure 13**). Other dominant species have a more centred position, indicating median properties. If management aims at promoting a target species such as *Poupartia* because of its favourable biomass and nutrient yield, one will also need to insure a complete ashing of its wood. The burning process might be better achieved if other dominant species such as *Tarena* and *Fernandoa* or non-dominant species such as *Zantophyllum decaryi* or *Calopyxis grandidieri* of the “Picea” type were still available as fuel for sustaining large flames.

5.5. Conclusion

Flammability is the most critical variable for efficiently managing forests in the context of fire hazard and an important component of optimization of secondary vegetation in slash-an-burn cultivation. The secondary vegetation of dry forests of southern Madagascar has some potential for optimizing the traditional slash-and-burn cultivation. Species such as *Poupartia sylvatica* could play a key-role since they produce much biomass and high quality ashes for sustaining short-term cyclic cultures. Nevertheless, for insuring complete burning of woods, additional species with complementary flammability properties are required. Gathering of logs and woody debris into local fire-places and subsequent redistribution of ashes might constitute a complementary measure, albeit more labour demanding.

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Chapter VI

Soil fertility in secondary slash and burn successions in Central Menabe, Madagascar

Chapter VI: Soil fertility in secondary slash and burn successions in Central Menabe, Madagascar (submitted in Agricultural system, October 2011)

Abstract

Madagascar forests are among the most biologically rich ecosystems in the world. In Central Menabe, a region on the West coast of Madagascar, the primary dry deciduous forests are strongly endangered by clearance for agricultural use. In Central Menabe, local farmers cultivate the land for 4-5 years and then abandon it because soils fertility decreases. In this paper we analyze long-term changes of soil fertility along a gradient of age of abandonment and study soil regeneration processes after slash and burn cultivation. In particular we determine after how many years of abandonment soil fertility has recovered sufficiently to allow re-cultivation. The results show that for most chemical variables a significant increase is observed between six and ten years after abandonment. After this period, soil parameters either increase steadily such as nitrate and ammonium, show a humped-shaped curve (magnesium, calcium and potassium), remain constant (total carbon and total nitrogen), or decrease (pH and cation exchange capacity). We conclude that a fallow period shorter than 10 years would lead to an unsustainable agricultural system and recommend a turn-over period of 11 to 30 years since last cultivation to permit soil recovery to a sufficient fertility level to start a new cycle of cultivation

6.1. Introduction

Madagascar is one of the eight leading hotspots of biodiversity in the world, particularly in terms of endemic species (Myers, 2000). Madagascar forests are among the most biologically rich ecosystems (Ganzhorn et al., 2001) and provide many goods and services for the local population such as construction and fire wood, and other essential natural resources like tubers, fruits, honey, medical plants and bushmeat (Favre, 1996; Dirac Ramohavelo, 2009).

On the west coast of Madagascar, the dense, deciduous dry forest with a high level of endemism (Sorg, 1996; Koechlin et al., 1997) tends to disappear because of clearance for agricultural use. Slash and burn agriculture is the traditional and predominant land use practice in all forested regions of Madagascar (Styger et al., 2007) and the major cause of forest destruction, particularly along the West coast (Genini, 1996). During the period 2000-

2005, the yearly deforestation rate of the dry deciduous forests was estimated to be 0.42%, slightly lower than for the period of 1990 - 2000 when it was 0.70% (USAID, Conservation international).

In Central Menabe, a region on the West coast of Madagascar, some forest protection measures have been implemented on small areas, but incursions into unprotected intact forests continue and contribute to their disappearance (Réau, 2002). The main reason for forest clearance is cultivation of groundnuts, cassava and maize, which is the principal activity of the villagers in Central Menabe as agricultural products are the basis of the local commerce (Dirac Ramohavelo, 2009).

The process of forest clearing usually goes as follows (Genini, 1996): during the cooler and dry season, i.e., from June to September, logs and branches are cut, gathered around larger trees and left to dry for several weeks; at the end of the dry season, typically in October, all woody material is burnt and during the following year the remaining vegetation and the new sprouts are cut and burnt again. After three or four slash and burn cycles, fire destroyed all the vegetation except big trees like baobabs (*Adansonia* sp.). On the land made available, farmers first cultivate maize for two to three years, but soil fertility then starts to drop and weeds become invasive. Farmers then grow cassava and groundnuts for a few more years before abandoning the land. These abandoned lands are called “*monkas*”. After some years of abandonment, some farmers re-cultivate *monkas* whereas others prefer to burn new patches of primary forest because they are easier to clear (Genini, 1996).

Traditional slash and burn agriculture is considered a sustainable land use system under conditions of abundant land and low population density (Kleinman et al., 1995). However, when these conditions are not fulfilled, soils cannot recover their fertility before being re-cultivated (Van Noordwijk, 2002). Moreover, repeated clearings lead to a change in the vegetation so that land will be converted to a grass savannah with a low potential for cultivation (Milleville et al., 2000).

Soil-vegetation patterns in secondary slash and burn succession in Central Menabe suggest that *monkas* which have been abandoned for twenty years or more have recovered enough fertility to be re-used as agricultural land (Raharimalala et al., 2010). This study focuses on the regeneration processes of soil chemical properties after abandonment of *monkas* in Central Menabe and draws attention to its agriculture implication. In particular, the following main questions will be addressed: (1) How does soil fertility evolve in relation to the age of abandonment? (2) After how many years of abandonment has the soil recovered enough fertility to allow re-cultivation?

6.2. Materials and methods

6.2.1.Description of study area

The study area is located in Central Menabe, South-Western Madagascar, about 75 km north of Morondava, around the village of Andranolava . The study area is near the protected Kirindy forest. The area is delimited by old sisal plantations in the North, by the Andranolava river in the South, by the Kirindy forest in the East and by the littoral forest in the West.

Geological conditions are characterised by sedimentary deposits dating back to the Pliocene corresponding to lagoon and marine deposits represented by limestone as well as continental deposits represented by sandstone (Bourgeat, 1996).

The predominant soils are ferruginous red and yellow soils of the “luvisols ferric” category, and can be named Lixisols after the World Reference Base for Soil Resources (Raharimalala et al., 2010). They cover from 90% to 95% of the area (Bourgeat, 1996). The distribution of these two types of soil seems to be random and no clear explanations about their formation have been found, even if some hypotheses have been made (Bourgeat, 1996).

Climatic seasonality is quite marked so that a hot and wet season between November and March/April is followed by a cooler and dry season between May and August. From October to November there is a period of transition which is hot with some rain. Basing on climatic data collected from 1906 to 1993, the mean annual rainfall for the study area is about 767 mm and the mean annual temperature about 24.7°C (Sorg and Rohner, 1996).

The ecosystem of the region is dominated by dry deciduous forests of various types depending on the edaphic conditions (Koechlin et al., 1997). The degradation of these forests, especially by fire, leads to a temporal succession of an herbaceous layer (mainly dominated by *Cyrtococcum bosseri* and *Ocinum canum*) followed by a shrub and tree layer (mainly dominated by *Calopyxis grandidieri*, *Chadsia grevei*, *Cordyla madagascariensis*, *Dalbergia sp.*, *Poupartia silvatica*, *Diospyros perrieri* and *Strychnos decussata*), and finally trees become abundant as compared to shrubs and herbaceous plants which become scarce (mainly *Heteropogon contortus*, *Poupartia silvatica*, *Diospyros perrieri* and *Fernandoa madagascariensis*) (Randriamboavonjy, 1995; Raharimalala et al., 2010).

6.2.2.Selection of plots

Monkas were grouped in 7 classes according to the age of abandonment, ranking from plots still under cultivation to plots abandoned for more than 40 years. Age classes are: (II) 1-5 years; (III) 6-10 years; (IV) 11-20 years; (V) 21-30 years; (VI) 31-40 years; (VII) more than 40 years. Age class I corresponds to soils under cultivation according to Raharimalala et al. (2010). Each class of age was represented by four plots randomly taken across the entire study area (more than 1000 ha). The age of the *monkas* was estimated by a local guide who has already worked with scientists in the Kirindy forest and information was cross-checked with local farmers. Plots selected for this study were the same as in Raharimalala et al. (2010). Only plots on yellow soils were selected since the farmers tend to prefer these soils for their cultivation. The size of the plots ranged from 4 to 16 m^2 depending on the age of the plots and the structure of vegetation (Raharimalala et al., 2010).

6.2.3.Soil sampling and analysis

For each of the 28 plots, five soil samples (c. 400 g) were randomly taken at a depth from 0 to 10 cm. All soils were sieved at 2 mm and roots were removed. Half of each sample was taken freshly for the incubation experiment, whereas the other half was used as a pooled sample for each plot and air dried.

For each of the 28 plots, four soil respiration measurements were performed at the same location as for soil sampling with a PPSystem EGM-4 Environmental Gas Monitor device equipped with the dark respiration chamber SRC-1. The measures were done during 2 minutes and the carbon dioxide flux was calculated based on the linear slope and expressed as g CO_2 m^{-2} h^{-1}.

Soil pH was measured in a 1:2.5 soil:water suspension. Total carbon was evaluated after combustion at 980°C by measuring the carbon dioxide emitted with a non dispersive infra-red cell (NDIR) with a device SHIMADZU SSM-5000A. Total nitrogen was measured according to the Kjeldahl method. The process included the digestion of the sample with sulfuric acid, distillation and titration with a BUCHI B-339.

The cation exchange capacity (CEC) and the concentration of exchangeable cations (Mg^{2+}, Na^+, Ca^{2+}, K^+) were measured with a plasma atomic emission spectrometer

SHIMADZU ICPE-9000 after extraction of 10 g of soil with 50 mL of cobaltihexammine chloride ($Co(NH_3)_6Cl_3$) solution.

Ammonium, nitrates and phosphate were analyzed colorimetrically after extraction using a continuous flow analyzer (FLOWSYS, Systea, Roma). For nitrate, the extraction was made with milliQ water, for ammonium with a solution of potassium sulfate (K_2SO_4, 0.5 M) whereas for phosphate the extraction was made with Truog solution (Allen, 1989). For each extraction, 15 g of soils were agitated for one hour with 40 mL of extractant before being filtered at 0.45 µm.

6.2.4.Soil incubation

To determine the potential mineralization rate, 15 mL of milliQ water were added to 150 g of fresh soil. The soil was wet but the saturation level was not reached. Incubated soils were kept in covered plastic cups at ambient temperature (c. 30°C). Soils were mixed every few days and water content was adjusted two times by adding 5 mL of water. After five weeks of incubation, soil samples from each plot were pooled thus resulting in a total of 28 samples, which were analyzed for $N\text{-}NO_3$ and $N\text{-}NH_4$ as described above. A subsample was used to determine the water content of each sample.

6.2.5.Statistical analysis

A redundancy analysis (RDA) was implemented for analyzing the multivariate response of soil variables which were constrained by the age of the plots, followed by an analysis of variance (ANOVA). The nitrate and ammonium concentration as well as the respiration values were log transformed before analysis and all variables were standardized. To test for differences in soil variables between age classes, an ANOVA was applied, followed by a Tukey test. All statistical analyses were done using the R statistical language (R version 2.11.1).

6.3. Results

6.3.1. Global pattern of soil chemical variables along the gradient of age of abandonment

The RDA analysis permits to assess the relationship between all the soil chemical variables and their relationship with the gradient of age of abandonment (**figure 15**). The first axis explained about 33% of the variance whereas the second axis did about 17%. The centroids of age classes are mostly coherently distributed along a gradient across the scatter plot, except for class II (from 1 to 5 years since the abandonment), which lies apart. Most of the variables increase with age of abandonment, strong positive correlation being with nitrate and ammonium in dry soils ($p = 0.001$) and with soil respiration in the field ($p = 0.005$). Variables such as total carbon, total nitrogen, exchangeable magnesium and phosphate are less related to the overall gradient whereas pH and cation exchange capacity are negatively correlated with the age of abandonment.

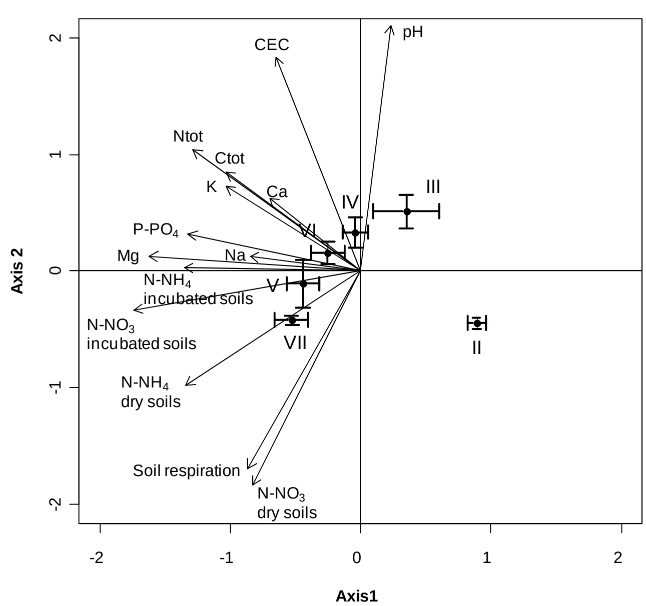


Figure 15 : Scatter plot of the redundancy analysis (RDA) of soil physico-chemical variables constrained by the age of abandonment. Dots represent centroids of age classes with error bars (n=4). Arrows represent soil variables. Age classes are: (II) 1-5 years; (III) 6-10 years; (IV) 11-20 years; (V) 21-30 years; (VI) 31-40 years; (VII) more than 40 years. The RDA was tested with an ANOVA, the model is significant with a p-value smaller than 0.001. Axis 1 represents 28.8 % of the variance ($p < 0.001$) and axis 2 represents 22.4 % ($p < 0.001$). Axis 3 is not significant.

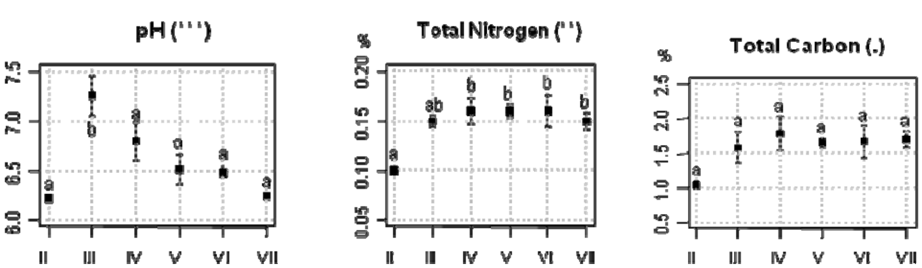
6.3.2.Change of soil properties along the gradient of age of abandonment

Long-term evolution of soil chemical variables after *monkas'* abandonment is rather complex as soil variables along our gradient of age of abandonment follow different patterns from positively correlated to negatively correlated with intermediate hump-shaped relationships. Soil pH and cation exchange capacity (CEC) showed low values after abandonment and a significant increase after 5 years by about one pH-unit in the case of soil acidity. Subsequently pH decreases to attain its initial value 20 year after abandonment (Fig. 2). Soil respiration remained low for the first 20 years since abandonment and nearly doubled if abandoned for 40 years (Fig. 2).

Total nitrogen increased significantly by about 50% in the first 5 years after the abandonment, but remained at similar concentration of about 0.16% in the following years (Fig. 3). A similar trend, although only marginally significant, was observed for total carbon concentration reaching a maximum value of about 1.8% (Fig. 3). Available phosphorus did not show any significant trend, but after more than 40 years since the abandonment its concentration was about five times higher than after 5 years (Fig. 3).

The concentration of major cations increased with the age of abandonment, particularly in the case of magnesium (Fig. 4), but after about 20 years they flattened out or tended to decrease.

In dry soil, nitrate and ammonium concentrations increased with the age of abandonment so as to reach the highest concentration after more than 20 years since the abandonment (**figure 16**). In incubated soils, nitrate concentration increased steadily so as to reach a final concentration up to five times higher than in dry soil (**figure 16**). Ammonium concentration in incubated soils showed a tendency to increase with age of abandonment, but the concentration was lower than in dry soils (**figure 16**).



