Improving slash-and-burn agriculture in Central Menabe, Madagascar

THÈSE N^{O} 7839 (2017)

PRÉSENTÉE LE 27 OCTOBRE 2017
À LA FACULTÉ DE L'ENVIRONNEMENT NATUREL, ARCHITECTURAL ET CONSTRUIT
LABORATOIRE DES SYSTÈMES ÉCOLOGIQUES
PROGRAMME DOCTORAL EN GÉNIE CIVIL ET ENVIRONNEMENT

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

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ÉCOLE POLYTECHNIQUE
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Suisse
2017

This work is dedicated to my parents who revealed the traveler inside me.

“Be the change you want to see in the world.”

Gandhi


CE QUE JE PENSAIS FAIRE PENDANT MA THÈSE
Sauveuse de la Planète
COMMENT MES PARENTS ME VOIENT
COMMENT MES COLLÈGUES ME VOIENT
HiPS!
CE QUE JE FAIS VRAIMENT
NAAAANNN

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Acknowledgments

Ce projet n'aurait pas pu exister sans le soutien financier de l'EPFL (Ecole Polytechnique Fédérale de Lausanne), du WSL (Swiss Federal Institute for Forest, Snow and Landscape Research), et du SNSF (Swiss National Science Foundation). Un projet appliqué a vu également le jour grâce aux résultats de cette thèse. Ce projet a été financé par la FEDEVACO (Fédération Vaudoise pour la Coopération et le Développement), la commune de Rolle, l'association Ingénieurs du Monde et la DDC (Direction pour le Développement et la Coopération Suisse) et de nombreux donateurs.

Mes premières notes concernant mon projet de thèse remontent à juin 2012. Ce travail est donc né il y a 5 ans. A l'époque, je travaillais à l'EPFL pour les Prof. Rizlan Bernier-Latmani et Daniel Alessi en tant qu'ingénieure de recherche. Je me suis retrouvée à leur côté pour travailler sur la bioremédiation d'une nappe phréatique. Ce travail m'a enthousiasmée. J'étais entourée de gens passionnants, intelligents, drôles qui m'ont donné le goût de la recherche et l'envie de faire un doctorat. J'aimerais donc remercier l'équipe de l'EML de l'époque et surtout Rizlan et Dan pour m'avoir motivée à entamer une carrière de chercheuse. Un grand merci à Dan pour les sorties terrain et les excellents fous rire que nous avons faits ensemble. Surtout lors du terrain mythique à Thoune !

Cette thèse n'aurait également pas pu voir le jour sans le soutien précieux de mon professeur Alexandre Buttler. J'aimerais le remercier pour sa confiance et son appui durant ses 5 ans. Si les notes de thèse remontent à 2012, c'est parce qu'Alexandre m'a permis de co-rédiger avec lui les demandes de financement de mon projet de thèse, bien avant que je sois engagée officiellement comme doctorante. Un grand merci à toi Alexandre pour ta patience, ta flexibilité et surtout ta grande tolérance durant ma thèse. C'est grâce à toi que j'ai pu rester motivée du début à la fin. Un grand merci également à mes co-directeurs Robert Mills et Bjorn Robroek pour leur encadrement, leur gentillesse et surtout leur nombreux conseils. Un merci spécial à Bjorn pour ses multitudes corrections durant mon année de rédaction. Sans toi Bjorn, ce travail ne serait pas autant abouti. Merci de tes nombreuses heures passées sur mon manuscrit.

Merci également à tous mes co-auteurs pour leur aide sur mes articles. Merci à Thomas pour ses conseils très utiles sur mon premier article, à Dominique Hervé pour sa vision d'agronome, son aide précieuse sur le terrain et surtout sa grande connaissance de Madagascar. Merci au professeur Emmanuel Frossard pour ses explications et corrections précises qui m'ont grandement aidée à améliorer certains de mes manuscrits, ainsi qu'appris beaucoup quant à la rédaction d'articles. Merci à Chiara Pistocchi pour m'avoir enseigné les techniques de laboratoire et aidé à mesurer précisément le phosphore de mes sols. Merci à

Saleem Arif pour sa motivation, ses blagues, sa bonne humeur et ses conseils sur ma vie amoureuse aha ! Merci enfin à Patrick Waeber et à Claude Garcia pour leurs corrections et remarques sur la partie sociale de ma thèse. Je remercie également les membres de mon jury de thèse, les professeurs Emmanuel Frossard, Stephan Hättenschwiler et Stéphanie Carrière, pour leur relecture du présent document, leurs remarques pertinentes et le temps qu'ils ont consacré à ma soutenance privée, ainsi que le professeur François Golay pour avoir présidé le jury.

Un énorme merci à mes merveilleux collègues et amis malgaches : Philippe, Auréla, Marcel et Gilbert. Grâce à vous, je suis tombée littéralement amoureuse de Madagascar !! Heureusement que vous étiez là pour me soutenir, partager mes joies et ma frustration, mes tristesses, mon excitation sur les expériences scientifiques et pour tous ces moments incroyables de rire, de fête, de bonheur. Merci à Gilbert et Marcel pour avoir été nos anges à gardiens à tous dans la brousse, avoir tracé à la machette les chemins jusqu'aux champs de maïs, coupé sans relâche des branches d'arbres pour réaliser du compost, aidé à réparer le 4x4 tombé pour la millième fois en panne, négocié âprement avec les chefs de village, surveillé et porté tout le matériel. Toutes ces données scientifiques n'existeraient pas sans vous ! Merci à Philippe et Auréla également pour leur aide et leur amitié. C'était génial de travailler avec vous. Merci d'avoir observé, mesuré, pesé sans doute plus d'un millier de plants de maïs en ma compagnie. Merci pour vos imitations, vos farces et blagues et votre entrain. Merci enfin d'avoir continué à travailler pour moi de manière sérieuse et appliquée malgré mon retour en Suisse.

Merci également à toute l'équipe du projet AGRIFEU à Madagascar pour leur collaboration, leur excellent accueil et leurs conseils : les professeurs Bruno Ramamonjisoa, Samuel Razanaka et Jean-Chrysostome Randriamboavonjy, ainsi que Linja Rakotomalala et Mr. Harifidy. Merci à mes aides de terrain de la première année Michael et Ravaka. Merci enfin à mes amis malgaches en dehors du projet de thèse, Christophe, Naval, Christian, Mmes Lala & Nana, Mr. Rémi, Jaco, Mr. Sylvain et tous les villageois de Beroboka, Andranolava, Kirindy et Marofandilia pour leur aide lors de mes séjours à Madagascar. Merci à l'équipe incroyable du CNFEREF qui m'a accueillie dans la forêt de Kirindy durant les 6 missions de terrain du projet AGRIFEU.

Merci à mes amis et collègues du laboratoire ECOS actuels Amarante, Paola, Juan, Thomas, Constant, Pierre, Rodolphe, Florian, Tom, Claire, Sandra, Pascal, Lucas et ceux qui étaient de passage auparavant : Arthur, Ioana, Liam, Mathieu, Rocio, Esther, Felix, Adrian, Timothée, Johanna, Lia et ceux que j'oublierais! Merci pour les pauses café, les rires, les conseils, les grandes discussions sur la science et le reste. Un merci particulier à mes collègues doctorants Amarante, Paola et Juan de leur ENORME soutien! Je vous souhaite tout le meilleur pour la fin de votre thèse et pour votre continuation dans la recherche, vous étiez de super compagnons de bureau! Enfin, un merci spécial à Rodolphe pour ses conseils stat’ et sa présence toujours bienveillante, ainsi qu’à Sandra pour sa gestion efficace de la comptabilité du projet AGRIFEU.

Merci aux étudiants que j’ai encadrés et qui m’ont aidée à avancer: Clara, Nuria, Paul, Lucas et Nicolas. Merci en particulier à Clara qui m’a beaucoup fait rire durant les 3 mois que nous avons partagés ensemble à Madagascar. Merci de t’être battue avec les gros cafards de notre chambre ahah, d’avoir couru avec Philippe et moi dans la forêt en pleine nuit pour aller rechercher les touristes espagnols têtus ! Ah oui et merci d’avoir retrouvé… Finalement… Le tournevis pour réparer le panneau solaire !!! Merci aussi de t’être super bien adaptée aux conditions de travail et de n’avoir jamais râlé, malgré les 38 degrés en plein soleil, les toilettes bouchées, les passages intempestifs des fosas, les nombreuses autres bestioles et le riz matin, midi et soir ! Tu étais une compagne de terrain inestimable !

J’aimerais remercier ensuite plusieurs autres amis qui ont contribué au développement de ma passion pour l’Afrique et du monde en général. Merci d’abord à mon amie Leia Falquet, qui a partagé ces dernières années mes aventures les plus folles ! Le travail de terrain il y a 5 ans dans les tourbières du Limousin contaminées à l’uranium, les réparations de pompes dans les parkings à Thoune, les 10h de randonnée à ski de la Patrouille des Glaciers, les températures à -15°c au sommet de Riedmatten à 4h du mat avec les mains et les poumons gelés, les nuits dehors dans la boue en pleine saison des pluies à Madagascar, et enfin notre projet humanitaire en commun à Madagascar. Merci Leia de m’avoir aidé pour mon terrain de thèse et pour avoir contribuer à la réalisation de certains de mes rêves personnels.

Merci à mon ami de longue date Edouard Lehmann, ainsi qu’à mon cousin burkinabé Jeannau. Pendant mon master, en 2010, je suis partie en stage au Burkina Faso avec Edouard. J’ai vécu pendant 2 mois dans la belle famille de ma cousine Myriam, en compagnie de 18 burkinabés, de 3 chèvres, 10 poules, 2 chiens et 1 chat. Merci Edouard et Jeannau pour toutes nos conversations aux pauses de midi et en soirée qui m’ont donné l’envie de poursuivre mon travail en Afrique. Dans la même lignée, merci à mes amis qui sont partis en Inde pendant un an à mes côtés, Estelle, Mélina, Alexandra, Blaise et Zeno, avec qui j’ai partagé de nombreuses conversations qui ont avivé ma curiosité sur les pays en développement.

Ensuite, j’aimerais remercier l’équipe de l’association Ingénieurs du Monde : Sash, Armelle, Pauline, Paul, Antonin, Camille, Inès, Gwendoline, Nathan, Numa et tous les autres ! Et plus particulièrement Sash ! Merci Sash pour les WhatsApp que tu m’as envoyé quand j’étais coincée dans mon bureau, pour me changer les idées, aller boire des coups, rigoler, parler boulot, financement de l’assoc’, de voyage et surtout de comment on allait devenir super riches très bientôt, aha etc. ! Merci à Armelle pour son amitié et nos nombreux repas/bières qu’on a partagés ensemble. Merci de partager avec moi la même vision du monde. Ah oui ! Et désolée de t’avoir laissé l’assoc’ quand je suis partie sur le terrain aha! Un gros merci à Pauline, alias Pouley, pour tous les virements que tu as faits pour Leia et moi pour notre projet à Mada et toutes les corrections que tu as apportées à la compta pour l'assoc' !

Enfin, merci à tous mes amis en Valais, à Lausanne, à Zürich, au Chili, en Inde, à Mada, au Burkina et de partout ailleurs dans le monde pour avoir partagé des moments chaleureux avant, durant et sans doute encore après ma thèse et être là pour moi ! Un merci particulier à mes amis de Lausanne pour avoir supporté mes plaintes quand cela n'allait pas durant ma thèse et pour m'avoir sortie pour me changer les idées. Enfin, un grand merci à ma famille et mes parents et sœurs pour m'avoir soutenue dans la poursuite de mes études, m'avoir fait découvrir les voyages et montrer la beauté du monde. Finalement merci à Vincent Jassey, tout d'abord mon collègue, puis copain et à présent futur mari pour son aide inestimable !! Merci Vincent de m'avoir supportée pendant la rédaction de ma thèse, de m'avoir donné plein de conseils, de m'avoir préparé mon petit déjeuné tous les matins au réveil et d'avoir été là tout le temps, dans tous les moments quoi qu'il arrive! Merci pour ta patience et tes appels téléphoniques pour me conseiller, me rassurer quand nous étions à distance. Tu mérites des centaines de mercis!! Je me réjouis de continuer la suite de mes aventures sur le même chemin que toi.

Merci enfin aux gens que j'aurais oubliés et qui m'ont soutenue d'une manière ou d'une autre dans ce travail !

Summary

Slash-and-burn agriculture is considered as an important driver of deforestation in the tropics. In Madagascar, a biodiversity hotspot, this type of agriculture particularly threatens the tropical forest cover. On the south-western coast of the island, in Central Menabe, the dry tropical forest of Kirindy suffers from an annual deforestation of 2.6%. At such alarming rate, the forest will have entirely disappeared by 2050. The attention of past research programs and conservation actions were mainly on studying the forest or the general interactions between local populations and the forest, with little focus on the slash-and-burn agricultural system itself. Hence, understanding the cultivation practices and assessing alternatives to them is crucial to improve the current forest conservation initiatives.

The present thesis answers to the need of an in-depth study of the agricultural practices in Central Menabe. The project aims to (1) analyze the practices of slash-and-burn cultivation in Kirindy forest, (2) explore alternative slash-and-burn practices which may be more sustainable for the forest, (3) determine the implementation perspectives of these alternatives. In a first stage, we have characterized soil productivity along repetitive slash-and-burn cultivation cycles and the farmer's perception of their agricultural system. Then, we experimented a selective slash-and-burn agriculture (where trees are left intentionally within the cultivated fields), coupled with compost amendment. Finally, we have assessed the implementation potential of that technique through interviews and participating workshops with local farmers.

Our findings highlighted that soil depletion due to plant uptake and erosion or leaching by heavy rains, as well as weed invasion were important problems of slash-and-burn cultivation in Central Menabe. Farmers perceive weeding as a work overload. Decrease in grain yield due to slash-and-burn agriculture reaches about 40% after three years of cultivation on the same field (from 4 to 2.5 t ha^{-1}), and decreases up to 75% after a single cyclonic rainy season (from 4 to 1 t ha^{-1}). Further, we demonstrated that combining compost and wood ashes (from the burnings) seems a promising solution to sustain cultivation on the fields. Compost, combined with wood ashes, multiplied corn yield by 5 compared to traditional slash-and-burn agriculture. Growth rates were accelerated and phenology stages of maize plants advanced. Furthermore, this combination also increased soil security by improving the remaining stock of nutrients after a rain simulation. On the other hand, a partial remaining tree cover (selective slash-and-burn agriculture) improved corn yields only when the soil was amended with ashes, not with compost, nor the combination of both. Implementing composting in the forest dwelling communities appears to be a challenging task. Several barriers were highlighted, among them the most important was the water constraints during a consequent period of time related to compost maintenance.

Alternative slash-and-burn practices have not been much studied so far because the use of fire was always considered as destructive. Thus, our result will contribute to the development of new forest management strategies which would balance conservation of habitats and rural communities agricultural needs, while minimizing the impact on primary forest.

Keywords
Tropical forests, deforestation, Madagascar, shifting cultivation, crop yield, soil nutrient, soil depletion, compost, wood ashes, forest dwelling communities.

Résumé

L'agriculture sur brûlis est considérée comme une cause importante de la déforestation dans les régions tropicales. À Madagascar, reconnu comme un hotspot de la biodiversité, la déforestation liée à ce type d'agriculture est particulièrement alarmante. Dans la région du Menabe central, la forêt tropicale sèche de Kirindy souffre d'une perte en couverture forestière de 2,6% par an. A ce rythme, la forêt aura complètement disparu d'ici 2050. L'attention des programmes de recherche passés a surtout porté sur l'étude de la forêt ou sur les interactions générales entre les populations locales et la forêt, sans se concentrer réellement sur le système agricole en lui-même. Cependant, l'étude des pratiques agricoles et leurs alternatives sont essentielles à l'amélioration des stratégies actuelles de conservation de la forêt.

Cette thèse vise donc à (1) analyser les pratiques de la culture sur abattis-brûlis dans la forêt de Kirindy, (2) explorer des alternatives durables de ce type d'agriculture, (3) déterminer leurs perspectives d'implémentation. Dans un premier temps, nous avons caractérisé l'évolution de la productivité des sols lors de cycles de culture répétés d'abattis-brûlis, ainsi que la perception des agriculteurs de leur propre système agricole. Ensuite, nous avons expérimenté une agriculture sélective sur abattis-brûlis (où certains arbres sont laissés intentionnellement dans les champs cultivés), couplée à un amendement en compost. Finalement, nous avons évalué le potentiel de mise en œuvre de cette technique par des entretiens et des ateliers participatifs avec les agriculteurs locaux.

Nos résultats ont mis en évidence que l'appauvrissement des sols par la répétition de cultures, leur érosion/lessivage lors de fortes pluies et leur invasion par des mauvaises herbes étaient des problèmes fondamentaux de la culture sur brûlis dans le Menabe Central. Les agriculteurs perçoivent le désherbage des mauvaises herbes comme une surcharge de travail. La diminution des rendements céréaliers atteint environ 40% après trois années de culture sur le même champ (de 4 à 2,5 t ha^{-1}), et diminue drastiquement de 75% après une saison des pluies cyclonique (de 4 à 1 t ha^{-1}). Dans un second temps, nous avons démontré que combiner compost et cendres semblait être une solution prometteuse pour améliorer la résistance du système agricole. Cette combinaison, amendée aux champs, multiplie les rendements de maïs par 5 par rapport à l'agriculture traditionnelle. Le taux de croissance du maïs a été accéléré, ainsi que sa phénologie avancée. De plus, cette combinaison augmente la résistance du sol au lessivage en améliorant le stock de nutriments restants après une simulation de pluies. Par contre, une couverte partielle d'arbres (agriculture sur brûlis sélective) n'a donné que des résultats mitigés, puisqu'elle a permis d'améliorer les rendements uniquement lorsque le sol était amendé avec des cendres et non avec du compost, ou une combinaison cendres et compost. Finalement, plusieurs obstacles ont été mis en évidence quant à la mise en œuvre

du compostage dans les communautés rurales, parmi lesquels l'arrosage du compost pendant une période de temps significative.

Ce type d'alternative à l'agriculture sur brûlis n'a pas été beaucoup étudié jusqu'à présent. Nos résultats contribuent donc à l'élaboration de nouvelles stratégies de gestion forestière qui permettraient d'équilibrer la conservation des habitats naturels et les pratiques agricoles des populations locales, tout en réduisant l'impact sur la forêt primaire.

Mots clés
Forêts tropicales, déforestation, Madagascar, culture itinérante, rendement des cultures, nutriments du sol, appauvrissement des sols, compost, cendres de bois, communautés rurales forestières.

- CHAPTER 1 -

General introduction

Picture: Groundnut and maize cultivations in a deforested landscape (Menabe region, Madagascar)
Justine Gay-des-Combes, 2015

1.1 Slash-and-burn agriculture and deforestation

Biodiversity loss is one of the most serious environmental threat of the 21st century , menacing important ecosystem services and human welfare (Ceballos et al., 2015). The fast decline of huge biomes, such as tropical forests, is one of the reasons for this disaster (Ceballos et al., 2015; Lamb et al., 2005). During the last century, approximately 500 million hectares of tropical forests have been degraded and 350 million hectares have been deforested (Lamb et al., 2005). In the recent decades only (i.e. 2000 to 2010), 7 million ha of forests have undergone deforestation or degradation (FAO, 2016). Tropical forests have been converted mainly to agricultural lands. This conversion was either done for large commercial plantations and forest products (Fitzherbert et al., 2008; Hamilton et al., 2016) , for livestock grazing (Calvo-Alvarado et al., 2009; Griscom and Ashton, 2011) or for subsistence agriculture, mainly through slash-and-burn cultivation (Geist and Lambin, 2002; Grinand et al., 2013; Kull, 2002; Zinner et al., 2014). FAO (2016) shows that the most cited cause of forest loss in a range of governmental documents across the world is slash-and-burn agriculture, and directly after that the global need in forest products (including wood fuel). Indeed, slash-and-burn or shifting cultivation is still the main agricultural production system for the rural poor living in tropical forest margins (Geist and Lambin, 2002; van Vliet et al., 2012). It impacts some 410 million ha of forests around the world –mostly in Latin America, Africa and Southeast Asia–, roughly one fourth of the global arable land (Fig. 1.1, Hurtt et al., 2011). The disappearance of these forests contributes largely to global warming, which is estimated to account for up to to 35% of the anthropogenic carbon emissions yearly (DeFries et al., 2002).

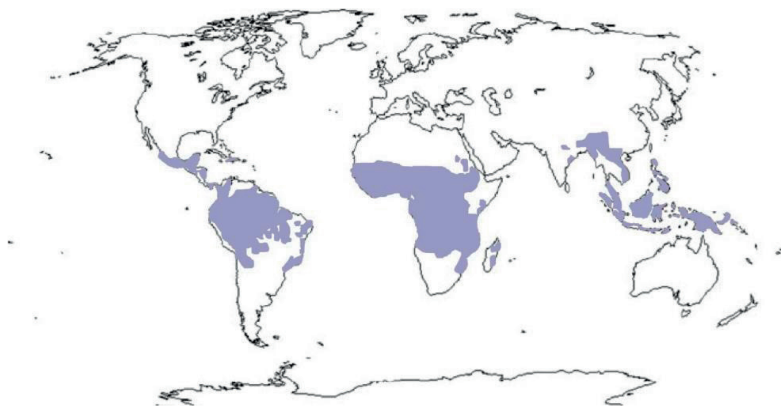

Figure 1.1 Worldwide distribution of slash-and-burn agriculture (map adapted form Hurtt et al., 2011)

In Madagascar, the problem of deforestation is particularly alarming (Dirac Ramohavelo, 2009; Genini, 1996; Zinner et al., 2014). While slash-and-burn cultivation is still the traditional and predominant land use practice in forested regions on the island (Styger et al., 2007), it has been pointed out as the major driver of current deforestation (Scales, 2012). Even though Madagascar is recognized as one of the major global biodiversity hotspots with a high priority for protection and conservation (Myers et al., 2000), the rate of deforestation does not diminish. As a noticeable example, on the south-western coast, in the Menabe region, one of the largest remnant of dry deciduous forest, the Kirindy forest, was predicted to disappear within the next 11 to 37 years (Zinner et al., 2014). The fastest deforestation rate was recorded between 2008 and 2010, with an annual loss of 2.6% of the forest cover, i.e. 1820 ha $year^{-1}$ (Zinner et al., 2014).