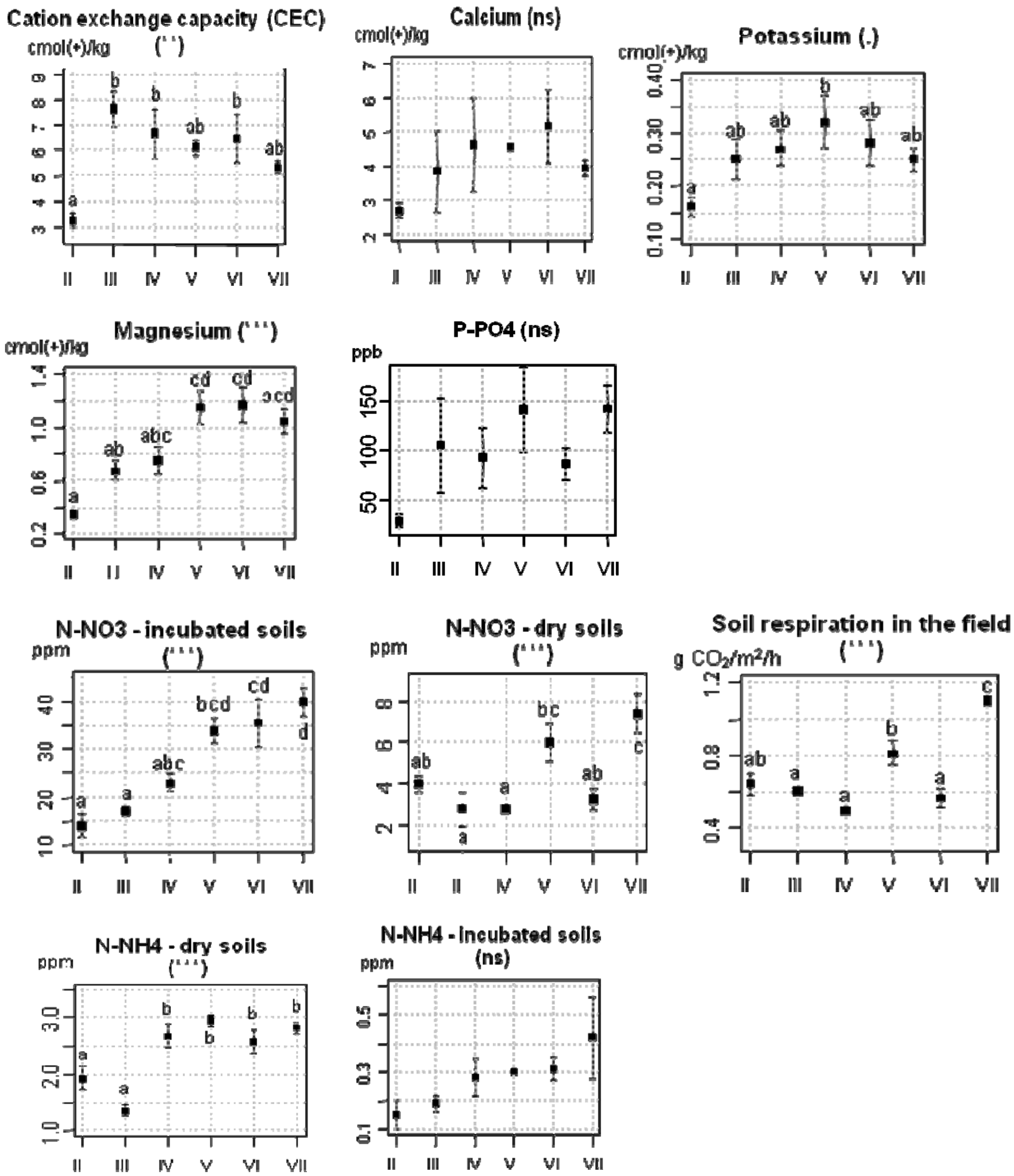


Figure 16 : Means and standard deviations (n=4) of soil physico-chemical properties in the different age classes of abandonment after slash and burn cultivation. Age classes are: (II) 1-5 years; (III) 6-10 years; (IV) 11-20 years; (V) 21-30 years; (VI) 31-40 years; (VII) more than 40 years. n = 4 plots. The variables were tested with ANOVA: $p < 0.001$: ***; $0.001 < p < 0.05$: **; $p > 0.05$: non significant (ns). Means that are followed by the same letter are not significantly different at $p < 0.05$ according to Tukey test.

6.4. Discussion

6.4.1. Temporal evolution of soil fertility along the gradient of age of abandonment

The temporal evolution of soil fertility after abandonment of *monkas* in Central Menabe shows for the majority of soil chemical properties a rapid increase after abandonment before either stagnation at a high level or even a slight decrease as for the major cations. The main reason for the increase may be found in the increasing amount of soil organic matter (SOM). Trees biomass and as a consequence soil litter quantity already reaches a high level 10 years after of abandonment (Raharimalala et al., 2010). This organic matter is released to the soil by litter and root exudates with a consequent increase of total dissolved carbon and nitrogen as observed for total carbon and total nitrogen concentration in our study and in South-West Nigeria where the increase of total soil carbon and nitrogen was about 60% between 1 to 3 years and 10 years since the abandonment (Aweto, 1985a). The significant increase of cation exchange capacity by 136% during the first 10 years since abandonment is probably also related to higher SOM. Variation in cation exchange capacity could be influenced by differences in soil texture, but in sandy soils the CEC is more frequently a function of organic matter rather than of clay mineralogy (Aweto, 1985a, 1985b; Stromgaard, 1988).

The increase of vegetation cover after several years of abandonment (Raharimalala et al., 2010) may also explain the overall increase of soil respiration with age of abandonment. We think that a higher belowground root biomass and a higher amount of decomposing litter increase soil CO_2 fluxes. Moreover, with increasing vegetation biomass, the shade of trees maintains a higher relative soil humidity, which leads to a higher rate of litter decomposition (Yan et al., 2009). In the present study, soil respiration measurements were made at the end of the rainy season in two periods with a one week interval. We cannot exclude that humidity of the soil changed during the measurement period, which could explain the less regular (but significant) pattern of increase along the gradient of age of abandonment. Similar measurements of soil respiration in the Malaysian tropical rainforest showed that the soil respiration rate was high in the rainy period and low in the dry period (Kosugi et al., 2007). Respiration rates are closely linked to environmental variables, mainly temperature and soil moisture content (Davidson et al., 2006; Yan et al., 2009), but in tropical regions soil temperature variations are small and indeed soil water content is the most important parameter affecting the seasonal variation of soil respiration rate (Kosugi et al., 2007).

Nitrate concentration in incubated soils was much higher than in dry soils, whereas ammonium concentration was lower. We observed a continuous increase in nitrate concentration over time and this pattern is in accordance with the pattern reported during secondary succession in sub-tropical rainforest of Australia (Lamb, 1980) where a gradual increase of the rate of nitrification is reported as the succession develops.

Most elements showed either a steady increase or the tendency to a humped-shaped curve (Figs 2-5). The highest values were often reached between 11 and 30 years (class IV or V) with an increase of about 240% for Mg, 200% for Na, 100% for K and 90% for Ca compared to the first 5 years since the abandonment (class II). Raharimalala et al. (2010) observed that after 21-30 years, trees become dominant and shrubs and herbaceous plants tend to decrease their above ground biomass. Therefore, after a period of building up, element concentration is expected to decrease because of vegetation uptake and accumulation in plant tissues (Harcombe, 1980).

6.4.2.Perspectives for the optimization of slash and burn cultivation

The temporal change of the selected chemical variables suggests that soils have recovered sufficient fertility to start a new cycle of cultivation after a period from 11 to 30 years since the abandonment (class IV and V). Such a conclusion is in line with the classical model of shifting cultivation developed by Nye and Greenland (1960) where the fallow is suggested to be cleared again in 15 - 20 years. In addition, our conclusion is also in accordance with findings by Raharimalala et al. (2010) who, based on natural vegetation succession, suggested to start a new cycle of cultivation after about 20 years since the abandonment.

The maximal soil chemical values are nevertheless low or medium compared to expected soil chemical values for cultivated soil in the tropics (**Table XV**) mainly due to low initial soil fertility after cultivation (**Table XVI**). Comparing soil chemical values from Table 1 shows that total carbon, total nitrogen and CEC are in the low range of fertility, whereas cations and pH can be classified in the medium range of fertility. However, these values should not be directly taken as a measure of potential soil fertility since before cultivation the vegetation will be cut and burnt and ashes will cause a rapid increase in soil pH, exchangeable bases, effective cation exchange capacity and available phosphorus in the top-soil due to the significant nutrient input by ash (Nye and Greenland, 1964; Uhl et al., 1984; Kyuma et al., 1985; Brand and Pfund, 1998). N and C inputs are difficult to estimate since an important part is lost by gas emissions during combustion of plant biomass and losses of 22%

of the original amount of N and 30% of the carbon during burning have been reported (Ewel et al., 1981).

Where nitrate and ammonium is concerned, there is a direct impact of fire on microorganisms, which influences the processes of nitrification. Stromgaard (1988) found that due to the heat, the burning kills off the nitrifiers thus resulting in a delay of the processes of oxidation of ammonium to nitrite and of nitrite to nitrate. Therefore, to have a better estimate of the actual soil nutrient content before starting a new cultivation, the vegetation biomass and the corresponding nutrient content must be estimated, although the carbon and nitrogen content in the soil before burning already seems to be a good indicator of the soil fertility after burning (Raharimalala et al., 2011).

It can be concluded that the studied soils can recover their fertility after a period from 11 to 30 years since the abandonment. We recommend to farmers to wait at least 10 years before starting a new cycle of cultivation and at least 20 years for ensuring a better build up of nutritive elements in the soil. However, due to the increasing population, more and more land is needed for agriculture in Central Menabe so that such a period appears rather long to farmers, but as highlighted, a shorter fallow period would lead to irreversibly infertile land. It is therefore necessary to increase farmers' awareness of alternative, more sustainable agricultural practices such as the direct planting on permanent soil cover, where seedling substitutes soil ploughing thus leaving a permanent plant cover (Rabary et al., 2008)

Table XIII: Expected values of the main chemical variables for cultivated soils in tropical climate (from Landon, 1984). CEC: cation change capacity

	pH	**C_{tot} (%)**	**N_{tot} (%)**	**CEC**	**Mg^{2+}**	**Ca^{2+}**	**K^{+}**
				cmol(+)/kg			
High	7 - 8.5	10 - 20	0.5 - 1	25 - 40	> 5	> 10	> 0.6
Medium	5.5 - 7	4 - 10	0.2 - 0.5	15 - 25	0.5 – 5	4 - 10	0.2 - 0.6
Low	< 5.5	2 - 4	0.1 - 0.2	5 - 15	< 0.5	< 4	< 0.2

Table XIV : A comparison of the main soil chemical properties in fallows of 1 to 5years old

Location	Age of fallow	C_{tot} (%)	N_{tot} (%)	CEC	Mg^{2+}	Ca^{2+}	K^{+}	Na^{+}
				cmol(+)/kg				
West of Madagascar (this study)	1-5	1.05	0.10	3.23	0.34	2.71	0.16	0.01
South West Nigeria (Aweto, 1985b)	3	2.18	-	9.17	1.78	3.55	0.07	0.1
East Madagascar (Brand and Pfund, 1998)	5	5.84	0.48	-	2.65	3.06	0.11	-
West Belize Brubacher et al. (1989)	1-3	3.91	0.36	56.3	-	-	-	-

Nevertheless, the inputs of N and C are less obvious since an important part is lost with gas emissions during combustion of biomass. A study conducted in Costa Rica (Ewel et al. 1981 in: Juo et al. 1996) measured a loss of 22% of the original amount of N and 30% of the carbon during burning, and according to Nye and Greenland (1964), the burning of vegetation caused little change in the level of C and N in the soil. Regarding nitrate and ammonium, there is a direct impact of fire on microorganisms, which influences the processes of nitrification. Stromgaard (1988) found that the heat during burning kills off the nitrifiers resulting in a delay of the processes of oxidation of ammonium to nitrite and of nitrite to nitrate. Therefore, to have an idea of the actual soil nutrient content before cultivation, the biomass of vegetation and nutrient content in the biomass is needed, but the carbon content and nitrogen content in the soil before burning already indicates well the content available after burning[1].

6.5. Conclusion

For most soil physico-chemical properties, the most significant increase was observed between 6 and 10 years of abandonment. After this first period of recovery, several elements increased either steadily or with a tendency to a humped-shaped curve. With vegetation growth and with the increase of organic matter returning to the soil, total carbon and total

[1] The nutrient content and the quantity of above-ground biomass of the same area of investigation are studied in Raharimalala et al. (submitted) and in another article by the same author in preparation.

nitrogen reached their maximum values after 11 years of abandonment and then stayed constant. The highest concentrations of exchangeable cations (Mg, Na, K and Ca) were found after 11 to 30 years of abandonment and concentrations decreased afterwards, because of vegetation uptake. Mineralization potential increased with age of abandonment and soil respiration rate was significantly higher after 11 years of abandonment already.

It can be concluded that soils can recover their fertility after a period of 11 to 30 years of abandonment, which suggests that farmers should wait at least 10 years before starting a new cycle of cultivation and 20 years for ensuring a better build up of nutritive elements. But with the increasing population, more and more land is needed for agriculture and therefore such a period is rather long for farmers. However, a shorter period of fallow would lead to irreversibly infertile land. It is therefore necessary to increase farmers' awareness of alternative, more sustainable agricultural practices.

Traditional practices usually include burning and ploughing the soil after each year of cultivation, which destroys the micro-organisms and severely alters the physical properties of the soils exposing them to erosion. One alternative to this practice, albeit a feasibility study should be made before, could be a permanent cover cropping system, a practice where direct seedling replaces soil ploughing, thus leaving a permanent plant cover. In this way a rotational system of cover plants and cultures could be put into place.

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Chapitre VII

Optimisation et synthèse générale

Chapitre VII : Optimisation et synthèse générale

7.1. Optimisation de la végétation secondaire et concentration des nutriments dans le sol

Le travail de master de Schneider (2011), nous donne les propriétés chimiques du sol en fonction de l'âge d'abandon de culture. Comme le N et C sont perdus pour l'essentiel sous forme de gaz à effet de serre après le brûlis, nous ne considérons ici que les éléments minéraux apportés par les cendres.

Le sol étudié qui est un FERRUGINOSOL LUVIQUE (Référentiel pédologique-2008 AFES 2009) présente un pH variant de 6,2 à 7,2 ; avec un ratio C/N faible (<12), une teneur en cation moyen et une CEC faible (Landon, 1996). Schneider (2011) a conclu que le sol atteint sa fertilité entre 11 à 30 ans après abandon de culture. La bonne période pour replanter est donc environ 20 ans.

<u>Calcul du stock en nutriments échangeable (kg/ha)</u>

Le volume de terre de l'horizon A (épaisseur=10 cm) pour 1 ha, soit pour 10.000 m^2 est 1000 m^3 à l'hectare.

Selon Felber 1984, la densité apparente correspondant à la masse volumique du sol en place, non tassée et vide compris, est de 1,36 g/cm3 ou 1360 kg/m3 dans notre type de sol. Selon Landon 1984, cette densité varie de 1,1 à 1,4 g/cm3 dans une surface non compacte et qui n'a pas été cultivée récemment.

Stock en nutriments (kg/ha)=

$$Concentration(cmol/kg) * épaisseur(m) * surface(m^2) * densité(kg/m^3)) * \frac{masse\_molaire(kg)}{valence}$$

Exemple de Ca (Rel_30, 1 - 5 ans):

2,59 (cmol/kg)* 0,10(m)*10^4(m^2)*1360(kg/m^3)*40/2,10 $^{-2}$$10^{-3}$(kg) = 705,788kg/ha

La quantité de cations échangeables en moyenne dans le sol est donnée par le **Tableau XVII**. Nous avons constaté que le Ca est l'élément le plus présent dans le sol, suivi par le K pendant 1 à 20 ans, puis le Mg et le Na de 21 à plus de 40 ans.

Tableau XV : Quantité de cations échangeables en moyenne dans le sol (kg/ha) en fonction de l'âge d'abandon de culture (n=4)

Age d'abandon	Nutriments dans le sol (kg/ha)			
	Na^+	Ca^{2+}	K^+	Mg^{2+}
1- 5 ans	4,4±0,4	737,2±55,4	84,4±9,6	56,0±3,5
6 - 10 ans	7,4±1,9	1047,5±319,8	131,9±19,5	108,78±12,4
11 - 20 ans	7,9±1,5	1261,6±372,7	145,5±18,7	122,7±17,0
21 - 30 ans	5,8±0,5	1245,3±20,8	169,7±22,7	187,0±19,5
31 - 40 ans	6,4±0,9	1408,2±291,0	149,7±23,0	190,5±20,8
Après 40 ans	9,2±0,9	1077,3±64,1	131,4±11,6	170,4±15,8

Par rapport aux résultats obtenus par Brandt et Pfund, 1998 dans les sols tropicaux à l'Est de Madagascar, dans la partie supérieure des sols, les valeurs des éléments K et Mg sont inférieures et le Ca est plus abondant. La quantité de cendres libérée après le brûlis de la biomasse n'arrive pas en totalité dans le sol, mais avec une perte de 10 à 60% selon Chadwick *et al*, 2003 et Giardina *et al*, 2000 (due au lessivage, à l'érosion et au vent) (**Tableau XVIII**). La différence 90% et 40% constituera donc les restes des cendres arriveront au sol après les pertes.