Slash-and-burn agriculture is a traditional and convenient way to cultivate under the tropics. The several following steps describe that type of agriculture: (i) a surface of forest is cleared by slashing the trees, (ii) the cut wood is burned and the ashes are used to amend the soil, (iii) the farmers cultivate during a brief period of time on the newly cleared field, (iv) the field is left into fallow for a long period (generally above 5 years) (Fig. 1.2, Dounias et al., 2000; Kleinman et al., 1995; Raharimalala, 2011). Thus, slash-and-burn agriculture alternates between cultivation and fallow periods. That system is also referred sometimes as shifting cultivation or swidden agriculture, with the difference that those two terms include also a notion of displacement in the space (Dounias et al., 2000). 'Slash-and-burn' refers only to the act of cutting and burning (Dounias et al., 2000). A common recognized definition for shifting slash-and-burn agriculture is given by Conklin (1957) as "Any agricultural system in which the fields are cleared by fire and cultivated for a short period to be subsequently left fallow for a relatively long duration". However, in the following work, to simplify the writing, we will refer only to « slash-and-burn » agriculture.

Slash-and-burn agriculture affects both soil chemical and physical properties. The soil amendment relies on wood ashes which contain mainly calcite, but also potassium carbonates and K, Ca, Mg, Na oxides and hydroxides (Demeyer et al., 2001; Ulery et al., 1993). Momentary, ash amendment provides nutrients to plants in two ways. First, ashes have a strong alkaline power due to the presence of oxides and carbonates. They increase soil pH, favour microbial activity and hence stimulate soil nutrient availability (Demeyer et al., 2001). This is particularly useful on tropical acidic soils. Second, ashes contain nutrients themselves. Hence, most of the nutrients released (about 50%) are either potassium (K) or calcium (Ca) (Ohno and Erich, 1990). Nitrogen (N) is generally not present in ashes, as it gets volatilized during the combustion. Thereby, ashes from slash-and-burn agriculture most probably leave the soil nitrogen limited, which may prevent a sustainable crop growth. Consequently, fertilization rates and nutrient uptake by plants are imbalanced, resulting in soil nutrient depletion after a few years of cultivation (Folberth et al., 2013).

Furthermore, rainfall can provoke a rapid leaching of nutrients (Thomaz, 2013). Indeed, the oxides present in the ashes are very soluble. Thus, they don't persist generally trough the rainy season (Ohno and Erich, 1990; Ulery et al., 1993). Calcite is lesser soluble and could resist during at least 3 years after burning, leaving a moderately basic pH in the soils (Thomaz et al., 2014; Ulery et al., 1993). In addition to soil depletion, slash-and-burn agriculture tends to weaken the top soil. Indeed, with tree removal through slashing-and-burning, the arable land remains bare, with no protection against winds and rains (Are et al., 2009; Comte et al., 2012; Thomaz, 2013). As most soils under the tropics are highly weathered and possess a light structure, the effects of the rain can be particularly damaging (Niu et al., 2015; Vezina et al., 2006). The tree cover can no longer offer protection against the splash-effect produced by raindrops, neither the tree roots retain the soil, leading to a rapid soil erosion (Nair, 2013; Vezina et al., 2006).

The combined effect of plant uptake, low fertilization rate and both wind and rain erosions can easily lead to the degradation of the nutrient rich top soil (Comte et al., 2012). It happens that the ecosystem sometimes never recovers from such degradation and consequently we assist to the deforestation of larges areas: the ecosystem switch from a previously forested ecosystem to a savannah-type secondary succession (Raharimalala et al., 2012). Slash-and-burn agriculture can become destructive for the forested ecosystems, especially when a high density of population applies this practice (Kleinman et al., 1995). The sustainability of slash-and-burn agriculture is a growing concern due the fast and significant climatic and economic changes of the last 50 years (Mertz et al., 2009; van Vliet et al., 2012). Cultivation and fallow time, together with population density, are fundamental factors to determine the sustainability of slash-and-burn practices (Kleinman et al., 1995; Mertz, 2002, Fig. 1.2, Fig. 1.3). For each cultural system, an optimal fallow duration is given: extended fallow periods are not necessary, but shorter fallow periods conducts to a decline in soil productivity (Mertz, 2002; Norgrove and Hauser, 2016, Fig. 1.2, Fig. 1.3). Increased people density often constraints the prolongation of cultivation times, with a concomitant reduction of fallow times. As a result, soil nutrient cycles are short-circuited, resulting in a drastic decrease of soil fertility (Ziegler et al., 2009). Generally, for most tropical ecosystems, forest regeneration can only be successful with a strict minimum of 10 years of fallow (Thomaz et al., 2014). In Madagascar, fallow time has been reduced from 8 to 4 years those last decades, leading to more deforestation (Jarosz, 1993).

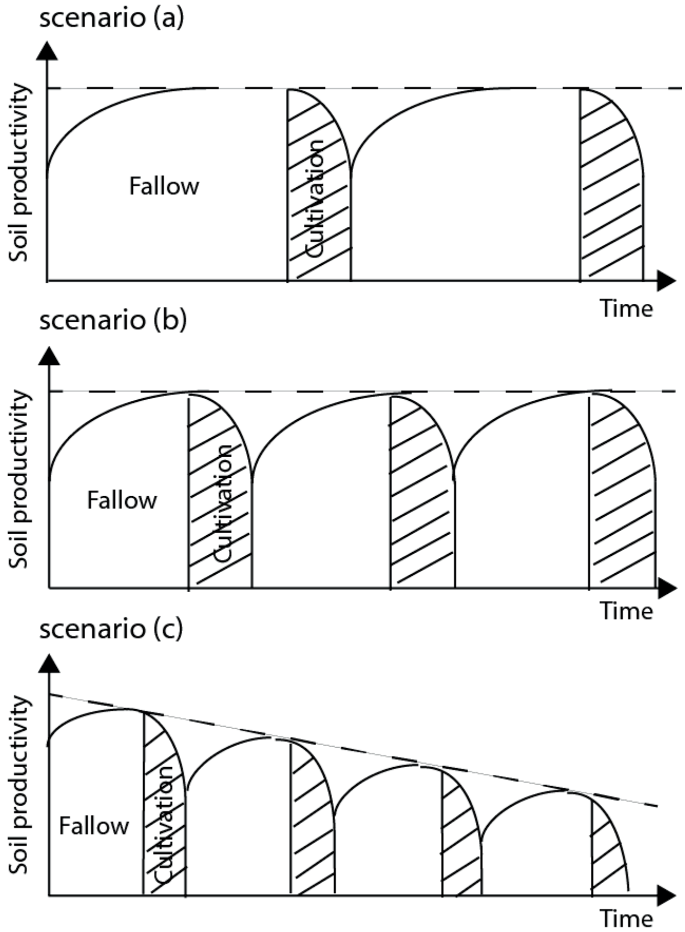

Figure 1.2 *Evolution of soil productivity according to time. Scenario (a) Fallow time is unnecessary too long, scenario (b) Fallow and cultivation time are correctly adjusted, scenario (c) Fallow time is to short, leading to a decrease in soil productivity. (Figure adapted from Mertz, 2002)*

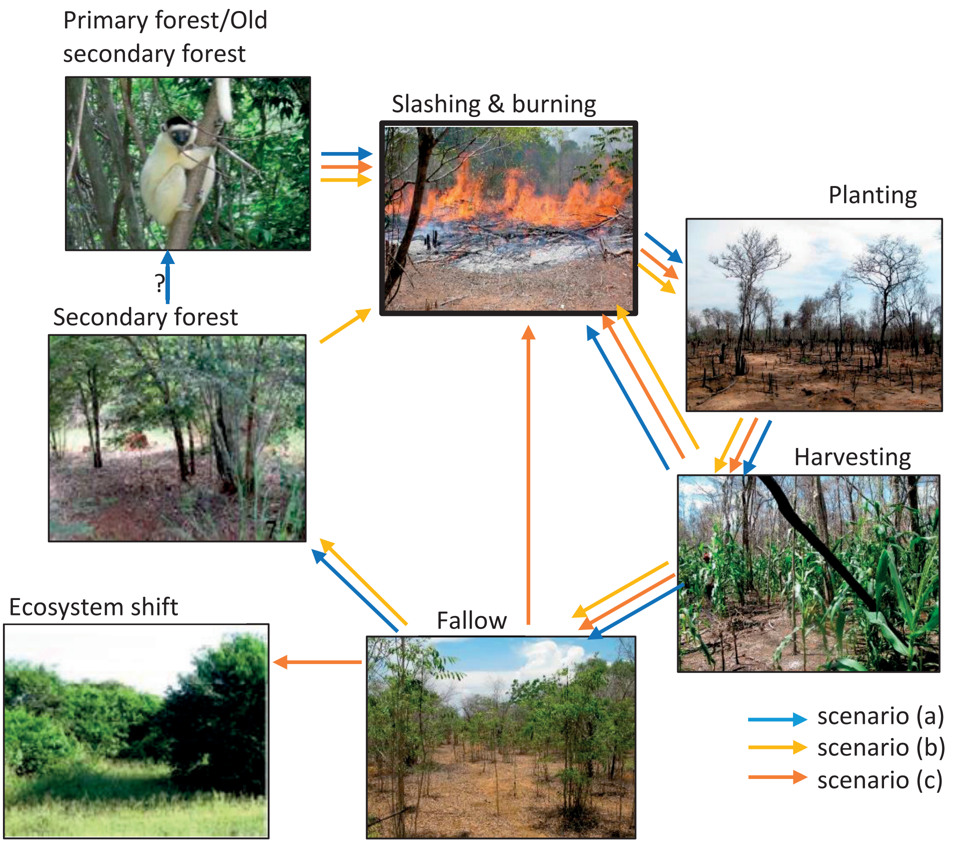

Figure 1.2 The different steps of slash-and-burn agriculture according to the scenarios of Fig.1.2

1.2. Alternatives to slash-and-burn agriculture

To fight deforestation from slash-and-burn agriculture, four common strategies exist: (1) building protected areas where human activity is forbidden to safeguard the remaining fauna and flora, (2) reforesting the degraded areas with the hope to restore biodiversity, (3) changing the lifestyle of the rural communities by offering new economic activities or involving them in forest management, (4) improving agricultural productivity on the degraded abandoned fields to alleviate the pressure on the primary forests. The first approach was mainly employed 50 years ago and is now highly criticized because it may push local communities outside of their home, and does not recognize their needs for forest use. It has generally resulted in poor results with rebellions from the forest-dwelling people and draw backs effects on the biodiversity at regional scale (Kaimowitz and Sheil, 2007; Laurance, 2012). The second approach implies a consequent money investment at the beginning of the project and does not treat the deforestation problem at its roots (Lamb et al., 2005). Furthermore, the risk of failure is high if the necessary care is not given for some time to the new plantations. The third and fourth approaches are considered as the most sustainable and promising solutions because they directly involve local people and do not need external financial support. The third approach has been studied under various forms of rural communities involvements (Payments for Ecosystem Services (PES), Networks for reduction of carbon emissions from deforestation and forest degradation (REDD+), Community-Based Resources Management (CBRM), Brimont and Karsenty, 2015; Dressler et al., 2010; Poudyal et al., 2016). However, there is an increased recognition on the complexity of considering different stakeholders and the difficulty of running truly participatory projects that balance conservation and development (Garcia et al., 2010; Scales, 2012). Environmental protection projects often do not sufficiently take into account the needs of local communities. If the local communities are not involved in the project, they end up with a very poor implementation of the results.

Concerning the fourth approach, improvement of system production in rural poor countries commonly involved organic fertilizations (e.g. compost or biochar), mulching instead of burning, or agroforestry (Agegnehu et al., 2016; Feng et al., 2017; Glaser et al., 2001; Mbau et al., 2014; Tully et al., 2015; Vezina et al., 2006; Zhang et al., 2016). Compost is the result of the mineralization and partial humification of organic matter (Zucconi and De Bertoldi, 1987). It leads to the formation of a stabilized final product, which can be employed as agricultural soil amendments (Zucconi and De Bertoldi, 1987). Compost is a low cost and easy method to enhance the soils' nutrient status, and to counter N deficiency provoked from the ashes of slash-and-burn agriculture. The most accessible manner to produce compost consists in forming heaps with organic residues (kitchen waste, plant residues, manure) with weekly mixing to enhance aeration and homogenization to increase the decomposition rate of the organic matter (Lima et al., 2004). Compost maturation can last about 6 to 18 months, depending on the surrounding humidity and temperature, and is obtained once compost physicochemical properties are stabilized (Albrecht et al., 2008). Once, maturity is reached, the compost should have the capacity to enhance seed germination and plant development (Albrecht et al., 2008). Compost enhances both water- and nutrient holding capacity of the soil (Zhang et al., 2016). It has been shown to increase crop yield in numerous studies (Abdel-Sabour and El-Seoud, 1996; Mbau et al., 2014; Zhang et al., 2016), with yields sometimes even superior to treatments with only mineral fertilization (Lyimo et al., 2012). Compost also helps fighting against soil-borne plant diseases (Lyimo et al., 2012; Mehta et al., 2014).

If compost has been used since many years, biochar, on the contrary, has been studied only since the last 25 years (Abiven et al., 2014; Butnan et al., 2015; Chaganti et al., 2015; Hass et al., 2012; Jiang et al., 2016; Laird et al., 2010; Reed et al., 2017). It was discovered in Brazil, along the Amazon river, under the form of a very dark earth, called "Terra Preta" by the local farmers (Glaser et al., 2001; Ponge et al., 2006). Archeologists explain that biochar is an anthropogenic material with very ancient roots that could be related to the existence of the El Dorado (Abiven et al., 2014; Cernansky, 2015). Biochar is closely related to wood ashes as both come from the combustion of wood. The pyrolysis or complete incineration of wood biomass results in the creation of biochar and ashes, respectively. The specificity of biochar relates to its content in 'black carbon', which results from the incomplete combustion of organic material. Black carbon possesses a polyaromatic structure which makes it chemically and microbiologically stable, leading, when amended to soils, to the formation of recalcitrant organic matter over several years (Glaser et al., 2001). Biochar benefits to the soil by enhancing its quality in terms of nutrient status, water holding capacity and microbial activity (Hass et al. 2012; Mitchell et al. 2015). Nonetheless, the efficiency of biochar is debated as the beneficial properties of biochar have largely been attributed to its high surface area, which, in turn, depends on the quality of pyrolysis achieved (Butnan et al., 2015). Such pyrolysis requires knowledge and has an economical cost that people in developing countries are not always willing to pay (Cernansky, 2015).

Mulching and agroforestry have been used also extensively in the past years (Carrière et al., 2002b; Kader et al., 2017; Nair, 2013; Reynolds et al., 2007). Both, trees and mulch, help to protect the soil from erosion and weed invasion. Mulch consist in any soft organic material which is applied on the land surface (Kader et al., 2017). It can be straw or crop residues for instance. It covers the soil surface and helps in conserving soil moisture and mitigating soil erosion by reducing water surface runoff (Kader et al., 2017). The best successful example concerning slash-and-burn agriculture is probably the Quesungual agroforestry system, in Honduras (Fonte et al., 2010; Pauli et al., 2011). It consists in a radical modification of slash-and-burn agriculture where burning was replaced by mulching and agroforestry. It started in a village called Lempira Sur in western Honduras where farmers were practicing slash-and-burn agriculture on slopping places. Due to soil erosion, the soil was degrading very fast after slashing-and-burning. Thus, they started keeping tall trees to protect the soil and banned the use of fire. Trees were valuable because they also provided the villagers with fruits and timber, improving the local livelihoods. Another example of mulching and agroforestry in response to slash-and-burn agriculture, is the Inga Alley Cropping method (Hands, 2014). That method uses alley cropping with tree species from the genus Inga. Those trees are nitrogen-fixing species and allow to preserve a suitable level of nitrogen in the soil.

Nonetheless, among all the various strategies to improve land productivity, it is very rare to observe studies where slash-and-burn practices are preserved and improved. Even though since 15 years, there is a growing recognition that slash-and-burn systems have been unnecessarily demonised and can be sustainable, even beneficial to the environment under some conditions (Carrière et al., 2002b; Dounias et al., 2000; Kull, 2000, 2002; Mukul et al., 2016; Scales, 2012). Undeniably, wood ashes are useful for tropical soils as they significantly increase nutrient availability (Ohno and Erich, 1990). Thus, a different approach where fire would be preserved could be imagined. Indeed, some examples of remarkable sustainable slash-and-burn systems can be found in Cameroon or in Philippines (Carrière et al., 2002b; Mukul et al., 2016). While those systems are performed with a low population density, they have interesting particularities that could be exported in other, less sustainable, slash-and-burn systems to improve them. Carrière et al. (2002a, 2002b) showed that Ntumu tribes in South Cameroun perform a selective slash-and-burn agriculture which is durable and preserves the forest. The method draws from agroforestry: some isolated trees are left within the future cultivated field and the others are cut and burnt to produce ashes. Ashes are then dispersed on the field as an amendment. The remaining standing trees help to maintain the soil fertility with their falling leaves, improve the surface microbiological activity and prevent erosion. These remaining standing trees are chosen very carefully according to the species, the umbrage, and the field orientation. Another example would be in the Philippines (Mukul et al., 2016) where shifting cultivation, locally called *kaingin*, is the main land-use in upland areas. It has been observed that the size of cleared areas for cultivation never exceeds 1.15 to 1.35 ha. This particular landscape patchiness is responsible for a faster biomass recovery. The surrounding trees of each patch provide an effective seed source to recolonize the cleared surface.

1.3. The dry tropical forests of western Madagascar

1.3.1 General context

In Madagascar, slash-and-burn agriculture, or *tavy* in Malagay, is still the main driver of the deforestation of the island. Slash-and-burn agriculture has been seen as destructive for the biodiversity since the colonial time (Jarosz, 1993; Scales, 2012). Extensive researches have been done in Easter Madagascar in the humid tropical forests to find alternatives to slash-and-burn agriculture (Hume, 2006; Poudyal et al., 2016). However, on the western coast, the dry tropical forests have been neglected, even though those forests are equally or even more threatened than the humid forests (Waeber et al., 2015). Indeed, tropical dry forests are under pressure worldwide: they are very appreciated by the farmers because of their mild climate, which make them favourable for agriculture (Calvo-Alvarado et al., 2009; Griscom and Ashton, 2011). Those forests possess also an endemic and rare fauna and flora. For instance, the semi-arid western coast of Madagascar is the home of the endemic baobab Adansonia grandidieri, found at the famous "Baobab Alley" touristic site (Fig. 1.4., Marie et al., 2009).

Figure 1.3 Baobab alley, near Kirindy forest (Picture by Leia Falquet, 2015)

In Menabe, slash-and-burn agriculture, *hatsake* in the regional dialect, follows the alternation of the dry and rainy seasons. Forest are cleared during the dry season, i.e. from June to September. Tree logs and branches are slashed and gathered in big piles left to dry for 2 to 3 weeks. When the dry season is close to end, in October, the dried wood is burnt. Farmers light the big piles usually when a light wind blows. The wind allows to propagate the flames in the piles. The fire is fast and controlled. The surrounding forest is protected by grooves, 5 to 10 cm large, dug in the soil around the wood heaps. When the fire is over, the ashes are spread equally on the surface of the newly cleared fields. Crop seeds, generally corn, are then planted under the ashes in December after the first rain. Plants grow from January until March. Harvests occur generally between May and June.

The remaining vegetation and the new sprouts are cut and burnt every year to allow replanting crop. After several slash-and-burn cycles, fire has removed all the vegetation except large trees such baobabs (Adansonia sp.). Farmers first cultivate maize for two to three years, but soil fertility then declines and weeds become invasive. Then, either they abandon the land, either they switch to cassava or groundnuts for a few more years. These abandoned surfaces are called monkas. After some years of abandonment, some farmers attempt to re-cultivate the monkas. However, the majority prefers to burn new patches of primary forest because they are more fertile (Genini, 1996).

Commonly, the government and conservation NGOs blame rural households to practice slash-and-burn cultivation and to be responsible of the deforestation of Menabe (Favre, 1996). However, this practice contributes intensively to the alimentary and financial safety of the population (Kull, 2000). From the perspective of the indigenous ethnic of Menabe, the Sakalava, slash-and-burn practices are associated with rituals which permit to sustain soil fertility (Hume, 2006; Scales, 2012). In turn, they blame migrant communities, which settled during the last century in the region, for exacerbating slash-and-burn practices. Indeed, due to several migratory fluxes, Menabe is nowadays a multi-ethnic region. Between 1900 and 1940, Betsileo and Antsaka ethnics, from the center of the island, and Tandroy tribes, from the south, established in the region. They were attracted by the work opportunities offered by the colonial state, and by the economic development of maize cultivations (Fauroux, 1999). Incontestably those large migrations contributed to increase people density and to disrupt the sustainable loop of slash-and-burn agriculture (Fig. 1.2, Fig. 1.3), leading to the rapid degradation of the forest in only 60 years (Fauroux, 1999).

The persistence of slash-and-burn agriculture can be explained by the insecurity of land tenure and a limited access to the markets (Styger et al., 2009; van Vliet et al., 2012). In Menabe, land ownership is recognized according to two different systems: either traditional, or national legislation. According to the traditional system, called *dina*, the land belongs to the person who clears it first. Then, arable fields are inherited within the family (Casse et al., 2004). However, that system is unsecure, because if plots are abandoned during some time, either because of soil fertility declines or any monetary or other issues within the family, a new household can take them over and use them. On the other hand, officially acquiring the land through the national legislation is done only through a long and fastidious administrative process (Casse et al., 2004). Consequently, only 20% of the land owners chose this way to acquire their fields. Most of the farmers are discouraged to undertake the complicated administrative procedures. Further, in Madagascar, slash-and-burn agriculture is commonly linked with spiritual practices, to appease gods and ancestors, and with the hierarchy of the community (Desbureaux and Brimont, 2015; Hume, 2006). Accordingly, losing this practice would have not only an economic costs for the families living from this practice, but also a cultural cost (Desbureaux and Brimont, 2015; Kull, 2000). Farmers state that they would even fell like losing a part of their identity (Hume, 2006).

Numerous attempts were taken to counter the deforestation resulting from slash-and-burn practices. Those strategies draw from the similar kind of approaches that we have described in the previous chapter. They varied from very strict measures like the complete ban of fires during the colonial times and the imposition of reserve areas (Jarosz, 1993) to modern methods implying the involvements of rural communities like community-based natural resource management (CBNRM; Dressler et al., 2010, Rasolofoson et al., 2015), or Payment for Environmental Services (PES; Brimont and Karsenty, 2015). The current direction of conservation programs and forest policy is not to ban local communities from the forests, but to set up multifunctional management schemes of forest areas that allow biodiversity conservation and the improvement of local living conditions at the same time. Yet, results are still modest and the deforestation remains unabated (Fig. 1.5, Fig. 1.6, Fig. 1.7). The most probable reason of the limited outcomes of conservation initiatives could be that the cultural importance of slash-and-burn agriculture for the indigenous communities was never recognized (Desbureaux and Brimont, 2015; Hume, 2006; Scales, 2012), or actions did not involve local farmer's sufficiently during the development steps of new resource management schemes (Marie et al., 2009; Rives et al., 2013).