Tableau XVI : Quantité de cations apportée par les cendres (kg/ha) après le brûlis en supposant des pertes de 60% et 10 % **(source : Tableau X)**

Age d'abandon	Na		Ca		K		Mg	
	40%	90%	40%	90%	40%	90%	40%	90%
1- 5 ans	0,09	0,20	0,94	2,11	0,91	2,04	0,14	0,32
6 - 10 ans	0,37	0,84	3,89	8,76	2,66	5,99	0,43	0,97
11 - 20 ans	0,68	1,54	9,84	22,14	6,55	14,73	1,00	2,24
21 - 30 ans	4,18	9,41	57,48	129,34	35,16	79,10	6,12	13,76
31 - 40 ans	11,77	26,49	145,78	328,01	80,66	181,49	16,06	36,14
Plus de 40 ans	17,28	38,88	193,82	436,10	118,55	266,73	21,87	49,20

Le **Tableau XIX** nous donne la quantité des nutriments disponibles pour les plantes après addition des quantités de nutriments obtenus par les cendres et de ceux disponibles dans le sol.

Tableau XVII : Stock total (kg/ha) contenus dans les cendres et dans le sol

Age d'abandon	Na		Ca		K		Mg	
	40%	90%	40%	90%	40%	90%	40%	90%
1- 5 ans	4,44	4,55	738,12	739,29	85,31	86,44	56,21	56,39
6 - 10 ans	7,73	8,20	1'051,38	1'056,25	134,59	137,92	109,21	109,75
11 - 20 ans	8,59	9,45	1'271,44	1'283,74	152,04	160,22	123,71	124,95
21 - 30 ans	10,00	15,23	1'302,79	1'374,65	204,90	248,84	193,12	200,76
31 - 40 ans	18,15	32,87	1'553,96	1'736,19	230,39	331,22	206,59	226,67
Plus de 40 ans	26,45	48,05	1'271,17	1'513,45	249,97	398,15	192,25	219,58

Après une année d'abandon de culture et jusqu'à 20 ans d'abandon environ, le sol apporte plus de nutriments que les cendres (Tableau XVII). Nous pouvons dire qu'à partir de 20 ans d'abandon de culture, la grande partie des nutriments pouvant potentiellement arriver au sol par les cendres se trouve dans la biomasse (**Figure 17**).

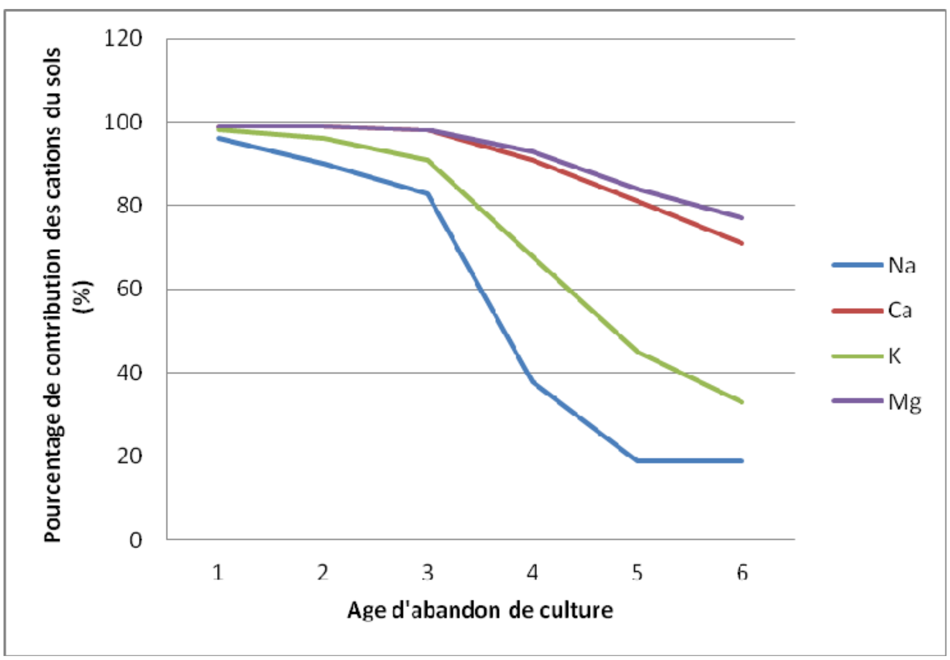

Figure 17 : Pourcentage de contribution des cations du sol dans le stock total (cendres + sol) par âge d'abandon de culture (1 : 1-5 ans ; 2 : 6–10 ans, 3 : 11-20 ans, 4 : 21-30 ans, 5 : 31-40 ans et 6 : plus de 40 ans).

Nous pouvons dire que la contribution des cations du sol est importante dans les 20 premières années (jusqu'à 99% pour le Ca et Mg), et que cette contribution diminue jusqu'à 20% pour le Na (pour plus de 40 ans d'abandon de culture) et 45% pour le K à partir de 31 ans d'abandon de culture. Remarquons aussi la richesse en Ca et Mg dans le sol, ces 2 quantités diminuant très faiblement. Cette richesse est due à la nature de la roche mère.

Dans la région de Serra Talhada, (Pernambuco, Brésil), où la moyenne de la température annuelle est de 803 mm, et qui est dominée par la forêt tropicale semi-aride décidue « caatinga », Boone Kauffman et al. 1993 ont démontré que le feu a affecté la biomasse aérienne, la biomasse souterraine et les pertes des nutriments. En ce qui concerne la biomasse aérienne, il existe trois sources majeures de pertes de nutriments associées aux cultures sur brûlis: les transports de bois dans le champ de culture, les pertes atmosphériques durant la combustion et le lessivage ou l'érosion. Dans leur région d'étude, la production peut être maintenue si les perturbations anthropiques sont équilibrées avec le taux naturel des apports de nutriments, mais cela est improbable en considérant la densité actuelle de la population et l'exploitation de la forêt. Par ailleurs, l'équilibre nutritif de ces écosystèmes par la culture sur brûlis peut être maintenu pour une période de rotation de 15 à 20 ans.

7.2. Optimisation de la végétation secondaire en prenant quelques exemples d'espèces cultivées (manioc, maïs, arachide et patates douces)

Sur la base des stocks disponibles issus du **Tableau XIX**, les **Tableaux XX** et **XXI** nous donnent les quantités des nutriments (IIAT, 1990) utilisés par le manioc dans les sols latéritiques de Madagascar.

Tableau XVIII : Quantités des nutriments extraites par le manioc jusqu'à la récolte dans différents types de sols à Madagascar pour une année (de la plantation à la récolte)

Type de sols	Partie de la plante	Nutriments utilisés par la plante (kg/ha)				
		N	P	K	Ca	Mg
Sols lateritiques, argileux	Racines	178	20	91	26	3
	Tige	107	16	31	30	9
	Total	*285*	*36*	*122*	*56*	*12*

Sols lateritiques, phosphate élevé, K bas	Racines	138	28	24	47	6
	Tige	108	23	12	42	30
	Total	*246*	*52*	*36*	*89*	*36*

Source : International Institute of Tropical Agriculture, Ibadan, Nigeria, 1990

Tableau XIX : Besoin en pH et nutriments de quelques plantes cultivées

Plantes	pH optimum	Besoin en nutriments (kg/ha) pendant la période de croissance			Nutriments importants
		N	P	K	
Maïs	5,5 -7,0	100-200	50-80	60-100	N élevé
Arachide	5,3-6,6	10-20	15-40	25-40	Moyen
Cassava	Peu exigeant				Faible
Patate douce	5,8-6,0				K élevé

Source : Landon, 1996

Dans les **Tableaux XX et XXI**, nous voyons que les besoins des nutriments N, P, K sont largement couverts pour ces plantations, mais seuls les éléments susceptibles de passer rapidement en solution peuvent être qualifiés d'assimilables (Callot et al 1982). L'assimilabilité d'un élément est fonction de son état chimique et des conditions physico-chimiques du milieu. Le pH du sol, le CEC, les matières organiques du sol ont une influence importante sur la solubilité et la disponibilité des éléments pour amender le sol.

Concernant le pH, l'optimum pour que les éléments chimiques soient disponibles est entre 6,0 et 7,5 (Landon 1996). Le pH du milieu est un facteur important de la solubilité des éléments minéraux, la plupart d'entre eux étant davantage solubles à des pH légèrement acides ou neutres. Comme notre pH se situe entre 6,2 et 7,2, il constitue donc une valeur optimale pour l'assimilabilité des éléments mais d'autres facteurs physico-chimiques influencent l'absorption des ions (Gobat et al 2010) comme le potentiel redox, la texture, la structure, la porosité et la perméabilité du sol. De même, les espèces végétales ne présentent pas le même comportement d'absorption et les différences se marquent aussi entre individus de la même espèce à âges différents (Gobat et al 2010).

Pour le CEC, notre valeur qui se situe entre 2 et 9 cmol+/kg, se trouve dans la classification de Landon (1984) comme bas voire très bas, d'où la nécessité d'apporter des matières organiques (système de couverture végétale) pour améliorer la fertilité du sol.

Les matières organiques du sol constituent une réserve d'éléments minéraux. La libération de ces minéraux est due à l'action des micro-organismes qui détruisent les molécules complexes et libèrent dans le milieu un certain nombre d'ions minéraux dont les plus importants sont NH_4^+,NO_3^-,HPO_4^{2-}, $H_2PO_4^-$, SO_4^{2-},K^+,Ca^{2+},Mg^{2+},Fe^{2+} (Callot et al 1982).

Notons aussi que les stocks de nutriments diminuent rapidement avec les successions culturales (Nye and Greenlamd 1960 ; Pfund et al 1997). En forêt dense humide, cette perte est variable d'un élément à l'autre (Pfund et al 1997), exemple : pour le P, il diminue de 52% dans la première étape suivi par des pertes de 9-12% ; le K, 83% pendant le passage de forêt vers jachère.

Comme nous nous sommes basés sur les stocks disponibles dans le sol et les quantités apportées par les cendres, d'autres études complémentaires s'avéreront nécessaire pour connaître les quantités des éléments nutritifs biodisponibles en tenant compte de tous les paramètres physico-chimiques du sol et des besoins physiologiques des plantes dans les formations secondaires.

7.3. Synthèse

Comme cette thèse comporte plusieurs chapitres, cette dernière partie résume les points importants de chaque chapitre sous forme de synthèse; les recommandations sont également présentées.

7.3.1. Sols et végétations dans la région d'Andranolava

Comme dans les autres pays en développement, l'agriculture occupe à Madagascar une place importante dans l'économie nationale. Dans le Menabe, la population vit en majorité (85%) de l'agriculture (exploitants ou ouvriers) (PRDR_Menabe 2007). L'économie régionale repose essentiellement sur le secteur agricole. Le Menabe dispose d'un potentiel agricole important caractérisé par une immense superficie cultivable et des milieux naturels diversifiés favorables aux différents types d'activités telles que l'agriculture (cultures vivrières, de rente, industrielles), l'élevage, la pêche et l'exploitation forestière.

Dans notre site d'étude, les paysans préfèrent cultiver les sols jaunes plutôt que les sols rouges pour les raisons suivantes :

- Le pH des sols jaunes est légèrement supérieur à celui des sols rouges
- Le rapport C/N est légèrement élevé dans le sol jaune que dans le sol rouge
- Les espèces principalement cultivées dans cette région (maïs, arachides et manioc) sont plus productives dans le sol jaune.

En ce qui concerne la végétation, les relevés floristiques nous ont permis d'identifier, en fonction des âges d'abandon de culture, les espèces décrites ci-dessous :

- *1 à 5 ans après l'abandon de culture* :

La végétation est dominée par des herbacées (21 espèces) comme *Commelina ramulosa, Cirtococcum bosseri*, *Heteropogon contortus*, mais on constate déjà l'apparition de quelques espèces d'arbres (8 espèces) comme *Fernadoa madagascariensis ou Apaloxylon tuberosum.*

- *6 à 10 ans après abandon de culture :*

La végétation est toujours dominée par les herbacées (22 espèces) avec l'apparition d'espèces d'arbres et buissons pionniers (17 espèces) comme *Albizia bernieri,* ou *Ziziphus mauritiana.*

- *11 à 30 ans après abandon de culture*

Le nombre d'espèces des herbacées a atteint son maximum (30 espèces). Les arbres, les buissons et lianes se diversifient de plus en plus (au total : 46 espèces).

- *Après 30 ans d'âge d'abandon de culture*

Le nombre d'espèces herbacées (21 espèces) diminue en raison de l'insuffisance de luminosité due aux arbres et buissons présents et dont le nombre augmente encore (60 espèces après 30 ans d'abandon).

Dans toutes les classes d'âge d'abandon, nous constatons la présence d'espèces comestibles comme *Dioscorea acuminata, Dioscorea trichopoda ; Arachis sp, Manihot esculanta, Zea mays* etc.., de plantes ornementales comme *Terminalia sp* et de plantes d'utilité économique (transformation du bois, fabrication de biens) comme *Dalbergia sp, Diospyros perrieri, Capurodendron perrieri* etc.

7.3.2. Biomasse de la végétation

Le deuxième chapitre présente les différentes méthodes que nous avons adoptées pour déterminer les biomasses des espèces herbacées et des espèces ligneuses. Pour les espèces herbacées, nous avons utilisé 2 méthodes : si le plot était homogène, un carrée de 2 m*2 m a été délimité. Toute la végétation herbacée a été coupé est pesée puis séchée pour avoir la biomasse sèche, la même procédure a été appliquée aux litières. Si le plot était hétérogène, nous avons délimité 2 carrés différents de 2 m*2 m dont une sur la surface où la végétation herbacée était dominante et l'autre sur la surface où les litières étaient dominantes.

Concernant les espèces ligneuses, nous avons utilisé la méthode directe, c'est-à-dire, nous avons inventorié toutes les espèces, classées en fonction du nom de l'espèce, du type de croissance, de la hauteur, de la circonférence à hauteur poitrine, et de l'âge d'abandon de culture. Pour chaque classe, nous avons sélectionné une espèce médiane à couper, puis à séparer le tronc, les branches et les feuilles, à les peser et à prendre un échantillon pour sécher à l'air libre et au four. A la fin de la manipulation, nous avons obtenu la biomasse fraîche, la biomasse séchée à l'air libre et la biomasse séchée au four.

Les résultats montrent que la biomasse des herbacées augmente avec l'âge d'abandon de culture jusqu'à 20 ans d'abandon de culture et peut atteindre 2,1 t/ha (de biomasse sèche). Puis cette quantité diminue jusqu'à 1,2 t/ha (de biomasse sèche) après 40 ans d'abandon de culture.

Pour les espèces ligneuses, la biomasse sèche augmente avec l'âge d'abandon de culture. Ici, la quantité est de 0,43 t/ha pour la période de 1 à 5 ans et atteint 66,9t/ha après 40 ans d'abandon de culture.

En résumé, la biomasse sèche totale des herbacées, des litières et des espèces ligneuses augmente avec l'âge d'abandon de culture. En biomasse sèche, la quantité est de 2,8 t/ha pendant 1 à 5 ans après abandon de culture et atteint 71,6 t/ha après 40 ans d'abandon de culture.

7.3.3. Inflammabilité et contenu en nutriments des espèces

Dans l'expérience décrite au chapitre V, nous avons déterminé les propriétés physico-chimiques des quelques espèces tropicales en nous référant aux espèces européennes dans notre zone d'études, selon 20 paramètres du feu:

- Type *Fagus* : les espèces de ce type brûlent très vite, la température augmente très vite (en 2 minutes); il s'agit donc d'une combustibilité élevée mais qui ne dure pas (feu total : 11 minutes): *Albizia sp, Psorospermum androasaemifolium, Capurodendron perrieri*
- Type *Picea* : la température de brûlis de cette groupe d'espèces augmente très lentement (en 4 minutes) ; les espèces brûlent assez lentement mais longtemps (feu total : 21 minutes) : *Fernandoa madagascariensis* ou *Tarenna sericea*

- Type *Quercus :* L'espèce prend du temps pour atteindre la température maximale (6 minutes) mais la combustion dure longtemps (19 minutes) et la température diminue lentement : *Cordyla madagascariensis* ou *Poupartia sylvatica*

Concernant la concentration des nutriments apportés par les cendres, les feuilles contiennent plus de nutriments que les troncs et les branches. En outre, la quantité de nutriments augmente en fonction de l'âge d'abandon de culture, la quantité des cendres provient essentiellement de la biomasse des espèces ligneuses qui augmente avec l'âge d'abandon de culture. Cette affirmation est valable pour les 5 éléments nutritifs analysés à partir de cendres qui sont P, K, Na, Ca, et Mg (ex : pour le Ca : 2,34 kg/ha pour les 1-5 ans et jusqu'à 484,55 kg/ha pour plus de 40 ans d'abandon de culture). Pour le C et le N analysés à partir des biomasses sèches, cette quantité augmente en fonction de l'âge d'abandon de culture (ex : 96,61 kgC/ha libérés dans l'atmosphère pour les 1 à 5 ans et jusqu'à 35,5 tC/ha pour plus de 40 ans d'abandon de culture). Parmi les espèces étudiées, *Poupartia sylvatica* et *Tarenna sericea* fournissent, après 30 à 40 ans, la plus grande quantité de biomasse et libèrent le plus de nutriments par les cendres.