Figure 1.4 *Smoke from slash-and-burn agriculture, Kirindy forest (Picture: Alexandre Buttler)*

Figure 1.5 *Deforested areas wihtin Kirindy forest (Picture: Justine Gay-des-Combes)*

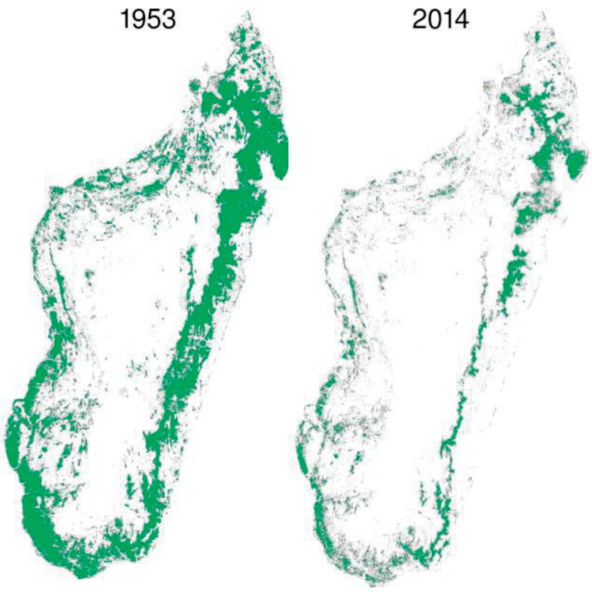

Figure 1.6 *Madagascar deforestation between 1953 and 2014 (Pictures taken from http://bioscenemada.cirad.fr/maps/, accessed in May 2017)*

1.3.2 Most recent research in Kirindy forest

In Menabe, the largest remnant of dry tropical forest is the Kirindy forest. However, slash-and-burn cultivation threatens that remnant to disappear in the next 11 to 37 years (Zinner et al., 2014, Fig. 1.5, Fig. 1.6). Kirindy forest is situated north of the large coastal city Morondava. The forest is bordered on the north by the river Tsiribihina, on the south by the Andranomena river and on the west by the coast of the Canal Mozambique. The "Baobab Alley" (Figure 1.3) is situated just at the northern entrance of the forest. As an important conservation priority is put on Kirindy forest, a standing collaboration exists since 30 years between Swiss scientists, Malagasy conservation and national organisations and the rural communities of the forest.

The earliest programmes in Kirindy forest dated from the late 80's. In 1987, Swiss Aid and the Food and Agriculture Organization of the United Nations (FAO) started the project "Sauvegarde et Aménagement des Forêts" - Côte Ouest (SAF-CO). This project aimed to use abandoned clearings for agriculture. They mainly studied the cultural association between corn and groundnuts. Later, in 1991, the various projects supervised by the Swiss Cooperation were assembled into a single programme "Programme Menabe", which focused on sustainable use of natural resources (Dirac Ramohavelo, 2009). In the 1990s, GELOSE (Gestion Locale Sécurisée - secure local management) and GCF (Gestion Contractualisée des Forêts - forest management contracts) initiatives were proposed by the Malagasy government to decentralise the management of natural resources and to emphasize community involvement (Dirac Ramohavelo, 2009).

More recently, since 10 years now, scientific research programmes were launched to seek for a better management of the forest resources. As the actual PhD thesis draws form the conclusions of those previous studies, we will present here a synthesis of the most important research works. In short, four key PhD theses were conducted before this work (Figure 1.8): Andriambelo **(1)** established an inventory of the tree species in the primary and secondary forests, Dirac Ramohavelo **(2)** studied the use of non-timber goods by the farmers, Razafintsalama **(3)** looked at the services provided by the secondary forests and finally, Raharimalala **(4)** studied the regeneration of the secondary forests.

(1) The work of Andriambelo (2010) provided a detailed inventory of the tree resources in Kirindy forest, and a specific understanding of the use in primary forest products of rural households. That work highlighted the differences in species composition between the primary and secondary forest formations. Tree inventory let to identify 192 species and among them, 136 were found in primary forest. Species richness was thus more important in the primary forest than in other kinds of formations. The relative abundance of the tree species in the primary forest was shown to be also 4 times higher than in the secondary successions. Sustainable management of natural resources of Central Menabe depends much on the adhesion of rural population, and especially on the appropriation of the management process. While surveying the local households, it appeared that the primary forests constitute their main source of wood construction. Andriambelo (2010) highlighted the difficulty to put in place a sustainable management of natural resources in Central Menabe such the GELOSE program. Villagers were aware of the negative impact of their forest use, but did not seem to be really interested in forest management, even though they use many resources from the forest in their everyday life. Rural populations preferred and favoured their own means to manage traditionally natural resources, without considering the administrative rules.

(2) The work of Dirac Ramohavelo (2009) is complementary to Andriambelo (2010). While Andriambelo (2010) focused on timber products, this author studied the non-timber product services. She demonstrated that both slash-and-burn agriculture and zebu livestock contribute largely to the negative impacts on forest biodiversity, while rice cultivation and non-timber forest products had limited effects on the environment. On the other side, slash-and-burn cultivation, rice cultivation and small livestock (goats, chickens) influence positively rural livelihoods by contributing to the food and economic security of the households, whereas zebu livestock and non-timber forest products have a minor positive effect on rural livelihoods. In Menabe, the most important wealth criteria is the number of zebus hold by one household. The more zebus a family has, the more prestige the family gets in the village. However, zebu livestock has a negative effect on the environment and do not contribute to the financial safety of families. Thus, one of the recommendation drawn from that work is to improve the livelihoods by switching from zebu livestock to small livestock or to rice cultivation. That solution would allow to gain in financial security and environmental benefits, even if those opportunities are less considered socially. Finally, concerning slash-and-burn agriculture, local farmers of the Menabe region state to be interested in alternative systems. They say being particularly interested in organic fertilization and agroforestry.

(3) According to Razafintsalama (2011), secondary forests can provide a major part of the products which households traditionally obtain from primary forests. This research showed that secondary forests help to meet the local population needs and reduce people dependency on primary forests which are now often included in protected areas with strict management status. The villagers use secondary forests as pasture and arable lands and as an important source of timber and non-timber forest products. The villagers have shown an ability for adaptation when their traditional tree species were not available in secondary successions. The particular tree species, present in secondary forests, *Rhopalocarpus lucidus, Zizyphus mauritiana, Grewia picta*, have been singled out as common substitutes for wood construction, compared to the species of the primary forest. These “new species” from secondary forests could be promoted in the regional wood market to value more secondary forest products and reduce the pressure on primary forest species. In conclusion, that work suggests to focus on secondary forest restoration and preservation to improve their production abilities, rather than focusing only on the primary forest as the current common tendencies.

(4) Finally, Raharimalala (2011) investigated the regeneration of the forest on secondary successions. This author looked at the gradual recolonization of abandoned fields by herbaceous and ligneous species. Her results demonstrated that herbaceous species were predominant in the plots from 1 to 10 years of abandonment. In the same time, the number of woody species were increasing slowly. The ratio herbaceous/ligneous species changes after 21 to 30 years, where the herbaceous species stop being dominant. Later, the total species richness continues to increase with age of abandonment, but flattened out by 40 years. Total biomass reached 72 t ha^{-1} after 40 years of abandonment, which is about half of the biomass found in the primary forest (Raharimalala et al. 2012). The species that had the largest contribution to aboveground biomass were *Fernandoa madagascariensis*, *Diospyros perrieri*, *Dalbergia sp.*, *Poupartia sylvatica*, *Tarenna sericea*, *Xeromphis sp.*, *Phylloctenium decaryanum*, *Stereospermum euphorioides* and *Croton greveanum* (Figure 1.7). The biomass of *Diospyros* increased regularly from 10 to 40 years of abandonment. *Dalbergia* also increased with the age of abandonment until 30 years of abandonment. Afterwards, the biomass of that species decreases again, due to harvest by farmers for sculpture and construction wood. Finally, *Fernandoa, Tarenna, Poupartia* biomasses augmented after 30 years. Yet *Poupartia* reaches the highest biomass just after 30 years of abandonment (Figure 1.7).

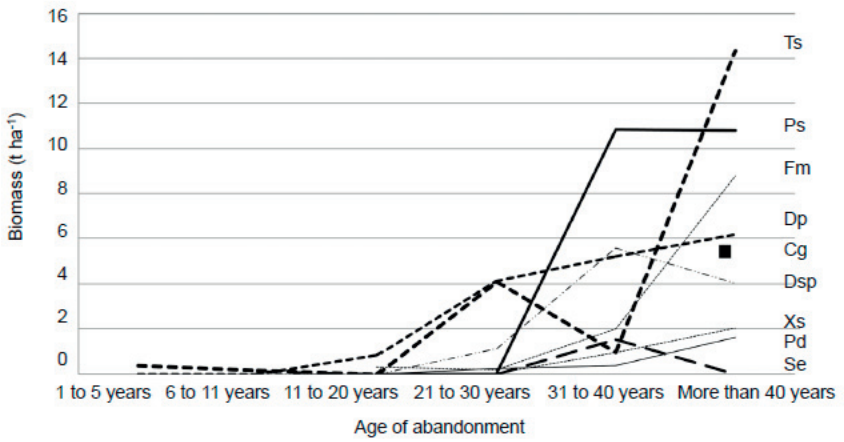

***Figure 1.7** Mean total aboveground biomass per age of abandonment (N=5). Ts: Tarenna sericea, Ps: Poupartia sylvatica, Fm: Fernandoa madagascariensis, Dp: Diospyros perrieri, Cg: Croton greveanum, Dsp: Dalbergia sp, Xs: Xeromphis sp, Pd: Phylloctenium decaryanum, Se: Stereospermum euphorioides. (Figure taken from Raharimalala 2012)*

Among those species, some have a higher nutrient content and thus a higher fertilization potential when slashed-and-burnt. *Poupartia sylvatica* and *Tarenna sericea* were especially the highest in terms of nutrient concentrations. In addition, those species are not used by the villagers for any traditional work. Therefore, they could be used as target species to promote a fast biomass recovery and develop a sustainable forest management. Other species such as *Dalbergia sp.* or *Diopyros perrieri* would also be interesting species in terms of biomass and nutrient concentrations. However, they are considered as precious and valuable wood to local farmers and should be preserved. *Dalbergia sp.*, commonly known as rosewood (there is three different rosewood species in Madagascar), is valued for its colour and perfumed wood, while *Diopyros perrieri* is a species from the family of the well-known ebony wood, used extensively in sculpture.

Further, the effectiveness of fertilization by slashing-and-burning depends not only on the amount and quality of ashes but also on the retention capacity of the soils to store these nutrients. Soil fertility characterization on the abandoned plots indicated that the concentration of most nutrients increase between six to ten years after abandonment. After ten years, some nutrients such as nitrate and ammonium continued to increase steadily, while others such as magnesium, calcium and potassium showed a humped-shaped curve. Consequently, any fallow period shorter than 10 years would lead to an unsustainable agricultural system and a decrease in soil productivity. Raharimalala (2011) recommended to observe a fallow period of 20 to 30 years since the last cultivation to allow a sufficient soil recovery before starting a new cultivation cycle.

In conclusion, according to the previous researches in Kirindy forest (Fig. 1.9), farmers have the ability to adapt and use woods and other products from the secondary forests. Secondary forests can provide similar services for human being as primary forests, even if secondary forests are less diverse and abundant in tree species. However, secondary forests are very slow to regrow after slash-and-burn cultivation. A duration of about 20 to 30 years of fallow is necessary before reaching a forested ecosystem again, which could potentially be re-used in the slash-and-burn cycle. Given that people are aware of their negative impacts on the forest, while remaining dependent on agricultural practices, one may consider solutions to improve the productivity of the soil and sustain re-cultivation on old abandoned fields. Two new research projects were started in 2013 according to those considerations: the thesis of Linja Rakotomolala and the current thesis. The first thesis investigates the knowledge of the farmers about their agricultural system and the second the potential for alternative slash-and-burn practices.

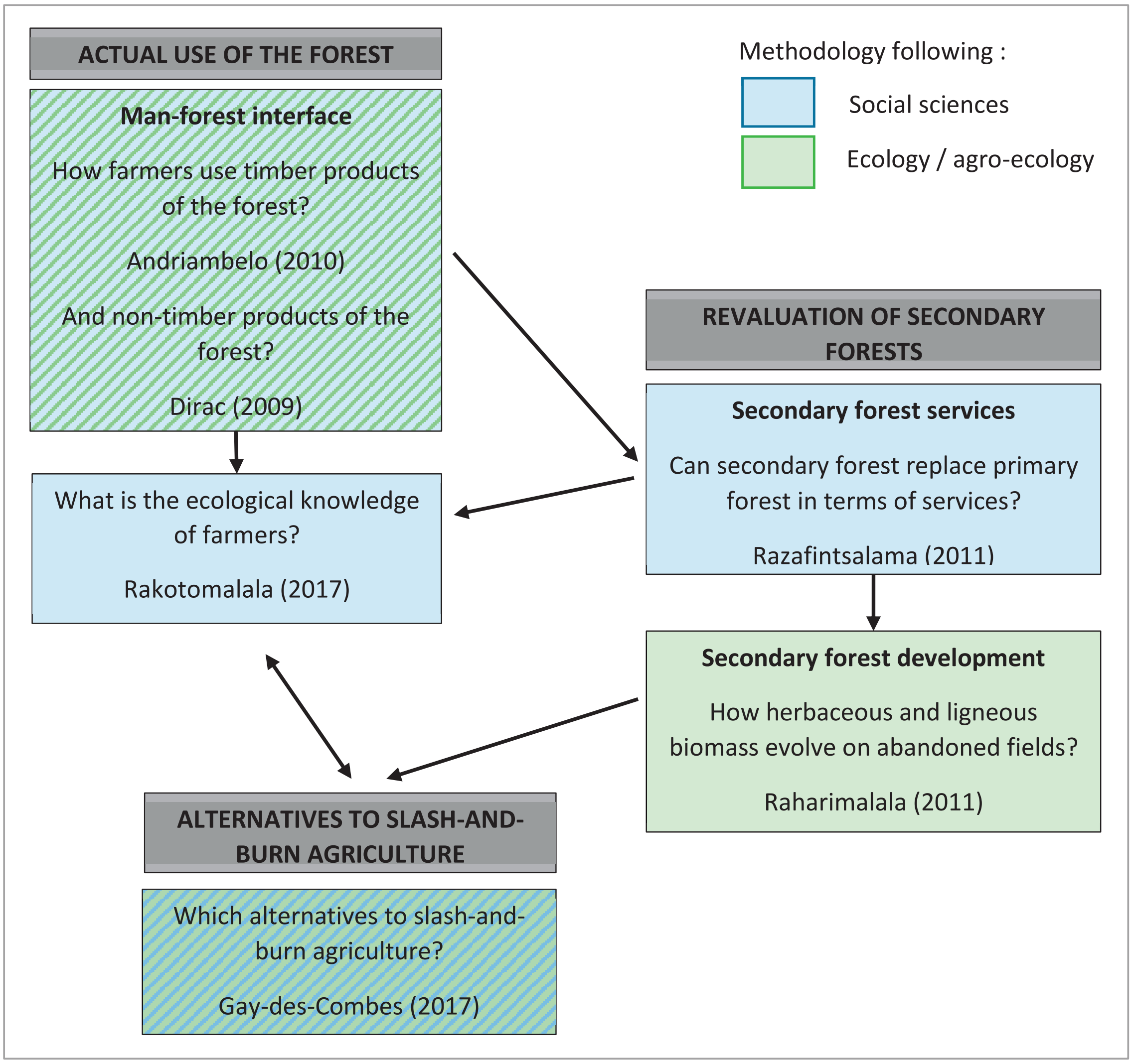

Figure 1.8 *History of some recent scientific research history in Kirindy forest (non-exhaustive list).*

1.4. Thesis objectives, research questions and hypotheses

Synthesis of the knowledge gaps

Limited research has been done on dry tropical forests, as compared to humid forests. Besides, Kirindy forest is undeniable one of the last large remnants of dry tropical forest in Madagascar (Waeber et al., 2015). Yet, the practice of slash-and-burn agriculture is the main cause of destruction of this valuable ecosystem (Zinner et al., 2014). Diverse reasons explain the maintenance of those practices, and among them a strong social background (Desbureaux and Brimont, 2015). Strangely, slash-and-burn agriculture has been overlooked by former research programmes: most studies were conducted on the forest itself, rather than on the cultural system (Dirac Ramohavelo, 2009; Raharimalala, 2011). Given the diversity of slash-and-burn systems, it is worthwhile having a closer look at the practices in Kirindy (Dounias et al., 2000). Besides, due to the importance of that practice for local households, it might be a good strategy to improve this practice and make it more sustainable, rather than suppressing it. However, among all the initiatives attempted against deforestation, that approach has rarely been attempted, even though there is a growing recognition of an exaggerated demonization of slash-and-burn agriculture (Kull, 2000; Mukul et al., 2016). In addition, previous research conducted in Kirindy forest demonstrated that local farmers of the Menabe region are willing to explore alternatives. They are particularly interested in organic fertilization and agroforestry (Dirac Ramohavelo, 2009).

The current thesis answers to the need of an in-depth study of the agricultural practices of Kirindy forest. The project targets to (1) analyze the practices of slash-and-burn cultivation in Kirindy forest, (2) explore experimentally alternative practices, (3) determine the implementation perspectives of these alternatives. Because farmers are willing to test organic fertilization and agroforestry (Dirac Ramohavelo, 2009), we build our experimental alternative practice on those considerations. The current thesis aims at testing a selective slash-and-burn agriculture, where trees are left intentionally within the fields (as in Carrière et al., 2002a, 2002b) coupled with compost amendment, to sustain cultivation on older fields (Fig. 1.10). Concerning the compost, we followed the results of Raharimalala et al. (2011, 2012), who showed that three local trees, *Poupartia sylvatica, Tarenna sericea* and *Fernandoa madagascariensis*, seem appropriate target species for forest management because of their high biomass and nutrient concentrations. Thus, those species could be used as resources for composting.

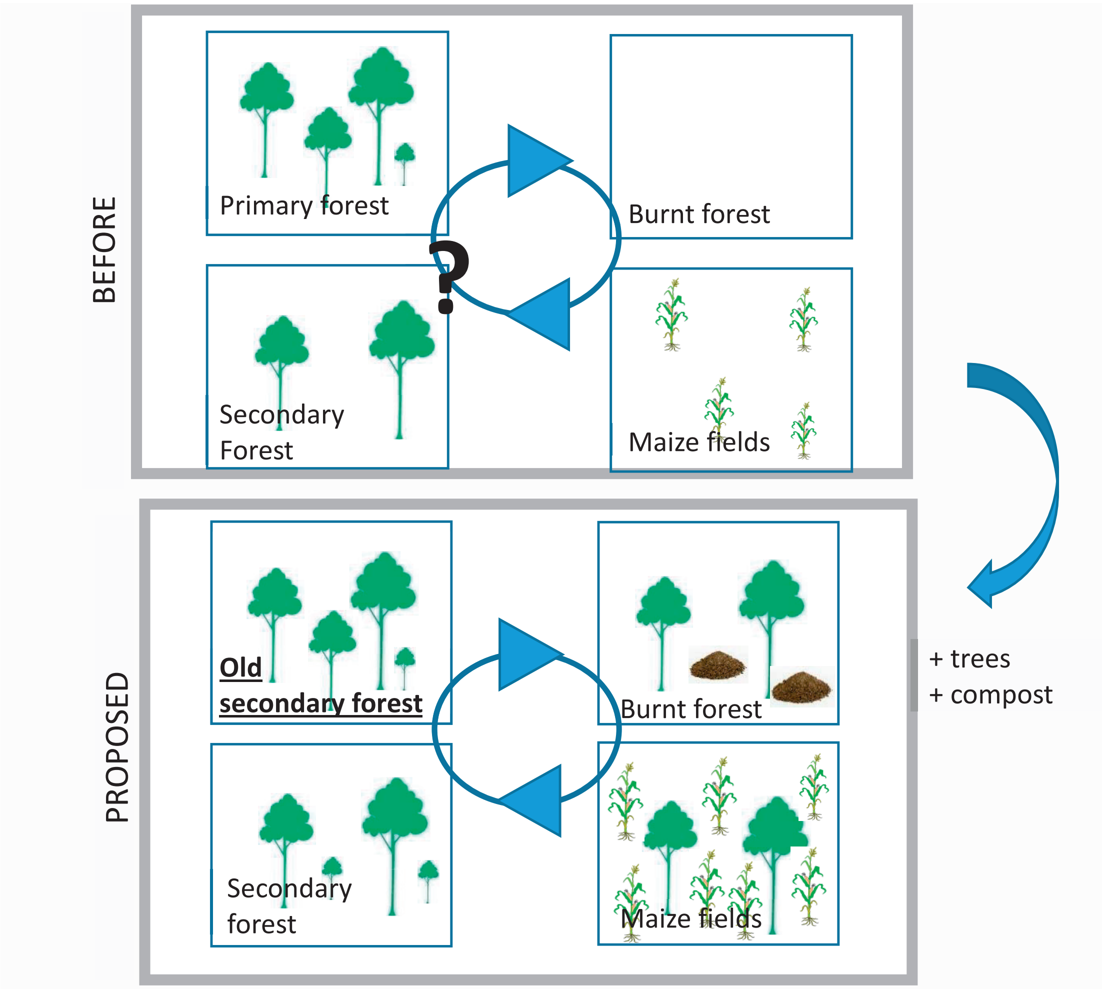

Figure 1.9 *Scheme of the proposed alternative slash-and-burn system*

The methodology draws predominantly from agro-ecology and soil sciences, but also in a less extent from sociology. The thesis is structured as follows (Fig. 1.11): First, we will characterize soil productivity along repetitive slash-and-burn cultivation cycles (**Chap. 2**) and the farmer's perception of their agricultural system (**Chap. 3**). Then, we will test the aforementioned alternative slash-and-burn practice in the fields (**Chap. 4**), as well as in controlled conditions (**Chap. 5**). We will also assess the potential for implementation of that technique in Kirindy forest (**Chap. 6**). Finally, the applications of some research results will be tested (**Appendix**).

The particular thesis answers to five general questions:

- **Q1**: How do crop yield and soil fertility evolve along slash-and-burn cultivation cycles?
- **Q2**: How do farmers perceive their agricultural system?
- **Q3**: What are the effects of leaving a partial tree cover and adding compost (made of local tree residues) amendment on slashed-and-burnt corn field yields?
- **Q4**: What are the effects of compost (made of local tree residues) addition to slash-and-burn agriculture on corn phenology and soil nutrient retention capacity?
- **Q5**: Can composting be implemented in local communities?