Comme les éléments nutritifs se trouvent essentiellement dans les branches et dans les feuilles, une campagne d'information sera nécessaire pour inciter les paysans à n'utiliser que ces parties et réserver les troncs à d'autres usages (bois de feu, construction).

7.3.4. Recommandations

Harwood (1996) a indiqué que la gestion des ressources en vue de leur utilisation durable dépend de facteurs d'ordre social, politique, géophysique et technologique, et de l'environnement économique local et national.

La configuration ci-après tirée de Harwood 1996 et adaptée à notre contexte local, nous donne les possibles transformations potentielles de la ressource en forêt dense sèche.

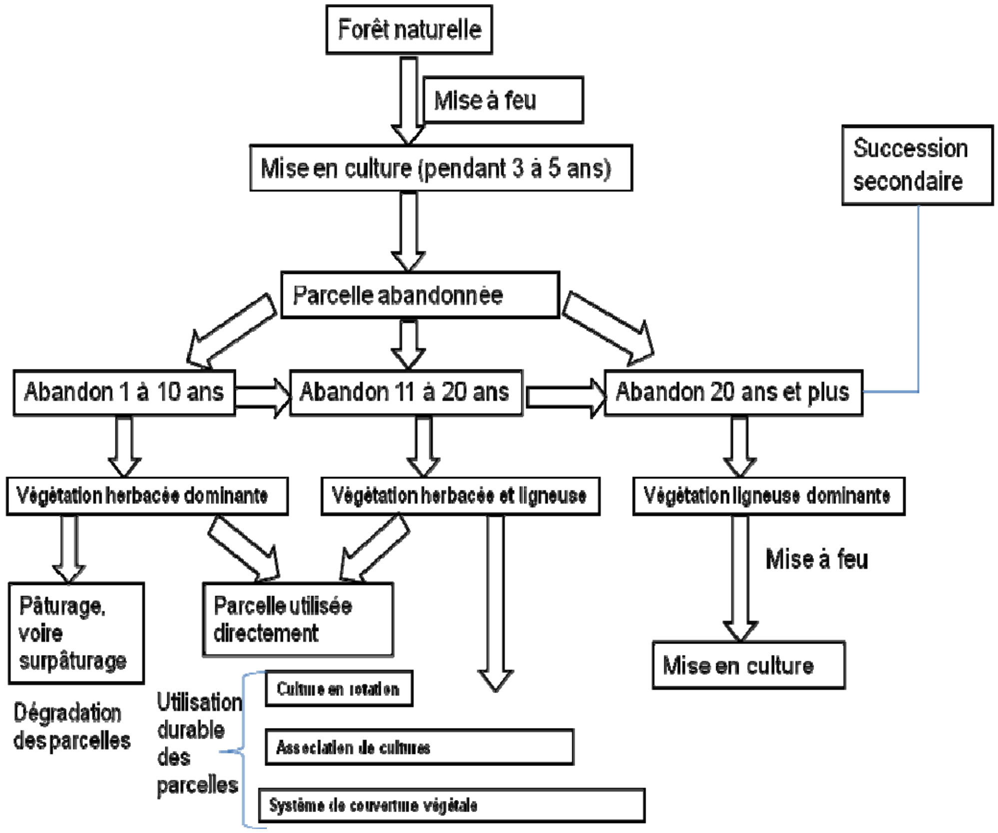

Figure 18 : Modèle conceptuel de la dynamique de formation secondaire dans la forêt dense sèche, cas de Menabe Central**.**

Cette figure nous donne les 3 destinées possibles d'une parcelle abandonnée.

1er cas : abandon entre 1 à 10 ans : c'est une période à dominance herbacée. La végétation a été directement pâturée ou surpâturée par le bétail. Les parcelles se dégradent vite et les éléments nutritifs diminuent rapidement ; les parcelles ne seront plus jamais utilisées à moins qu'intervienne un système de couverture végétale ou d'encloisonnement.

2ème cas : abandon des parcelles entre 11 à 20 ans. Les parcelles sont affectées directement à l'agriculture. Différentes techniques culturales peuvent intervenir, telles que la culture en rotation, l'association de cultures, le système de couverture végétale ou l'agroforesterie. Les espèces les plus riches en éléments nutritifs seront privilégiées comme *Poupartia sylvatica, Tarenna sericea*, ou *Fernandoa madagascariensis.*

3ème cas : abandon des parcelles de plus de 20 ans ou optimisation de la végétation secondaire.

D'après nos analyses, les parcelles anciennement brûlées et abandonnées retrouvent leurs biomasses et nutriments nécessaires (N, P, K, Ca, Na, Mg) à partir de 20 ans d'abandon de culture. En effet, le chapitre VI concernant l'étude de la fertilité du sol nous indique qu'à 20 ans le sol contient suffisamment de fertilité pour démarrer un nouveau cycle cultural (paragraphe 6.4.2), le stade optimum entre la biomasse sèche et les nutriments est atteint à 21 ans d'abandon de culture.

A partir de ce moment, les paysans peuvent revenir dans les parcelles pour effectuer la mise à feu pour une future campagne culturale. Ramakrishnan 1989, en Inde, dans la forêt dense humide (2200 mm de précipitation annuelle) a noté que le temps de retour à l'agriculture minimum est de 10 ans. La fertilité est adéquate à ce stage. Au Mexique, dans la forêt dense sèche (951mm de précipitation annuelle) (Williams-Linera et al 2011), le temps de retour est de 7 à 10 ans. Les auteurs se sont basés sur la structure de la végétation et sur la composition des espèces.

Pour conclure, notre choix de retourner dans les parcelles après 20 ans d'abandon de culture est démontré par :

- La structure et la composition de la végétation
- La quantité des biomasses disponibles
- La quantité des nutriments disponibles apportés par les cendres
- Les stocks des éléments nutritifs disponibles dans le sol.

7.3.5. Dynamique de la succession végétale

Les changements de la végétation et du milieu sont, surtout pour les stades forestiers, beaucoup trop lents pour qu'ils soient perceptibles par une approche directe (Lepart et Escarre 1983). De plus, la reconstitution de la succession secondaire implique un certain nombre de conditions : (i) la relative uniformité du climat, du substrat et de l'environnement de toutes les stations étudiées (Lepart et Escarre 1983); (ii) un même degré et un même nature de la perturbation jouant sur les écosystèmes ; (iii) parmi les étapes de l'évolution de la végétation doivent figurer une placette résultant d'une perturbation plus récente, cessation de l'activité humaine après la perturbation. Grouzis et al. 2001 ont indiqué que, dans le sud ouest de Madagascar, sur sols ferrugineux non lessivés, et sur une série d'abandons de cultures de 2 à 30 ans, l'évolution de la végétation et du milieu après abandon conduit à une formation ligneuse-herbacée ouverte à caractère savanicole. La dynamique post-culturale se caractérise par un processus de savanisation. En effet, l'écosystème évolue vers un système de type savanicole en raison de la réaffectation des terres à d'autres usages (pastoralisme, prélèvement sélectif du bois). En d'autres termes, la résilience de la forêt dense sèche est faible. Trois raisons ont été évoquées pour expliquer cette faible résilience (Grouzis et al, 2001):

- La savanisation qui est essentiellement une conséquence de l'intensité et de la durée de la perturbation. La phase culturale qui dure généralement 5 ans, mais parfois 7 à 10 ans, épuise les capacités de régénération du système.

- Les conditions climatiques et édaphiques (variabilité des écosystèmes, températures et évaporations élevées, forte saisonnalité avec une longue saison sèche, substrat sableux pauvres) sont plus drastiques.

- La fragilité de cette flore insulaire, isolée du continent africain depuis le Crétacé et sa faible compétitivité face aux espèces allochtones, ainsi que l'absence d'une flore forestière secondaire, vigoureuse et bien différenciée diminuant la résilience du système forestier.

7.3.6. Perspectives :

D'autres études seront nécessaires pour compléter les données acquises, comme :

- Préciser la relation entre les nutriments dans la biomasse sèche et ceux dans les cendres pour quantifier les pertes par le feu. Pour ce faire, des méthodologies adéquates seront nécessaires pour déterminer les éléments nutritifs contenus dans la biomasse sèche. L'obtention de ces données permettra d'effectuer un bilan complet des nutriments avant et après le brûlis.

- Préciser les besoins en nutriments des plantes, en particulier des plantes cultivées dans le Menabe. En effet, l'acquisition de ces données permettra d'éviter les approximations qui résultent de l'utilisation des connaissances bibliographiques.

- Etudier les propriétés du sol : perméabilité, infiltration, fertilité en profondeur. Ceci permettra de déterminer avec exactitude les quantités de cendres arrivées et retenues dans le sol et ainsi mises à disposition des plantes.

- Etudier l'impact du feu sur les communautés microbiennes du sol complètera les données tropicales sur la diversité microbienne du sol.

- Etudier la régénération des plantes (recrûs) et des sols après le feu. Comme nous avons effectué des brûlis sur une surface dans chaque classe d'abandon, des suivis périodiques seraient nécessaires pour compléter nos données.

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ANNEXES

Annexes

Chapitre I : Introduction générale

1- Granulométrie des sols jaunes dans 2 profils pédologiques (moins de 5 ans et plus de 40 ans d'abandon de culture)

fractions individuelles [%]					triangle des textures [%]			
A (< 2μm)	LF (2-20μm)	LG (20-50μm)	SF (50-200μm)	SG (200-2000μm)	Argiles	Limons	Sables	code client
13.2	6.8	5.0	18.2	56.8	13.2	11.7	75.1	1 (5 ans)
13.1	8.3	5.0	18.0	55.7	13.1	13.3	73.6	2 (5 ans)
19.1	7.0	4.3	18.8	50.8	19.1	11.3	69.6	3 (5 ans)
19.7	6.8	5.1	21.3	47.2	19.7	11.8	68.5	4 (5 ans)
14.3	7.1	6.3	19.8	52.6	14.3	13.4	72.3	5 (5 ans)
11.8	7.1	5.5	16.5	59.0	11.8	12.6	75.6	6 (5 ans)
15.0	5.7	4.6	19.5	55.2	15.0	10.3	74.7	1 (40 ans)
18.5	8.5	3.9	19.8	49.3	18.5	12.5	69.1	2 (40 ans)
25.6	3.8	3.3	18.8	48.6	25.6	7.0	67.4	3 (40 ans)
19.9	8.4	4.8	19.3	47.7	19.9	13.2	66.9	4 (40 ans)
14.2	10.3	6.4	20.8	48.3	14.2	16.7	69.2	5 (40 ans)

Mesure des pH eau et pHKCl dans les 2 profils pédologiques (moins de 5 ans et plus de 40 ans d'abandon de culture)

code client	pH(H_2O)	pH(KCl)
<5ans 1	5.8	5.1
<5ans 2	5.6	4.8
<5ans 3	5.8	5.1
<5ans 4	6.1	5.5
<5ans 5	6.2	5.8
<5ans 6	5.0	4.8
>40ans 1	6.2	5.5
>40ans 2	5.5	4.7
>40ans 3	5.8	5.0
>40ans 4	5.7	5.0
>40ans 5	5.9	5.4

Analyse du fer et d'autres éléments minéraux dans le sol jaune dans les 2 profils pédologiques de (moins de 5 ans et plus de 40 ans d'abandon de culture)

n° LABO	PROFONDEUR	AGE	FeTamm [mg/kg]	FeMJ [mg/kg]	Fe_2O_3	Al_2O_3	SiO_2	MnO
1395	0-8 cm	1-5 ANS	222.00	11450.00	4.54	17.97	71.16	0.10
1396	8-12 cm	1-5 ANS	256.00	13150.00	4.44	18.53	70.31	0.10
1397	12-23 cm	1-5 ANS	128.20	13950.00	5.51	22.49	65.49	0.03
1398	23-68 cm	1-5 ANS	93.40	11900.00	5.36	21.83	66.83	0.01
1399	68-100cm	1-5 ANS	106.60	13200.00	4.62	19.11	70.79	0.01
1400	>100cm	1-5 ANS	108.20	10450.00	4.31	17.98	69.03	0.01
1401	0-8 cm	PLUS DE 40 ANS	230.00	6000.00	4.18	19.34	66.63	0.07
1402	8-20 cm	PLUS DE 40 ANS	183.20	5900.00	4.02	21.83	67.47	0.06
1403	20-47 cm	PLUS DE 40 ANS	163.20	11000.00	4.42	23.91	64.93	0.02
1404	47 - 80 cm	PLUS DE 40 ANS	98.60	9550.00	4.77	24.77	63.71	0.02
1405	>80 cm	PLUS DE 40 ANS	90.80	10200.00	4.92	25.65	62.80	0.02

2- Profil pédologiques : Description détaillée du profil pédologique :

a- moins de 5 ans

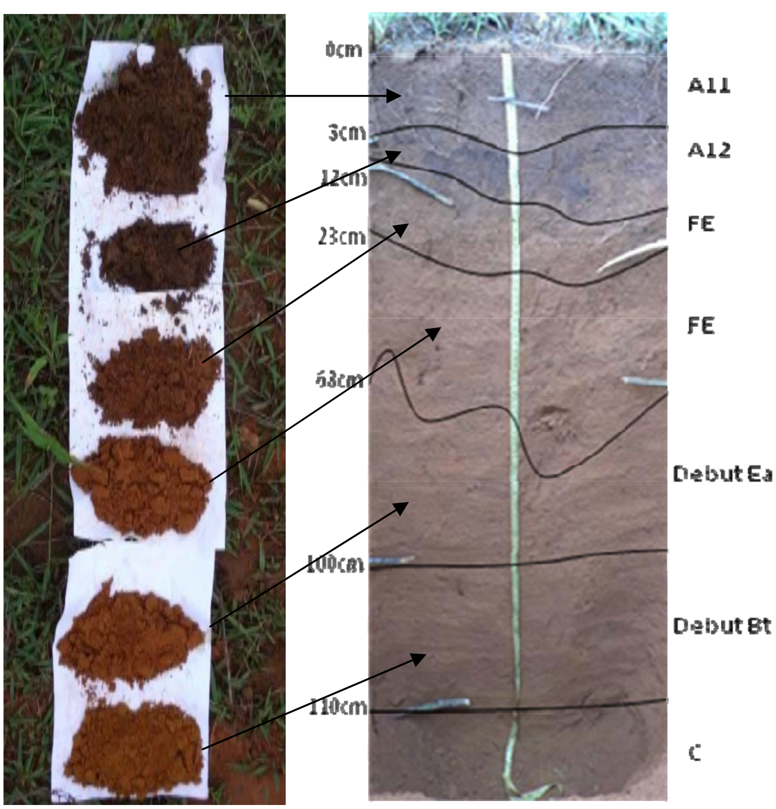
Profil pédologique : **moins de 5 ans** après l'abandon de culture (d'après le Référentiel Pédologique- 2008, AFES 2009)

- 0- 8 cm : pas de litière, présence de racines- et de charbon, de structure grumeleuse fins; de texture sablo-argileuse, couleur 5YR 3/3, pH (Hellige) : 4.5, pH eau : 5.8 et pH KCl : 5.1. On est en présence de l'horizon **A1,** taux de fer 4.54%
- 8-12 cm : on est en présence de quelques racines, d'une structure grumeleuse fines, d'une texture sablo-argileuse; de couleur 5YR 3/3, pH (Hellige) 4.5, pH (eau) : 5.6, pH KCl : 4.8. On est en présence de l'horizon **A2**, à taux de fer similaire à l'horizon précédent (4,44%).
- 12-23 cm : zone d'accumulation de fer, de structure particulaire, de texture sablo-argileuse , de couleur 5YR 4/4, pH (Hellige) : 4.5 à 5, pH (eau) : 5.8 et pH (KCl) : 5.1. C'est une zone où la concentration de fer (Fe_2O_3) est la plus importante : 5.51%. Cette accumulation est la résultante :
  - de la dissolution ou de la transformation de minéraux altérables ;

- ➢ de l'élimination de minéraux secondaires argileux, principalement des kaolinites, entraînés par l'eau des nappes temporaires qui se forment en saison de pluie (Baize et al, 2008)

On est en présence de l'horizon ferrugineux (**FE)**

- 23 - 68cm : très peu de racines, traces de racines en décomposition, de structure particulaire, de texture sablo-argileux, de couleur 5YR 5/8, pH (Hellige) :4.5 à 5, pH (eau) 6.1, et pH (KCl): 5.5. On est encore dans la zone FE avec la concentration de Fe_2O_3 : 5.36%, similaire au précédent.
- 68 – 100 cm : peu de racines, traces d'anciennes racine en décomposition, particulaire, de texture sablo-argileux, pH (Hellige) : 4, pH (eau) : 6.2, et pH (KCl) : 5.8. C'est le **début de Ea** car l'horizon n'est pas bien différencié (la couleur devra être plus claire par rapport au précédent)
- >100 cm : peu de racines, de structure particulaire, de texture sablo-argileux, de couleur 5YR 5/8, pH (Hellige) : 4, pH (eau) : 5.0, et pH (KCl) : 4.8. C'est une zone **début de BT** car l'accumulation d'argile et celle du fer ne diffèrent pas.