For each question, a specific research hypothesis was determined. Thus, the research hypothesis of the present work are the followings:

- **H1**: Field yield decreases with repetitive slashed-and-burnt cultivations on the same field. That yield decrease can also be due to soil depletion with heavy tropical rains.
- **H2**: The decision-making process of farmers to abandon their fields (and burn a new area of forest) is driven by soil fertility decrease and weed invasion.
- **H3**: A partial tree cover, combined with compost amendments, can improve field yields in slashed and burnt surfaces by improving the soil quality and nutrient status.
- **H4**: Compost, combined with wood ashes, advances corn maturation by improving the nutrient availability in the soil.
- **H5**: Composting could be implemented in the local communities if time, labor and social constraints are taken into account.

This thesis constitutes a first step towards the development of management strategies aiming to balance conservation of habitats and development of agriculture and thus minimizing the impact on natural undisturbed forest.

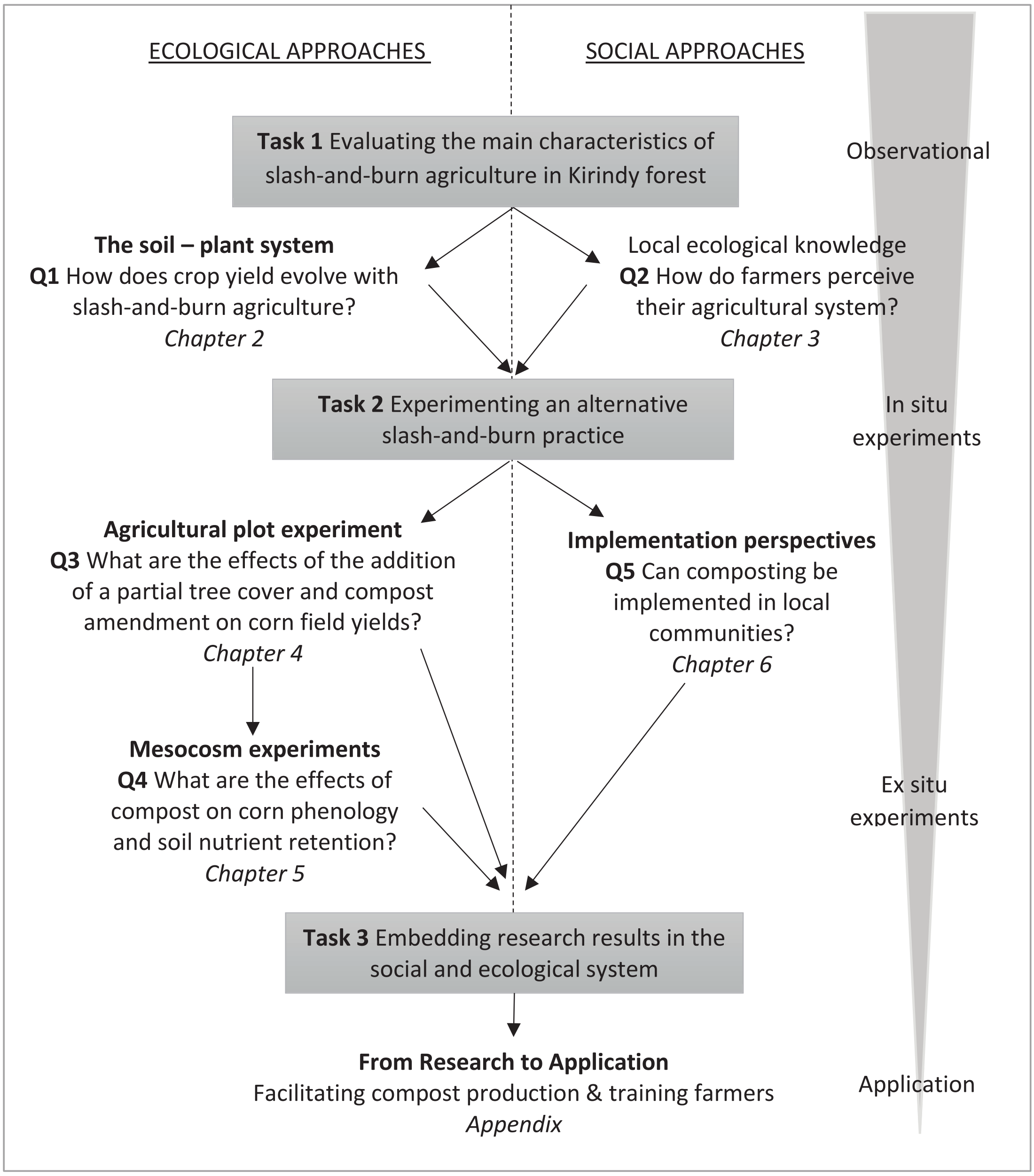

Figure 1.10 *Thesis structure, research questions and main tasks. Chapter 1 & 7 are not mentioned in that figure but referred to the general introduction and discussion.*

- CHAPTER 2 -

Slash-and-burn agriculture and tropical cyclone activity in Madagascar: implication for soil fertility dynamics and corn performance

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Published in 2017 in Agriculture, Ecosystems & Environment

Picture: A freshly cultivated maize field, trees are still present within the field, Kirindy forest
Justine Gay-des-Combes, 2014

Abstract

On the western coast of Madagascar, the dry tropical forest of Kirindy may disappear in the next 50 years because of its rapid conversion into agricultural land by slash-and-burn cultivation. The slash-and-burn fields are cultivated during 3 years in average and are further abandoned because of soil depletion, weed invasion and finally lower crop yields. As a consequence, new forest areas are regularly cleared from the primary forest, causing deforestation. In addition, Madagascar is situated in a region with high cyclonic activity. Violent storms hit the western coast every 3-4 years, leading to intense rainfalls and floods. These events may enhance soil physical degradation and nutrient leaching, thereby accentuating the soil depletion by slash-and-burn agriculture and with it, the forest conversion rate. Focusing on the combined effects of historic land management and prevailing climatic conditions, this paper investigates: (1) the temporal evolution of soil fertility along with crop performance from cultivation up to field abandonment, and (2) the relative effects of land use (crop cultivation) and extreme climatic events (heavy rain, cyclonic storms) on soil and crop properties. We used a space-for-time substitution approach in slash-and-burn corn (Zea mays L.) fields to describe dynamics of soil fertility and crop performance. We sampled soils and plants during two seasons: (a) a normal rainy season, in 2014, and (b) a cyclonic rainy season, in 2015. We found that under the cyclonic storm, soil becomes not only N and P deficient, but the K concentration also steeply drops. Overall, this leads to a dramatic reduction of corn performance. While a decrease in grain yield due to slash-and-burn agriculture reaches about 37.5% after three years of cultivation on the same field (from 4 to 2.5 t ha^{-1}), it decreases up to 75% after a single cyclonic rainy season (from 4 to 1 t ha^{-1}). On the sidelines of the study, a locust pest also damaged half of the corn fields in 2014, driving the corn yield down to zero on those particular fields. Given what precedes, the study points out the fragility of traditional agricultural techniques against natural hazards. Along with global warming, the frequency and intensification of natural disasters are expected to increase, impacting negatively and strongly the livelihoods of rural farmers. This raises the urgent need to increase farmer's awareness to alternative and more sustainable agricultural practices.

Keywords

Slash-and-burn cultivation, corn yield, soil depletion, tropical dry forest, deforestation, cyclone, plant nutrients, tropical soil

2.1 Introduction

Primary forests of Madagascar are home to a rich and unique biodiversity, but they are endangered by severe deforestation. On the south-western coast of the island, in the Menabe region, deforestation rate of the dry deciduous forest has been estimated at 2.6% per year between 2008 and 2010, i.e. to 1820 ha per year (Zinner et al., 2014). At that rate, the forest and most, if not all, of its endemic species, will have entirely disappeared by 2050 (Zinner et al., 2014). Slash-and-burn shifting cultivation is the main cause of deforestation in Madagascar (Dirac Ramohavelo, 2009). In this traditional cultivation practice, forest is converted into agricultural land by partial clearing and subsequent burning of the cut trees. The ashes are used then to amend the soil. However, after three years, crop yield already decreases and weeds invade the field, forcing the farmers to abandon the land and to burn new areas of primary forest (Raharimalala et al., 2010; Styger et al., 2007). Therefore, whilst convenient to the farmers, shifting cultivation contributes largely to the rapid ongoing deforestation (Dirac Ramohavelo, 2009; Genini, 1996).

The duration of cultivation and of fallow, together with population density, are key factors when determining the impact of slash-and-burn practices on forest cover (Kleinman et al., 1995; Ziegler et al., 2009). An increase in population density often forces an extension of cultivation duration whilst fallow periods are reduced. Across Madagascar, average fallow duration has decreased from 8 to 4 years over the last century (Jarosz, 1993). As a result, fallow periods became too short to allow recovery of the soil nutrient status, leading to soil depletion and ultimately to secondary successions to savannah (Raharimalala et al., 2012, 2010). In most tropical ecosystems, forest regeneration can only be successful with a strict minimum of 10 years of fallow (Thomaz et al., 2014). Yet, Raharimalala et al. (2010) showed that in the dry deciduous forests of Menabe, fallow duration should be doubled to 20 years.

Slash-and-burn agriculture affects both soil chemical and physical properties. Ashes are strongly alkaline, and therefore increase soil pH, favouring microbial activity and therefore soil nutrient availability (Demeyer et al., 2001). This is particularly useful on tropical acid soils, where nutrient availability is low due to leaching, translocation or binding in strong metal-anion complexes (Frossard et al., 1995). However, large ash inputs can impact upon soil macronutrient stoichiometry, as ash is generally N-poor, mainly due to volatilisation during combustion (Demeyer et al., 2001). Hence, ash input most likely leads to N limitation in the soil, which is problematic for sustainable crop growth. Nutrient limitation becomes even more prominent as corn (Zea mays L.), an especially N-demanding plant, is one of the most cultivated crops in Madagascar, after rice. Not surprisingly, corn yield is very low in Madagascar, with a national average of 1.5 to 2 t ha^{-1}(FAO, 2013). Consequently, fertilization rates are not sufficient to compensate for the high nutrient uptake by corn, resulting in soil nutrient depletion (Folberth et al., 2013).

In addition to the effect on soil chemical properties, slash-and-burn agriculture tends to degrade soil structure, mainly as a consequence of wind and rain erosion (Comte et al., 2012; Thomaz, 2013). Indeed, soil physical degradation is of main concern for the western coast of Madagascar. Heavy rains are common under tropical cyclone activity, leading to soil saturation and overland flow, which further causes soil erosion even on slightly sloping terrains. During the rainy season (November to April), up to nine cyclonic storms can cross the south-west Indian Ocean (Nash et al., 2015). Every three to four years, one of these storms hits the west coast of Madagascar, leading to violent wind and rain over a short period, which can negatively impact both the anthropogenic and the natural environment (Rakotobe et al., 2016).