Profil pédologique d'un sol jaune après 5 ans d'abandon de culture

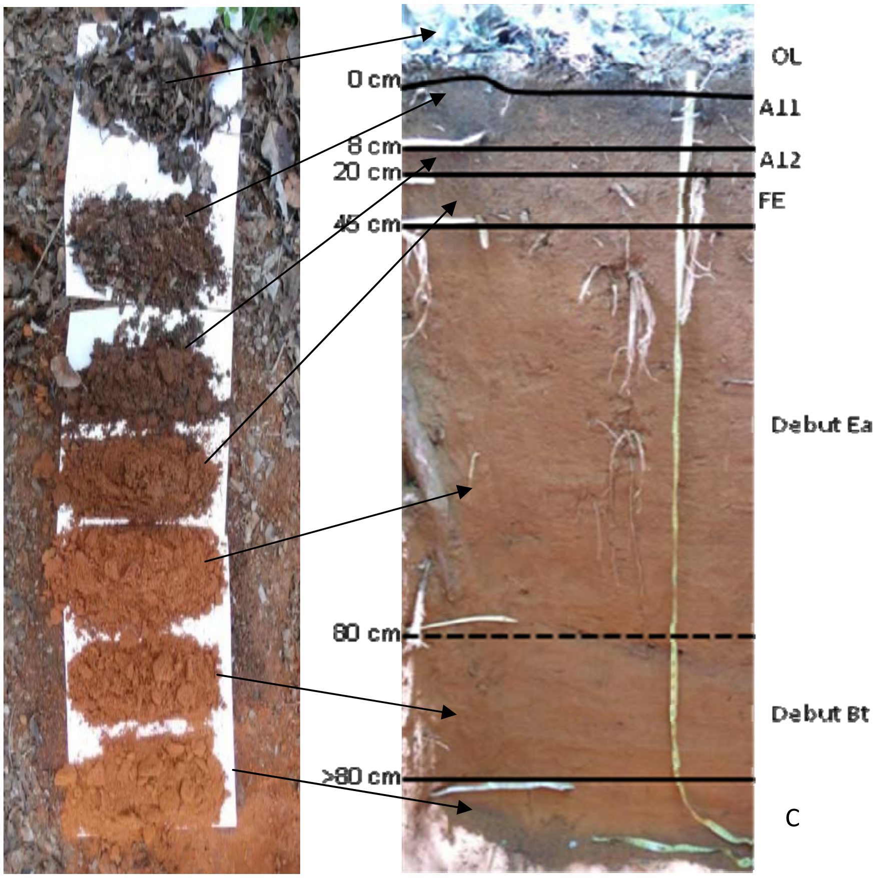
On est en présence d'un **FERRUGINOSOL LUVIQUE peu prononcé**. En WRB, c'est un « Lixisols »

b- **Profil pédologique** pour le sol jaune de **40 ans et plus** après abandon de culture

- Litière en abondance : Horizon **OL**
- 0- 8 cm : racines fines, matières organique en abondance, de structure grumeleux particulaires, de texture sablo-argileux (selon Jamagne, 1999), couleur 5YR 3/3, pH (Hellige) : 4.5, pH eau : 6.2 et pH KCl : 5.5. On est en présence de la zone **A11** car Fe2O3 se trouve légèrement entre 3 et 4%, on a obtenu 4.18% de Fe2O3.
- 8-20 cm : on est en présence de quelques racines avec des charbons (témoins de brûlis), de structure grumeleux particulaires, de texture sablo-argileux, de couleur 5YR 4/4, pH (Hellige) 4.5, pH (eau) : 5.5, pH KCl : 4.7. On est en présence d'un horizon **A12** avec un léger appauvrissement d'argile.
- 20-45cm : zone d'une légère accumulation de fer, de structure particulaire, de texture sablo-argileux, de couleur 5YR 5/6, pH (Hellige) : 4.5 à 5, pH (eau) : 5.8 et pH (KCl) : 5.0. C'est une zone où la concentration de fer (Fe_2O_3) a augmenté : 4.42%. Cette accumulation est la résultante :
    - de la dissolution ou de la transformation de minéraux altérables ;
    - de l'élimination de minéraux secondaires argileux, principalement de la kaolinite, entraînés par l'eau des nappes temporaires qui se forment en saison de pluie (Baize et al 2008)

  On est en présence de l'horizon ferrugineux **(FE).**
- 45-80cm : très peu de racine, de structure particulaire, de texture argilo-sableuse, de couleur 5YR 5/6, pH (Hellige) :4.5, pH (eau) 5.7, et pH (KCl): 5.0. C'est un début de **E** car la couleur n'est pas nettement plus claire que les horizons sus-jacents**.**
- >80cm : peu de racines, de structure particulaire, de texture sablo-argileux, de couleur 5YR 6/6, pH (Hellige) : 4.5, pH (eau) : 5.9, et pH (KCl) : 5.4. C'est un début de **BT** car on a la plus importante accumulation de Fe mais pas d'argile.

→ On est en présence d'un **FERRUGINOSOL LUVIQUE peu prononcé.** En système WRB, c'est un « Lixisols ». L'horizon **Ea** ne se distincte pas correctement.



Profil pédologique d’un sol jaune après 40 ans d’abandon de culture

Chapter III : Quantifying biomass of secondary forest after slash and burn cultivation in Central Menabe, Madagascar

3.1. Water losses (%) of the 28 most frequent species. The water loss in percent of fresh biomass is given after 45 days of air-drying (ADB) and after 30 days of oven-drying (ODB) at 60°C for bottom of stems (A), top of stems (B), bottom of forks (C), top of forks (D) and leaves (E). Mean values and standard errors are given

Species	Vernacular name	Water loss (%) in different part of tree								
		A (%)		B (%)		C (%)		D (%)		E (%)
		ADB	ODB	ADB	ODB	ADB	ODB	ADB	ODB	ADB
Albizia bernieri	Alim-boro	22.5±1.0	34.7±2.4	27.6±1.6	37.8±2.1	28.1±1.1	38.1±2.1	21.5±6.4	75.8±3.9	59.1±0.7
Apaloxylon tuberosum	Talamena	32.8±2.9	48.5±1.3	37.8±1.8	50.7±0.8	37.1±2.0	49.3±1.2	32.1±6.7	54.5±0.7	61.4±1.6
Brachylaena microphylla	Mangily an-kelika	21.0±7.6	30.8±4.1	16.9±2.9	26.6±1.1	16.0±1.2	28.0±0.8	15.8±4.8	78.5±1.6	64.2±0.3
Capurodendron perrieri	Nato	22.7±1.7	34.1±1.4	27.7±1.8	37.5±1.3	29.2±1.8	38.9±0.9	35.2±5.1	49.5±5.0	54.6
Chadsia grevei	Remoty	24.1±0.7	33.1±1.0	26.2±0.4	36.3±0.6	28.0±1.9	36.4±1.7	27.8±3.8	60.5±6.1	n.d
Chloroxylon falcatum	Mandakolahy	19.1±0.3	31.3±1.0	22.5±0.6	34.5±1.1	24.9±1.6	37.3±1.7	37.8±2.4	66.7±5.5	60.9±2.8
Clerodendron sp	Tsivakinampy	23.4±2.7	33.9±3.1	29.5±2.5	37.9±2.2	28.2±3.7	36.6±3.6	22.5±9.8	60.5±9.2	n.d
Cordia myxa	Gondara	58.5±2.0	65.5±1.9	57.9±3.3	65.5±0.9	56.9±2.0	64.5±1.3	57.2±0.4	67.5±1.6	50.5
Cordyla madagascariensis	Anakaraka	21.0±2.0	38.3±2.9	25.0±0.5	41.8±3.7	24.6±0.6	41.8±3.6	29.1±5.8	69.6±3.2	52.8±3.8
Croton greveanum	Somory be	12.9±4.9	23.6±4.5	25.1±7.7	34.4±6.0	27.4±9.0	36.8±7.4	35.2±7.4	47.3±2.3	n.d
Croton sp	Poapoaky	9.9	31.7	19.7	30.3	18.3	31.9	37.6	73.4	47.0
Dalbergia sp	Manary	21.7±2.1	33.4±1.8	21.9±5.1	31.8±4.6	26.3±2.9	37.0±2.2	37.8±5.7	52.1±5.7	54.5±14.1
Diospyros perrieri	Mainty fototra	21.1±0.6	34.3±1.8	26.1±0.6	40.0±1.2	27.8±0.7	41.7±1.2	23.4±0.6	53.2±11.0	49.9±10.9
Fernandoa madagascariensis	Somtsoy	20.1±8.4	34.4±4.7	32.1±3.7	40.1±8.9	24.7±6.4	39.3±3.7	29.4±21.7	58.9±3.0	67.5
Grewia sp	Sely	28.8±2.6	37.8±2.3	34.8±3.4	43.2±3.1	35.8±1.9	43.0±1.9	29.0±9.1	56.3±2.9	n.d
Hydrostachys maxima	Tsilavondria	23.4±0.6	34.4±0.5	24.9±0.5	35.3±1.0	26.5±0.5	36.6±0.8	27.9±6.1	72.6±4.0	42.5
Jatropha curcas	Boy	41.6±4.6	60.5±3.1	38.1±7.3	62.4±2.0	37.9±8.1	62.2±2.8	31.5±11.5	63.6±16.8	n.d
Phylloctenium decaryanum	Pitik'ala	16.2±5.9	30.6±0.9	22.1±2.3	33.9±0.5	25.5±4.0	33.7±4.0	34.6±11.5	60.1±10.0	n.d
Poupartia minor	Sary sakoam-banditsy	33.0±4.8	67.4±0.8	58.6±8.7	71.9±3.4	61.2±3.6	70.2±1.0	38.6±9.9	64.8±3.8	n.d
Pourpartia sylvatica	Sakoam-banditsy	35.1±5.7	45.0±3.0	36.4±0.6	36.4±2.4	37.2±3.1	41.3±7.1	48.5±3.2	59.5±0.6	n.d
Psorospermum androasaemifoli	Harongam-panihy	25.7±1.8	33.5±1.8	25.0±2.3	33.1±2.1	23.0±3.9	31.9±3.1	23.0±5.9	44.3±10.0	n.d

um										
Securinega seyrigii	Anatsioky	19.6±1.0	30.0±1.2	21.9±1.2	32.1±0.9	21.3±1.4	31.6±1.5	30.2±4.0	58.4±10.6	45.0±4.1
Stereospermum euphorioides	Mangarahara	41.2±1.1	51.8±1.3	44.9±1.8	53.4±0.6	43.8±1.4	52.1±0.6	53.2±4.7	63.6±3.7	n.d
Strychnos decussata	Hazom-by	16.5±0.0	27.9±0.4	19.5±1.0	30.2±1.0	20.8±0.6	30.5±0.2	24.1±3.5	66.4±3.6	46.4±3.6
Tarenna sericea	Papolahy	27.1±0.6	39.3±0.6	32.6±0.7	42.3±0.8	32.1±0.8	43.2±0.4	40.8±2.7	62.3±1.8	n.d
Terminalia boivinii	Amanin'omby	18.5±1.8	29.6±0.8	23.4±1.7	33.7±0.8	23.3±2.0	33.7±0.9	18.6±5.7	63.9±10.9	51.8±5.2
Xeromphis sp	Lamotim-boay	25.4±1.3	35.5±1.4	27.2±1.3	34.9±2.7	28.1±1.6	36.7±1.0	35.5±3.6	74.2±6.1	n.d
Ziziphus mauritiana	Konazy	41.9±0.7	49.4±1.0	46.6±1.3	53.4±1.4	46.4±2.3	53.1±2.2	41.0±7.8	65.4±9.0	59.6±5.1

n.d: no data

3.2. Trees and lianas frequency in the 30 plots (number of individuals among a total of 1101 recorded plants) according to growth type and age of abandonment

Species	Growth type					Age of abandonment																																		
.						1- 5 years						6 to 10 years						11 to 20 years						21 to 30 years						30 to 40 years						More than 40 years					
	I	II	III	IV	freq	I	II	III	IV	Tot	Tot/ ha	I	II	III	IV	Tot	Tot /ha	I	II	III	IV	Tot	Tot /ha	I	II	III	IV	Tot	Tot /ha	I	II	III	IV	Tot	Tot /ha	I	II	III	IV	Tot	Tot /ha
Fernandoa madagascariensis	103	4	76	7	190	-	-	-	-	0	0	-	-	-	-	0	0	7	-	3	5	15	469	5	3	3	1	12	375	42	1	33	1	77	602	49	-	37	-	86	672
Diospyros perrieri	10	5	98	2	115	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	2	3	94	2	-	14	-	16	500	8	2	62	-	72	563	-	3	21	-	24	188
Acalypha diminuata	-	-	-	101	101	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	7	7	219	-	-	-	5	5	156	-	-	-	58	58	453	-	-	-	31	31	242
Dalbergia sp	46	9	22	2	79	-	-	-	-	0	0	-	-	-	1	1	125	-	-	-	1	1	31	27	1	1	-	29	906	18	8	13	-	39	305	1	-	8	-	9	70
Tarenna sericea	3	1	44	11	59	-	-	-	1	1	125	-	-	-	1	1	125	-	-	-	-	0	0	3	1	6	-	10	313	-	-	7	-	7	55	-	-	31	9	40	313
Ziziphus mauritiana	25	-	11	4	40	-	-	-	1	1	125	1	-	2	1	4	500	22	-	7	2	31	969	2	-	2	-	4	125	-	-	-	-	0	0	-	-	-	-	0	0
Poupartia silvatica	10	17	9	1	37	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	31	1	-	-	-	1	31	5	9	5	-	19	148	4	8	4	-	16	125
Croton greveanum	13	4	6	11	34	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	13	4	6	11	34	266
Mussaenda arcuata	-	-	-	34	34	-	-	-	-	0	0	-	-	-	1	1	125	-	-	-	10	10	313	-	-	-	16	16	500	-	-	-	5	5	39	-	-	-	2	2	16
Xeromphis sp	5	1	27	-	33	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	-	-	1	31	1	-	13	-	14	109	3	1	14	-	18	141
Apaloxylon tuberosum	15	1	9	4	29	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	10	1	3	2	16	500	5	-	4	2	11	86	-	-	2	-	2	16
Strychnos decussata	-	-	22	6	28	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	1	2	63	-	-	13	4	17	133	-	-	8	1	9	70
Grewia sp	7	1	17	1	26	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	1	-	2	63	-	1	7	1	9	70	6	-	9	-	15	117
Phyllocteniumdecaryanum	12	-	12	1	25	-	-	-	-	0	0	-	-	-	-	0	0	5	-	-	-	5	156	2	-	1	-	3	94	1	-	5	1	7	55	4	-	6	-	10	78
Ripikala	1	-	9	10	20	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	1	2	4	125	-	-	8	6	14	109	-	-	-	2	2	16
Stereospermum euphorioides	6	1	10	3	20	-	-	-	-	0	0	-	-	-	1	1	125	-	-	-	-	0	0	2	-	1	-	3	94	3	1	9	2	15	117	1	-	-	-	1	8
Byttneria voulily	-	-	-	18	18	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	3	3	94	-	-	-	4	4	125	-	-	-	-	0	0	-	-	-	11	11	86
Clerodendron sp	2	-	15	-	17	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	-	0	-	-	2	-	2	16	2	-	13	0	15	117

Brachylaena microphylla	14	-	-	-	14	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	14	-	-	-	14	438	-	-	-	-	0	0	-	-	-	-	0	0
Calopyxis sphaeroides	1	-	9	1	11	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	1	-	2	63	-	-	8	1	9	70	-	-	-	-	0	0
Chadsia grevei	4	3	4	-	11	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	1	-	-	2	63	-	-	-	-	0	0	3	2	4	-	9	70
Cordyla madagascariensis	2	4	5	-	11	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	-	1	8	2	4	4	-	10	78
Isolona madagascariensis	-	-	11	-	11	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	11	-	11	86	-	-	-	-	0	0
Cabucala madagascariensis	-	-	-	11	11	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	2	2	63	-	-	-	1	1	31	-	-	-	2	2	16	-	-	-	6	6	47
Psorospermum androsaemifolium	2	1	3	3	9	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	1	2	-	3	94	-	-	-	-	0	0	2	-	1	3	6	47
Albizia bernieri	1	-	7	1	9	-	-	-	-	0	0	-	-	-	1	1	125	-	-	-	-	0	0	-	-	-	-	0	0	1	-	5	-	6	47	-	-	2	-	2	16
Capurodendron perrieri	-	-	8	-	8	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	5	-	5	39	-	-	3	-	3	23
Jatropha curcas	7	-	1	-	8	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	2	-	1	-	3	94	3	-	-	-	3	23	2	-	-	-	2	16
Cordia myxa	4	1	2	-	7	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	4	1	2	-	7	219	-	-	-	-	0	0	-	-	-	-	0	0
Poupartia minor	2	2	2	-	6	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	2	-	2	-	4	31	-	2	-	-	2	16
Asparagus vaginellatus	-	-	-	5	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	3	3	94	-	-	-	1	1	8	-	-	-	1	1	8
Chloroxylon falcatum	2	-	3	-	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	2	-	2	-	4	31	-	-	1	-	1	8
Croton sp	-	-	4	1	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	2	-	2	16	-	-	2	1	3	23
Securinega seyrigii	-	-	5	-	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	4	-	4	31	-	-	1	-	1	8
Terminalia boivinii	-	-	5	-	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	4	-	4	31	-	-	1	-	1	8
Hydrostachys maxima	-	-	3	2	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	2	3	23	-	-	2	-	2	16

Dalechampia clematidifolia	-	-	-	5	5	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	31	-	-	-	-	0	0	-	-	-	4	4	31
Bridelia pervilleana	2	-	2	-	4	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	2	-	3	23	1	-	-	-	1	8
Lantana camara	3	-	1	-	4	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	-	1	31	-	-	-	-	0	0	3	-	-	-	3	23
Poivrea coccinea	-	-	-	4	4	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	2	2	63	-	-	-	-	0	0	-	-	-	2	2	16	-	-	-	-	0	0
Cryptostegia grandiflora	-	-	-	3	3	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	31	-	-	-	-	0	0	-	-	-	2	2	16	-	-	-	-	0	0
Canthium sp	-	-	3	-	3	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	3	-	3	23	-	-	-	-	0	0
Rothmannia tropophylla	-	-	-	3	3	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	31	-	-	-	-	0	0	-	-	-	2	2	16	-	-	-	-	0	0
Bivinia jalbertii	-	-	2	-	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	2	-	2	16	-	-	-	-	0	0
Fatsilo	1	-	-	1	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	8	1	-	-	-	1	8
Diospyros tropophylla	1	-	-	1	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	-	1	2	16	-	-	-	-	0	0
Hibiscus macrogonus	1	1	-	-	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	1	-	-	2	16	-	-	-	-	0	0
Mascarenhasia lisianthiflora	1	1	-	-	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	1	-	-	2	16	-	-	-	-	0	0
Protorhus humbertii	-	-	-	2	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	2	2	16
Taolakena	-	-	1	1	2	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	1	2	16
Deidamia sp	1	-	-	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	-	-	1	31	-	-	-	-	0	0	-	-	-	-	0	0
Dioscorea acuminata	1	-	-	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	-	-	1	31	-	-	-	-	0	0	-	-	-	-	0	0
Dioscorea trichopoda	-	-	-	1	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	31	-	-	-	-	0	0	-	-	-	-	0	0
Gardenia squamifera	-	-	-	1	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	1	1	8	-	-	-	-	0	0

Pandaca sp	1	-	-	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	-	-	1	8
Capurodendron sakalavum	-	-	1	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	-	1	8	-	-	-	-	0	0
Macrorhamnus sp	-	-	1	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	-	1	8	-	-	-	-	0	0
Astrocassine pleurostylioides	-	-	1	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	-	1	8
Grewia voloina	-	-	1	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	1	-	1	8
Tamarindus indica	1	-	-	-	1	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-	0	0	1	-	-	-	1	31	-	-	-	-	0	0	-	-	-	-	0	0
Total	310	57	472	262	1101	0	0	0	2	2	250	1	0	2	6	9	1125	34	0	11	37	82	2563	82	9	41	37	169	5281	95	24	235	95	449	3508	98	24	183	85	390	3047

3.3. Nom scientifique, nom vernaculaire, et famille des espèces ligneuses présentes dans nos placettes

Species	Family	Vernacular name
Acalypha diminuata	Euphorbiaceae	ohim-bango
Albizia bernieri	Fabaceae	alimboro
Apaloxylon tuberosum	Fabaceae	talamena
Asparagus vaginellatus	Liliaceae	rohimboalavo
Astrocassine pleurostylioides	Celastraceae	maronono
Bivinia jalbertii	Flacourtiaceae	sary goavy
Brachylaena microphylla	Asteraceae	mangily an-kelika
Bridelia pervilleana	Euphorbiaceae	Kitakitakala
Byttneria voulily	Sterculiaceae	volily
Cabucala madagascariensis	Apocynaceae	tandrokosy
Calopyxis sphaeroides	Combretaceae	voanjonala
Canthium sp	Rubiaceae	fatik'ahitra
Capurodendron perrieri	Sapotaceae	nato
Capurodendron sakalavum	Sapotaceae	Kironono
Chadsia grevei	Fabaceae	remoty
Chloroxylon falcatum	Rutaceae	mandakolahy
Clerodendron sp	Verbenaceae	tsivakinampy
Cordia myxa	Boraginaceae	gondara
Cordyla madagascariensis	Fabaceae	anakaraka
Croton sp	Euphorbiaceae	poapoaky
Croton greveanum	Euphorbiaceae	somorobe
Cryptostegia grandiflora	Asclepedaliaceae	lombiry
Dalbergia sp	Fabaceae	manary
Dalechampia clematidifolia	Euphorbiaceae	vahy telo ravy
Deidamia sp	Passifloraceae	papain'ala
Dioscorea acuminata	Dioscoreaceae	ovy
Dioscorea trichopoda	Dioscoreaceae	babo
Diospyros perrieri	Ebenaceae	mainty fototra
Diospyros tropophylla	Ebenaceae	hazom-boenga
Fernandoa madagascariensis	Bignoniacaeae	somtsoy
Gardenia squamifera	Rubiaceae	mahabiboala
Grewia sp	Tiliaceae	sely
Grewia voloina	Tiliaceae	Taila
Hibiscus macrogonus	Malvaceae	halampo
Hydrostachys maxima	Hydrostachiaceae	Tsilavondria
Isolona madagascariensis	Fabaceae	kililo
Jatropha curcas	Euphorbiaceae	boy
Lantana camara	Verbenaceae	radriaka
Macrorhamnus sp	Rhamnaceae	mamy aho
Mascarenhasia lisianthiflora	Asclepiadaceae	kidroa

Mussaenda arcuata	Rubiaceae	lengo
Pandaca sp	Apocynaceae	Kabokala
Phylloctenium decaryanum	Bignoniaceae	pitikala
Poivrea coccinea	Verbenaceae	tamenaka
Poupartia minor	Anacardiaceae	sary sakoam-banditsy
Poupartia silvatica	Anacardiaceae	sakoam-banditsy
Protorhus humbertii	Anacardiaceae	tokambahatra
Psorospermum androsaemifolium	Clusiaceae	harongam-panihy
Rothmannia tropophylla	Rubiaceae	piropitsok'ala
Securinega seyrigii	Euphorbiaceae	anatsioky
Stereospermum euphorioides	Bignoniaceae	mangarahara
Strychnos decussata	Loganiaceae	hazomby
Tamarindus indica	Caesalpiniaceae	kily
Tarenna sericea	Apocynaceae	papolahy
Terminalia boivinii	Combretaceae	amanin'omby
Xeromphis sp	Rubiaceae	lamotim-boay
Ziziphus mauritiana	Rhamnaceae	konazy
		Ripikala
		Fatsilo
		taolakena

3.4. Récapitulation des biomasses (calcul détaillé sur CD)

RECAPITULATION : pour les ligneuses

		Biomasse sèche (FB)		Biomasse séchée à l'air (ADB)		Biomasse séchée au four (ODB)	
		kg/aire minimale	kg/ha	kg/aire minimale	kg/ha	kg/aire minimale	kg/ha
moins de 5 ans	rel_30	6.30	3'937.50	3.542	2'213.75	3.21	2'005.94
16m2	biom_15	0.03	21.25	0.017	10.63	0.02	9.38
	biom_16	0.00	0.00	0	0	0.00	0.00
	biom_17		0.00	0	0	0.00	0.00
	Rel_31		0.00	0	0	0.00	0.00
Moyenne			791.75		444.9		403.06
Ecart-type			1'758.55		988.84		896.04
Erreur standard			786.47		442.24		400.74
6 à 10 ans			0.00				
16 m2	rel_81	12.20	7'626.25	8.28	5'174	6.20	3'877.98
	rel_80	1.20	750.00	0.89	556	0.66	411.56
	biom_12	1.77	1'105.00	0.913	571	0.79	494.95
	biom_11	2.71	1'696.25	1.68594	1'054	1.35	841.96
	biom_10	1.08	676.88	0.68	425	0.54	339.56
Moyenne			2'370.88		1'556.0		1'193.20
Ecart-type			2'965.36		2'036.82		1'513.16
Erreur standard			1'326.50		910.92		676.73
11 à 20 ans							
64m2	biom_13	28.02	4'378.13	19.314	3'017.81	13.43	2'098.40
	biom_42	51.18	7'996.41	32.1291	5'020.17	24.24	3'786.80
	biom_7	36.22	5'659.69	22.15444	3'461.63	14.17	2'214.65
	biom_8	27.46	4'290.47	18.0246	2'816.34	13.98	2'183.62
	rel_44	32.74	5'114.84	21.22268	3'316.04	13.92	2'175.07
Moyenne			5'487.91		3'526.4		2'491.71

Ecart-type			1'510.52		872.16		725.24
Erreur standard			675.55		390		324.35
21 à 30 ans	rel_97	166.99	26'091.72	114.67	17'917.19	88.83	13'879.67
64 m2	rel_96	282.27	44'105.31	197.5045	30'860.08	145.92	22'799.41
	biom_4	190.18	29'716.09	131.788	20'591.88	98.87	15'449.16
	biom_3	426.22	66'596.25	238.3425	37'241.02	189.89	29'671.04
	biom_14	64.56	10'087.03	43.59	6'810.94	32.62	5'096.88
Moyenne		1'130.22	35'319.28		22'684.2		17'379.23
Ecart-type			21'264.13		11'808.99		9'317.93
Erreur standard			9'509.90		5'281		4'167.23
31 ans à 40 ans							
256 m2	rel_91	3'170.75	123'857.46	2157.95659	84'295.18	1'672.61	65'336.28
	rel_48	2'513.52	98'184.30	1662.18018	64'928.91	1'303.03	50'899.49
	rel_29	1'336.48	52'206.17	863.47783	33'729.60	675.59	26'390.25
	biom_2	926.31	36'183.83	581.6084	22'719.08	476.17	18'600.43
	biom_1	2'125.10	83'011.69	1278.1987	49'929.64	1'133.43	44'274.64
Moyenne			78'688.69		51'120.5		41'100.22
Ecart-type			35'167.36		24'503.74		18'815.64
Erreur standard			15'727.80		10'959		8'414.87
40 ans et plus	rel_22	2'100.19	82'038.55	1339.69048	52'331.66	1'154.72	45'106.40
256 m2	biom_5	2'260.87	88'315.04	1574.58985	61'507.42	1'229.58	48'030.45
	biom_6	5'357.53	209'278.40	3706.70343	144'793.10	2'494.67	97'447.97
	rel_20	3'416.50	133'457.03	2321.21497	90'672.46	1'815.89	70'933.39
	rel_21	3'349.10	130'824.22	2'289.65	89'439.30	1'871.33	73'098.83
Moyenne			128'782.65		87'748.8		66'923.41
Ecart-type			50'813.93		36'084.77		21'324.22
Erreur standard			22'725.00		16'138		9'536.77

Récapitulations des herbacées

Age d'abandon	Relevé	Biomasse fraîche(FB) (kg/ha)	Biomasse sèche (ADB) (kg/ha)
1 à 5 ans	Rel _30	6'500.00	2'925.00
	Biom _17	5'500.00	2'475.00
	Biom_ 15	1'317.50	592.88
	Biom_ 16	2'500.00	1'125.00
	Rel _31	6'250.00	2'812.50
Moyenne		4'413.50	1'986.08
Ecart-type		2'353.37	1'059.02
Erreur standard		1'052.49	473.62
6 à 10 ans	Biom_ 10	5'500.00	2'475.00
	Biom_ 11	6'500.00	2'925.00
	Biom_ 12	5'167.50	2'325.38
	Rel_ 80	4'000.00	1'800.00
	Rel_ 81	5'397.50	2'428.88
Moyenne		5'313.00	2'390.85
Ecart-type		893.90	402.25
Erreur standard		399.77	179.90
11 à 20 ans	rel _42	3'250.00	1'462.50
	Rel_ 44	3'875.00	1'743.75
	Biom_ 7	1'890.00	850.50
	Biom_ 8	12'000.00	5'400.00
	Biom_ 13	2'750.00	1'237.50
Moyenne		4'753.00	2'138.85
Ecart-type		4'115.75	1'852.09
Erreur standard		1'840.67	828.30
21 à 30 ans	Biom_ 3	2'125.00	956.25
	biom _4	1'560.00	702.00
	Biom_ 14	1'625.00	731.25
	Rel_ 96	3'500.00	1'575.00
	Rel_ 97	3'612.50	1'625.63
Moyenne		2'484.50	1'118.03
Ecart-type		1'003.28	451.48
Erreur standard		448.69	201.91
31 à 40 ans	rel _29	3'311.75	1'490.29
	Rel_ 91	340.00	153.00
	Biom_ 1	3'143.75	1'414.69
	Biom_ 2	1'842.00	828.90
	rel _48	2'125.00	956.25
Moyenne		2'152.50	968.63
Ecart-type		1'194.65	537.59
Erreur standard		534.28	240.43

40 ans et plus	Rel_ 20	2'500.00	1'125.00
	Rel_ 21	4'725.00	2'126.25
	Rel_ 22	2'320.00	1'044.00
	Biom_ 5	875.00	393.75
	Biom_ 6	3'000.00	1'350.00
Moyenne		2'684.00	1'207.80
Ecart-type		1'387.84	624.53
Erreur standard		620.68	279.31

***ADB (Air dry biomass)est égale à ODB (oven dry biomass) après 3 semaines de séchage à l'air libre.**

Récapitulations pour les litières

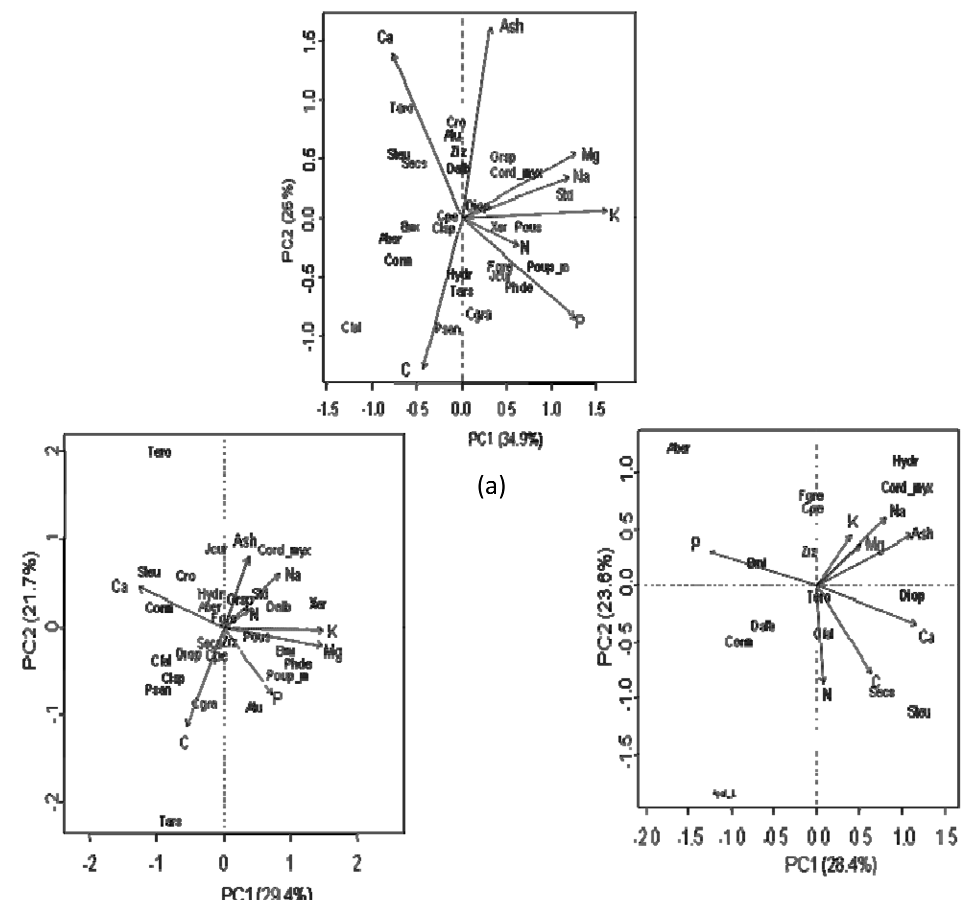
Age d'abandon	Relevé	Biomasse fraîche(FB) (kg/ha)	Biomasse sèche (ADB) (kg/ha)
1 à 5 ans	Rel _30	750.00	337.50
	Biom _17	237.50	106.88
	Biom_ 15	567.50	255.38
	Biom_ 16	3'100.00	1'395.00
	Rel _31	595.00	267.75
Moyenne		1'050.00	472.50
Ecart-type		1'161.09	522.49
Erreur standard		519.27	233.67
6 à 10 ans	Biom_ 10	1'625.00	731.25
	Biom_ 11	4'250.00	1'912.50
	Biom_ 12	1'375.00	618.75
	Rel_ 80	1'875.00	843.75
	Rel_ 81	7'300.00	3'285.00
Moyenne		3'285.00	1'478.25
Ecart-type		2'522.07	1'134.93
Erreur standard		1'127.94	507.57
11 à 20 ans	rel _42	635.00	285.75
	Rel_ 44	3'125.00	1'406.25
	Biom_ 7	3'875.00	1'743.75
	Biom_ 8	5'125.00	2'306.25
	Biom_ 13	8'000.00	3'600.00
Moyenne		4'152.00	1'868.40
Ecart-type		2'704.38	1'216.97
Erreur standard		1'209.47	544.26

21 à 30 ans	Biom_ 3	3'250.00	1'462.50
	biom _4	6'000.00	2'700.00
	Biom_ 14	3'375.00	1'518.75
	Rel_ 96	1'125.00	506.25
	Rel_ 97	9'000.00	4'050.00
Moyenne		4'550.00	2'047.50
Ecart-type		3'029.28	1'363.18
Erreur standard		1'354.77	609.65
31 à 40 ans	rel _29	8'425.00	3'791.25
	Rel_ 91	5'500.00	2'475.00
	Biom_ 1	1'875.00	843.75
	Biom_ 2	3'000.00	1'350.00
	rel _48	3'125.00	1'406.25
Moyenne		4'385.00	1'973.25
Ecart-type		2'615.85	1'177.13
Erreur standard		1'169.88	526.44
40 ans et plus	Rel_ 20	10'987.50	4'944.38
	Rel_ 21	7'312.50	3'290.63
	Rel_ 22	4'300.00	1'935.00
	Biom_ 5	8'400.00	3'780.00
	Biom_ 6	7'825.00	3'521.25
Moyenne		7'765.00	3'494.25
Ecart-type		2'398.04	1'079.12
Erreur standard		1'072.46	482.61

***ADB (Air dry biomass) est égale à ODB (oven dry biomass) après 3 semaines de séchage à l'air libre.**

Chapter IV : Nutrients released from ligneous vegetation in secondary forest after slash and burn cultivation in Central Menabe, Madagascar

4.1. Scatter plots of PCA analysis separately for (a) stem, (b) branches and (c) leaves in 28 species related to chemical variables (C, N, P, K, Ca, Mg) (a): stem, (b): branches, (c): leaves

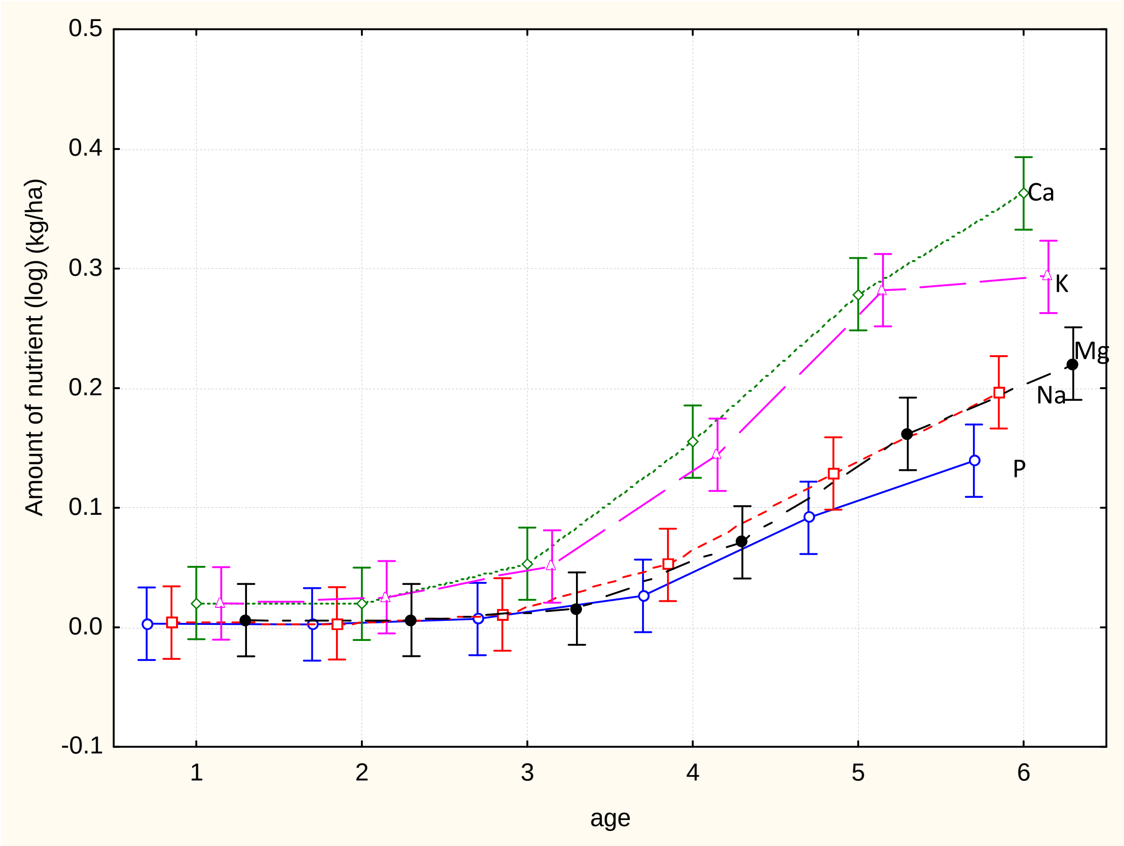


(a)

(b)

(c)

4.2. Amount of nutrients for 9 species in any age of abandonment



1: 1 - 5 years

2: 6 - 10 years

3: 11 - 20 years

4 : 21 - 30 years

5 : 31 - 40 years

6 : more than 40 years

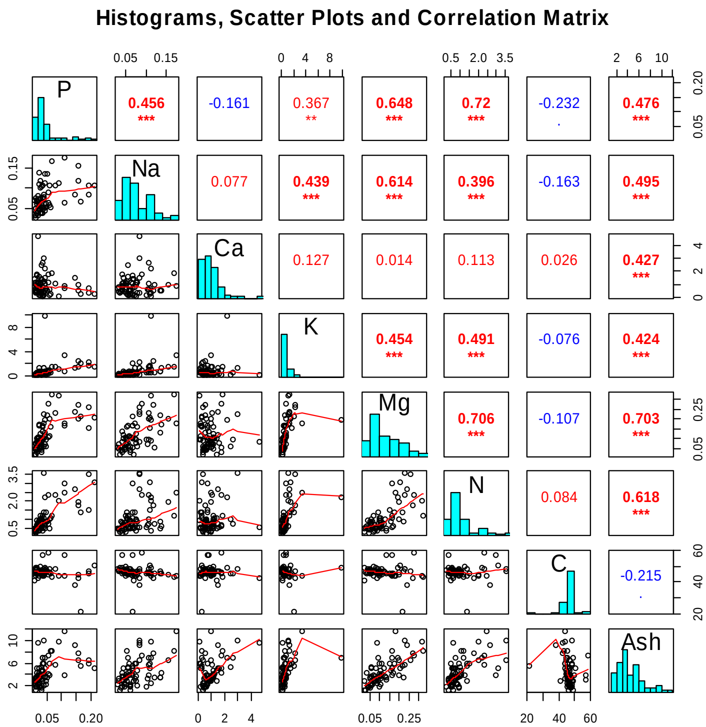
4.4. Recapitulation des résultats des minéralomasse des différents plots en fonction de l'âge d'abandon de culture (calcul détaillé sur CD)

		16	ODB tronc	Moyenne	ecart type	Erreur standard	ODB branche	Moyenne	ecart type	Erreur standard	ODB feuille	Moyenne	ecart type	Erreur standard
MOINS DE 5 ANS	REL_30		1'312.50				404.69				288.75			
	BIOM_15		7.20				0.00				2.50			
	Biom_16													
	Biom_17													
	Rel_31													
	moy		59.85	263.94	124.01	55.46		80.94				58.25	25.52	11.41
6 -10 ANS		16												
	biom_10		204.75				67.99				66.83			
	biom_11		549.28				161.88				130.81			
	biom_12		293.75				45.00				156.20			
	rel_80		374.06				37.50				0.00			
	rel_81		2'514.75				1'172.93				190.30			
				787.32	973.97	435.59		297.06	492.14	220.10		108.83	75.78	33.89
11-20 ans		64												
	biom_13		1'208.20				876.31				13.89			
	biom_42		1'535.85				1'371.36				879.59			
	biom_7		1'026.02				709.71				478.92			
	biom_8		1'490.58				503.61				189.43			
	rel_44		661.83				1'281.63				231.62			

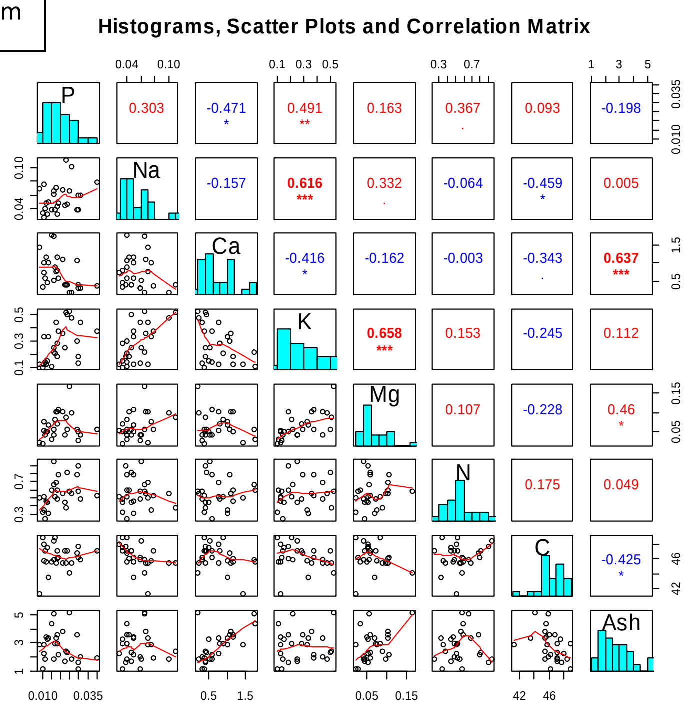
			1'184.50	359.16	160.63		948.52	370.79	165.83		358.69	335.22	149.92
21 -30 ans	64												
	biom_14	3'058.93				1'635.17				403.30			
	biom_3	19'105.43				7'572.88				2'992.73			
	biom_4	8'872.33				5'181.79				1'395.04			
	rel_96	14'403.41				7'322.49				1'073.52			
	rel_97	9'681.92				3'169.69				1'028.06			
			11'024.40	6'053.99	2'707.51		4'976.40	2'584.38	1'155.81		1'378.53	971.19	434.34
31-40 ans	256												
	biom_1	31'117.15				11'227.86				1'929.62			
	biom_2	12'950.84				4'768.82				880.76			
	rel_29	14'212.45				8'547.64				3'630.16			
	rel_48	33'316.04				14'754.44				2'829.01			
	rel_91	43'446.39				17'224.27				4'665.62			
			27'008.57	13'117.04	5'866.30		11'304.61	4'931.20	2'205.37		2'787.03	1'467.20	656.17
40 ans et plus	256												
	biom_5	37'788.37				8'346.35				1'895.72			
	biom_6	70'597.09				21'428.91				5'421.97			
	rel_20	50'806.18				16'487.97				3'639.24			

rel_21	52'427.30			18'697.49				1'974.11			
rel_22	30'327.57			13'422.71				1'356.12			
		48'389.30	15'442.95		6'906.51	15'676.69	5'041.97		2'254.90	2'857.43	746.59

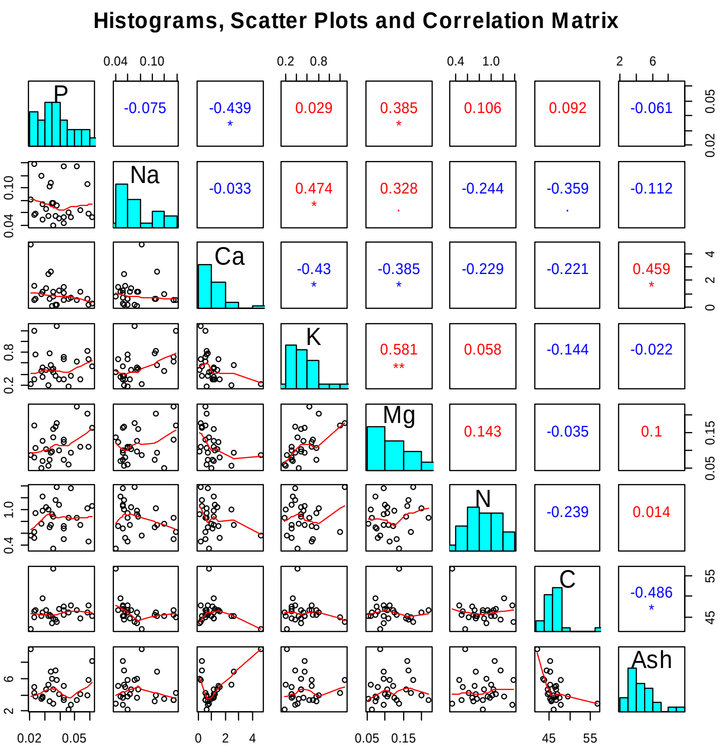
All (stem, branches, feuilles)



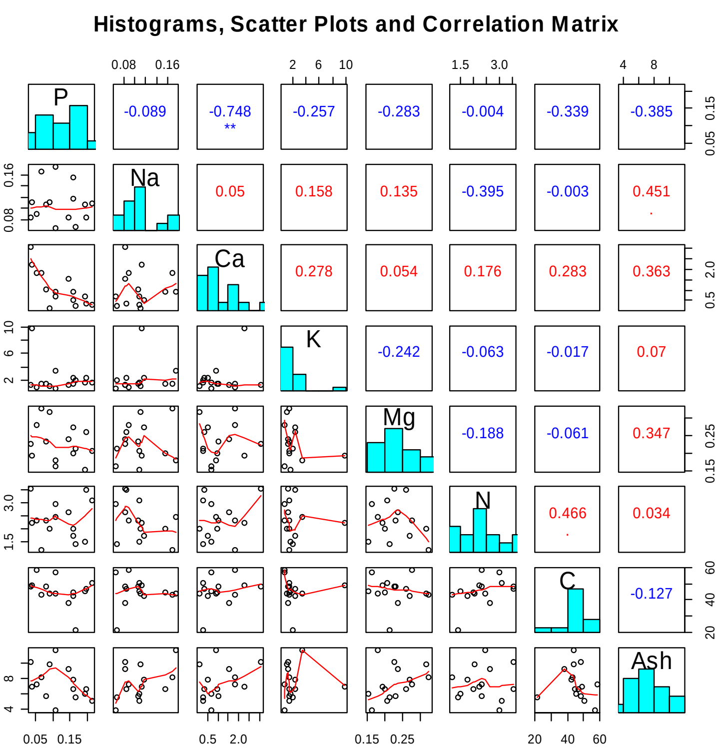
Stem



Branches



Leaves



Soil physico-chemical properties of the investigated plots according to the age of abandonment after cultivation (*monkas*).

Age classes	Age of *monkas*	Number of plots	pH		C_{tot} (%)		N_{tot} (%)		C/N		CEC (cmol(+)/kg)		Mg^{2+} (cmol(+)/kg)		Na^{+} (cmol(+)/kg)		Ca^{2+} (cmol(+)/kg)		K^{+} (cmol(+)/kg)		P-PO4 (ppb)	
I	Culture *	4	**7.99**	(0.168)	**1.84**	(0.207)	0.15	(0.035)	**12.51**	(1.533)	**7.69**	(1.125)	0.76	(0.089)	**0.03**	(0.003)	**7.05**	(1.184)	0.24	(0.090)	28.73	(6.561)
II	1 to 5	4	*6.22*	(0.067)	*1.05*	(0.115)	*0.10*	(0.000)	*10.53*	(1.147)	*3.23*	(0.500)	*0.34*	(0.043)	*0.01*	(0.002)	*2.71*	(0.407)	*0.16*	(0.036)	105.53	(48.648)
III	6 to 10	4	**7.26**	(0.418)	1.59	(0.453)	0.15	(0.013)	10.89	(2.914)	**7.65**	(1.433)	0.67	(0.153)	0.02	(0.012)	3.85	(2.351)	0.25	(0.074)	93.13	(30.318)
IV	11 to 20	4	6.80	(0.376)	**1.79**	(0.493)	**0.16**	(0.028)	10.89	(1.218)	6.68	(1.959)	0.75	(0.208)	**0.03**	(0.009)	4.64	(2.741)	0.27	(0.070)	141.40	(44.448)
V	21 to 30	4	6.51	(0.303)	1.66	(0.148)	**0.16**	(0.013)	10.55	(0.950)	6.13	(0.607)	**1.15**	(0.239)	0.02	(0.003)	4.58	(0.153)	**0.32**	(0.096)	85.93	(15.942)
VI	31 to 40	4	6.49	(0.094)	1.68	(0.463)	**0.16**	(0.034)	10.74	(0.568)	6.48	(1.967)	**1.17**	(0.255)	0.02	(0.006)	**5.18**	(2.139)	**0.28**	(0.087)	141.93	(24.415)
VII	>40	4	6.24	(0.059)	1.71	(0.235)	0.15	(0.017)	**11.29**	(2.010)	5.33	(0.549)	1.04	(0.193)	**0.03**	(0.006)	3.96	(0.471)	0.25	(0.044)	28.73	(6.561)

Age classes	Age of *monkas*	Number of plots	$N\text{-}NO_3$ in dry soils (ppm)		$N\text{-}NO_3$ in incubated soils (ppm)		$N\text{-}NH_4$ in dry soils (ppm)		$N\text{-}NH_4$ in incubated soils (ppm)		Soil respiration in the field (g $CO_2/m^2/h$)	
I	Culture *	4	3.99	(0.407)	28.12	(16.812)	1.94	(0.207)	**0.31**	(0.100)	*0.41*	(0.068)
II	1 to 5	4	2.75	(0.847)	*13.92*	(4.837)	1.36	(0.107)	*0.15*	(0.102)	0.64	(0.110)
III	6 to 10	4	2.74	(0.195)	17.11	(1.952)	2.69	(0.211)	0.19	(0.053)	0.60	(0.043)
IV	11 to 20	4	5.96	(0.885)	23.02	(3.289)	2.97	(0.099)	0.28	(0.130)	0.49	(0.042)
V	21 to 30	4	3.23	(0.505)	33.99	(5.335)	2.59	(0.194)	0.30	(0.009)	**0.81**	(0.136)
VI	31 to 40	4	7.38	(0.924)	**35.60**	(10.135)	2.84	(0.102)	**0.31**	(0.082)	0.56	(0.102)
VII	>40	4	3.99	(0.407)	**40.05**	(6.206)	1.94	(0.207	**0.42**	(0.287)	**1.10**	(0.051)

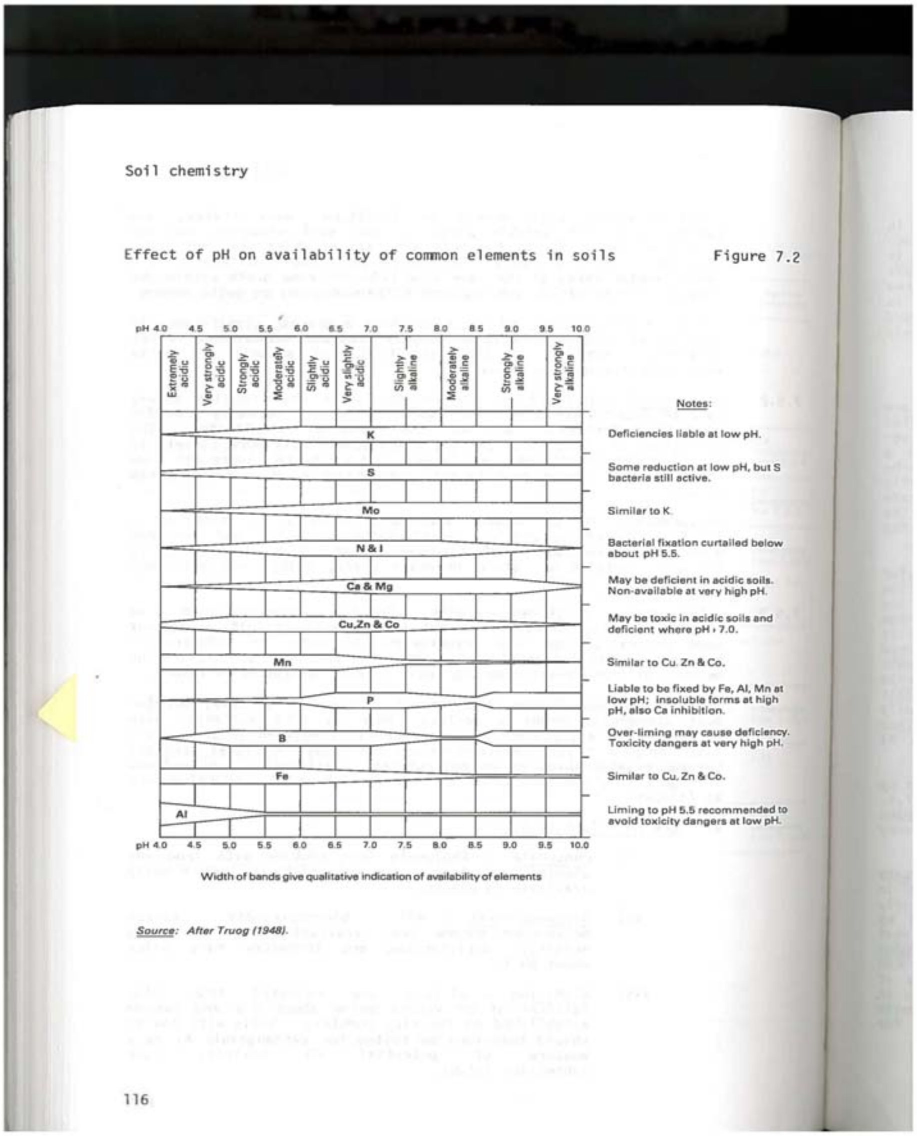
Means and standard deviations in the different age classes for pH (in water), total carbon (C_{tot}), total nitrogen (N_{tot}), total carbon on total nitrogen ration (C/N), cation exchange capacity (CEC), exchangeable soil nutrients: magnesium (Mg^{2+}), sodium (Na^{2+}), calcium (Ca^{2+}), potassium (K^{+}), available phosphorus ($P\text{-}PO_4$), nitrates in dry soils ($N\text{-}NO_3$), nitrates in incubated soils ($N\text{-}NO_3$), ammonium in dry soils ($N\text{-}NH_4$), ammonium in incubated soils ($N\text{-}NH_4$) and soil respiration in the field. For each variables, the two highest values are in bold and the lowest one is in italic.***** Different cultures were sampled: one plot of groundnut, 2 plots of maize and one plot of cassava in association with maize.

7.1. Moyenne des paramètres des sols jaunes en fonction de l'âge d'abandon de culture (n=4).

Age of abandonment	pH water	TOC %	N tot %	C/N	CEC (cmol/kg)	Mg^{2+} (cmol/kg)	Na^{+} (Cmol/kg)	Ca^{2+} (Cmol/kg)	K^{+} (Cmol/kg)
1-5 years	6.22±0.03	1.05±0.06	0.10±0.00	10.53±0.77	3.23±0.25	0.34±0.02	0.01±0.001	2.71±0.20	0.16±0.02
6-10 years	7.26±0.21	1.59±0.23	0.15±0.006	10.89±0.57	7.65±0.72	0.67±0.07	0.02±0.006	3.85±1.17	0.25±0.04
11 -20 years	6.80±0.19	1.79±0.24	0.16±0.01	10.89±1.45	6.68±0.98	0.75±0.10	0.03±0.005	4.64±1.37	0.27±0.03
21 - 30 years	6.51±0.15	1.66±0.07	0.16±0.006	10.55±0.61	6.13±0.30	1.15±0.12	0.02±0.001	4.58±0.07	0.32±0.05
31 - 40 years	6.49±0.04	1.68±0.23	0.16±0.02	10.74±0.47	6.48±0.98	1.17±0.13	0.02±0.003	5.18±1.07	0.28±0.04
More than 40 years	6.24±0.02	1.71±0.12	0.15±0.009	11.29±0.28	5.33±0.27	1.04±0.10	0.03±0.003	3.96±0.24	0.25±0.02

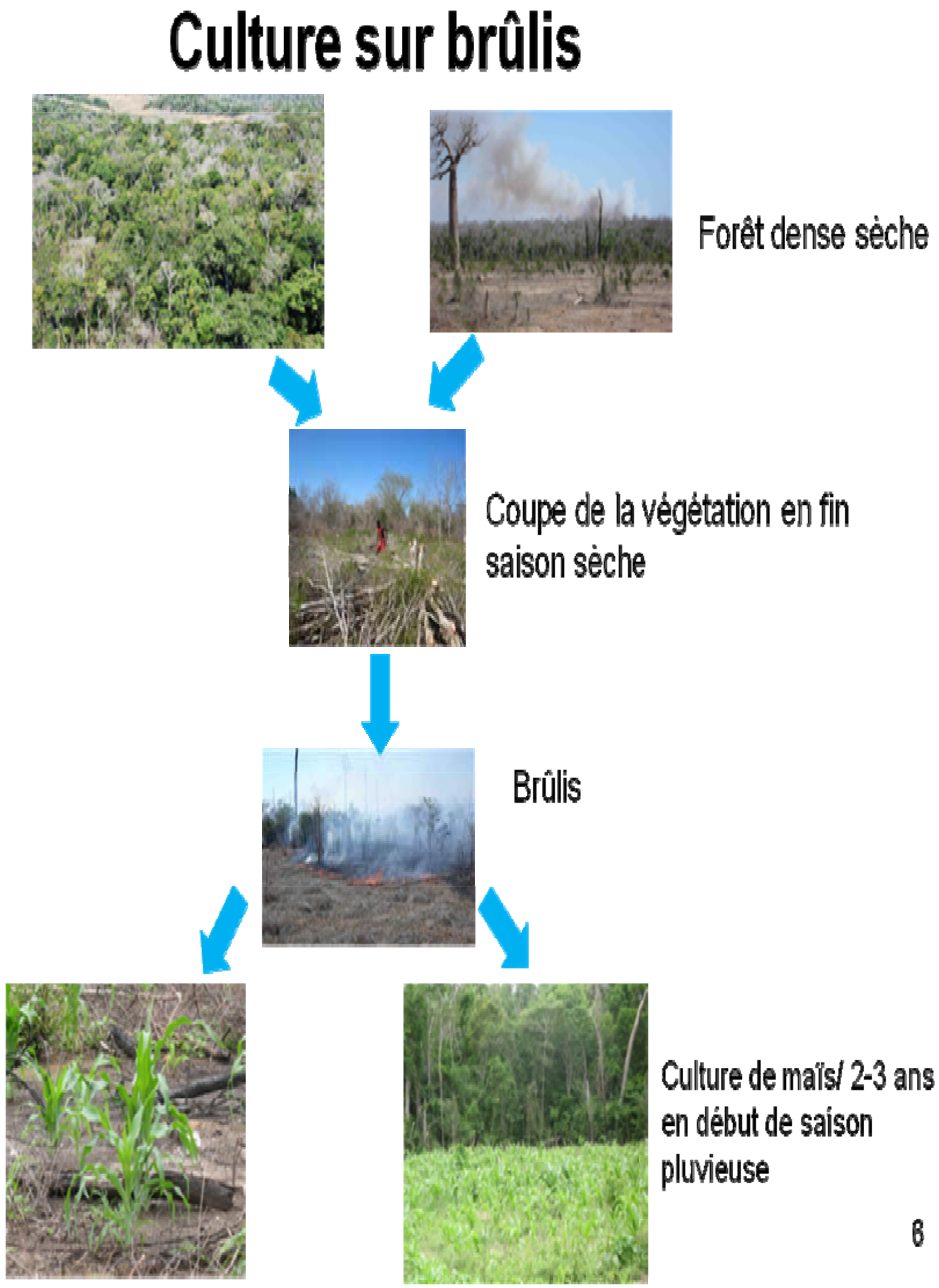
Source : Schneider, 2011

7.2. Effet du pH dans la disponibilité des éléments dans le sol



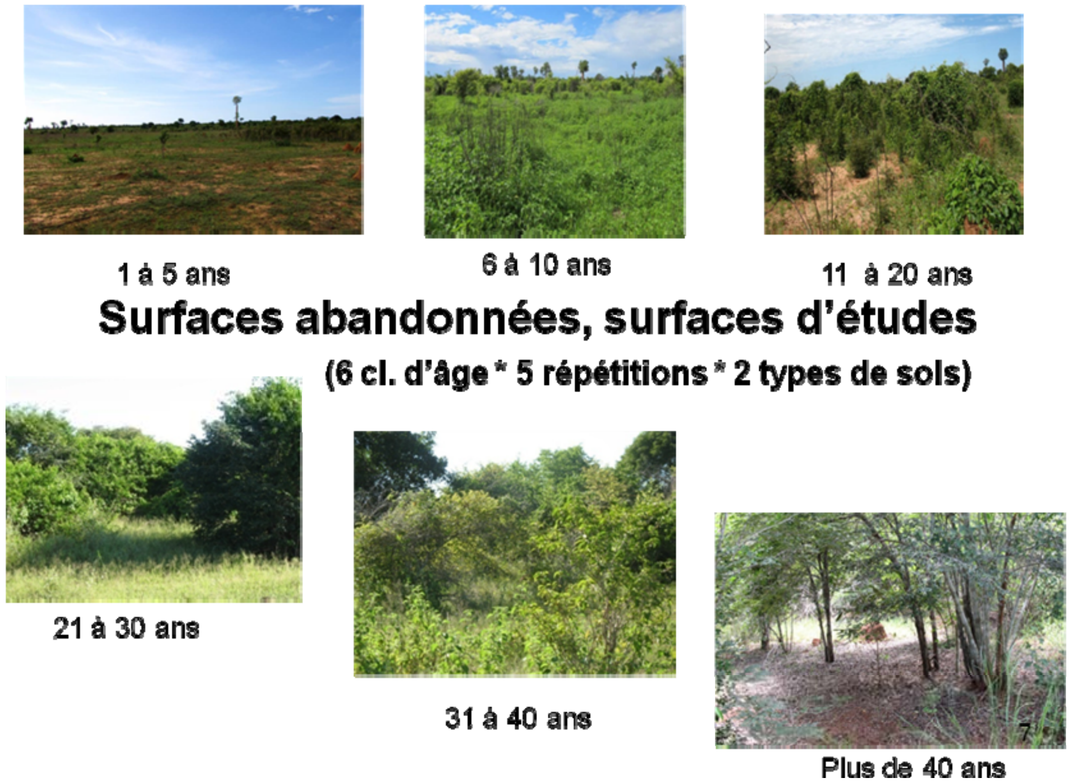
Source : Landon, 1996

Quelques photos



Surfaces d’études : formations

secondaires



Quelques exemples de plots choisis

Test d’inflammabilité

- Combustible: 28 espèces de bois tropicaux (130g, 4-5 répétitions) + 6 espèces (références européennes)

Tranche de tronc ou branche

Préparé et scié en bâton standard

Broyé

130g de bois broyé

- Source d’énergie:

32

Dispositif expérimental