Given the potential interactive effects of these drivers, there is an urgent need to modify slash-and-burn techniques and optimize soil fertilization while reducing soil erosion and thus, targeting a faster soil fertility recovery after cultivation. Yet, actual ecological research on slash-and-burn agriculture focuses either on soil properties shortly after burning or on forest regeneration and fallow duration. The full cultivation cycle has rarely been studied, even though understanding temporal patterns in soil fertility and its effect on crop performance are key to developing meaningful forest conservation strategies. This paper aims to answer two fundamental questions leading towards a practice modification: (1) what is the temporal evolution of soil fertility along with crop performance from cultivation up to field abandonment? (2) Within this temporal evolution, what are the respective effects of land use (crop cultivation) and climate (heavy rains, cyclonic storms) on crop and soil properties? We hypothesized that (i) under normal climatic conditions, soil fertility will decrease after approximately 3 years of cultivation, leading to a gradual decrease in crop performance. Such decrease (ii) will be accelerated under influence of a cyclonic rainy season. To test these hypotheses, we used a slash-and-burn chronosequence ranging from first year of cultivation to abandonment. Respective effects of land use and climate are disentangled by field comparisons under two different rainy seasons; one being a non-cyclonic, typical rainy season, and the other one affected by a cyclonic extreme event.

2.2 Material and methods

We used a space-for-time substitution approach in slash-and-burn fields to describe temporal patterns of soil fertility and crop performance. We sampled soils and plants in two sets of cornfields during two seasons: (a) a ‘normal rainy season’, i.e. when no cyclone occurred, in 2014, (b) a ‘cyclonic rainy season’ i.e. when a cyclone hit the region in January, at the beginning of the cropping season, in 2015.

2.2.1 Study site

Field sampling was conducted around the villages of Kirindy (20° 00’22.3’’ S – 44° 35’6.1’’ E) and Beroboka (20° 00’22.3’’ S – 44° 35’06.1’’ E), 30 km north of the larger city of Morondava (Fig. 2.1). The two villages were selected because they are severely affected by deforestation due to slash-and-burn agriculture (Dirac Ramohavelo, 2009). Also, both villages have a similar climate and comparable soils.

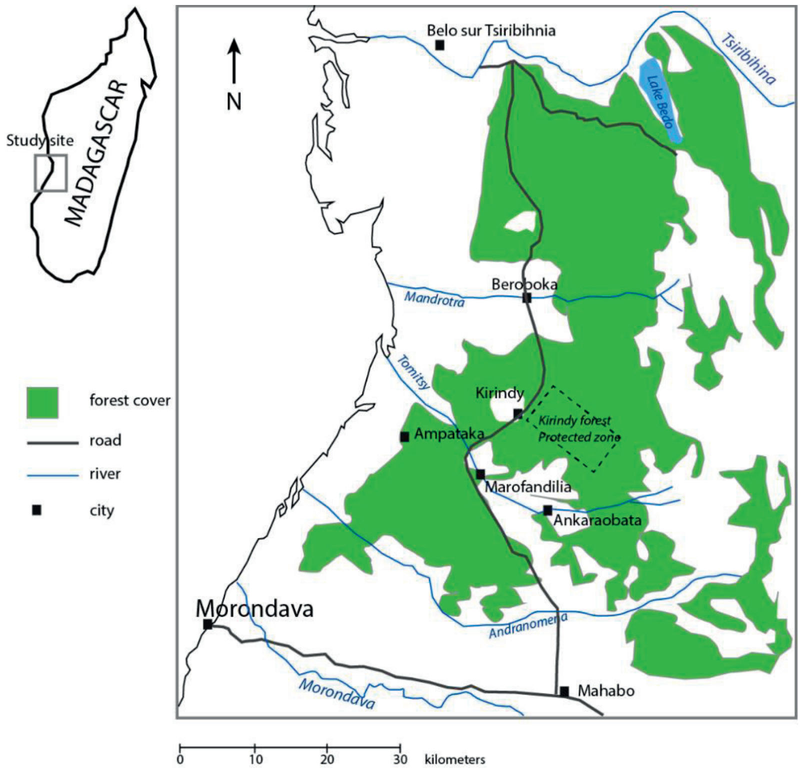


Figure 2.1 Geographical location of the study site in the Kirindy forest (adapted from (Scales, 2012))

The climate is tropical, but with a long dry season. The rainy season occurs from December to March, and the dry season from April to September (Table 2.1). October and November are transitional months with scarce rainfall. Mean annual rainfall is about 800 mm, but varies greatly between years (250–1400 mm), due, in part, to cyclonic activity (Sorg and Rohner, 1996). Cyclone activity peaks between January and February (Table 2.1), with a frequency of formation of about 0.60 yr^{-1} in the Mozambique Channel and of 2.5 yr^{-1} in the south-west Indian Ocean (Mavume et al., 2009).

Annual temperatures average 24.7°C. (Sorg and Rohner, 1996). The main vegetation type consists of dry deciduous forest (Koechlin et al., 1997; Raharimalala et al., 2010). However, due to slash-and-burn practices, temporary secondary successions of herbaceous and shrubs species tend to replace the dense forest around the villages (Raharimalala et al., 2010; Randriamboavonjy, 1995). The predominant soils (> 90 % of the region area) are ferruginous soils, corresponding to the Lixisols after the World Reference Base for Soil Resources (Raharimalala et al. 2010).

Corn cultivation is generally initiated during the rainy season (Table 2.1). During the dry season, 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 or November, all woody material is burnt. Corn seeds are then buried under the ashes in December after the first rain and plants grow from January until March. In April, plants start drying along with the soil. Corn cobs are finally harvested in May or June.

Table 2.1 *Rain occurrence and crop cultivation calendar in Menabe region, Madagascar.*

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Rain occurrence												
Cyclone peak period												
Fallow												
Tree slashing												
Burning												
Corn seeding												
Cropping												
Harvest												

2.2.2 Plot selection

We sampled slash-and-burn cornfields in 2014 and 2015, which were established on former primary forest. We used a chronosequence from plots cultivated one year after initial clearing to plots cultivated for up to three years (corresponding to three cycles of slash-and-burn agriculture, where farmers re-burn the same plot annually) after initial clearing. Cornfields older than three years exist but are either rare or intercropped with groundnuts (Dirac Ramohavelo, 2009; Raharimalala, 2011). So, we defined three classes of corn fields corresponding to their exploitation duration: one (hereafter called, A1 for 2014 and B1 for 2015, Fig. 2.3), two (A2 and B2), and three years of cultivation (A3 and B3). Per category, six cornfields (replicates) were sampled in both villages and in each year (i.e. a total of 36 plots). Plots differed between 2014 and 2015 to avoid confounding effects between land-use and climate. All plots were located within a radius of 10 km.

The cultivation history of the plots was assessed by the field owner, and crosschecked by a local guide and by field observations, such as tree cover, location with respect to the primary forest margin, or the amount of weeds. Cornfield sizes varied greatly (0.02 – 10 ha) depending on ownership (village president, council member, farmer, etc.), thus, a 10m x 10m plot was randomly selected in each field. This size captures field heterogeneity in terms of plant density and remaining tree cover. The same corn variety grew on the selected plots, which was the main variety of the region, a local yellow dent variety –*vonivony*- with a growth cycle of 110 days. All plots had similar topographical conditions (i.e. flat ground). Finally, the plots within each category were carefully selected in order to have similar soil types by assessing in situ the main soil characteristics such as texture (manual determination), color (Munsell code) and pH (Hellige pH meter). These characteristics were measured next to each field, in a non-cropped zone, to avoid potential alteration of the natural soil characteristics by slash-and-burn agriculture. Soils were all lixisols of a "yellowish red" color (5YR 5/8, Munsell code), having a pH between 5 to 6, holding a loose texture of approximately 75% of sand, 10% silt and 15% clay and having no particular coarse elements.

2.2.3 Meteorological data

Because of the absence of regional weather monitoring, extreme weather events in the study region were assessed by compiling the past cyclonic events. In the last four rainy seasons, two cyclones crossed the island near the study region: Giovanna in February 2012 and Chedza in January 2015 (Météo France, Fig. 2.2). Additionally, five pluviometers were installed in December 2014: three in the Kirindy forest, halfway between Kirindy and Beroboka, and two in Morondava (Fig. 2.1). Cumulative rainfall, from December 2014 to March 2015, reached 2377 mm and 2140 mm respectively in Kirindy and in Morondava, which was more than double the annual average rainfall in the region (757 mm; Sorg and Rohner, 1996). Rain distribution in both places was similar. Rain occurred approximately every two days from 25th December 2014 to 30th March 2015, with an average amount of 50 mm per rain event in Kirindy and of 54 mm in Morondava. Maximum rain for a single rainfall event reached 150 mm in Kirindy and 160 mm in Morondava on 17th January, when the cyclone Chedza crossed the island from the western coast.

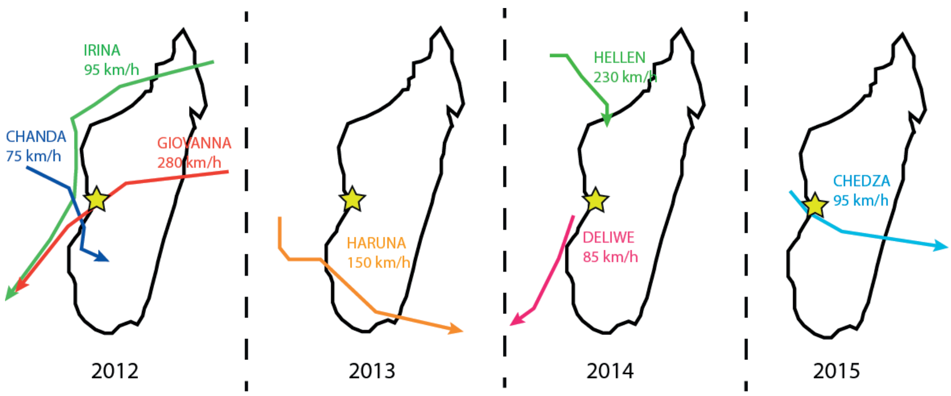


Figure 2.2 *Cyclonic events and their trajectories over Madagascar* (météo France, La Réunion, http://www.meteofrance.re/cyclone/). The yellow star indicates the study site.

2.2.4 Soil sampling and plant measurements

Soil samples were collected in each plot by the end of the growing season (March 2014 and March 2015). For each year, five topsoil samples (c. 100 g) were taken with an auger within each plot at two different depths: 0 to 10 and 10 to 20cm. For each depth, the five samples were then pooled into one sub-sample of 500 g. All soil samples were air-dried, then sieved to 2 mm. Roots were removed.

For every plot, we assessed the plant density, by counting the number of corn stalks, and also the number of cobs per stalk. At the end of the growing season, ten physiologically mature plants were then randomly chosen in each cornfield. Physiologically mature plants are recognized by fully developed corn cobs, black and dry silk, and a black layer at the base of the kernels. For each plant, the following traits were measured: total height, basal stem diameter at 10 cm above soil level, length and diameter of the corn cobs. In May, when the plants were sun-dried, we finally assessed the dry weight of grains for each previously measured cob (husk and central part of the cob were removed prior to weighing), as well as the total dry weight of grains for the entire plot. Because of an unforeseen locust plague that occurred in 2014 shortly before the harvest, yield data had to be extrapolated in that year as all the grains were eaten in the attacked fields. This phenomenon was not predictable because of the absence of historical records of migratory locusts in Kirindy Forest before that year. The relationship between yield and corn cob parameters (diameter, length and dry weight of the grains) was determined with averages of 10 random matured plants of the same variety growing on same soil conditions but coming from 18 other fields left intact by the insects ($P < 0.01$, R2 = 0.84, Fig. S2.1). Yield data were then extrapolated using cob diameters and lengths – two parameters that were not affected by the locust plague - from corn cobs of the study fields, combined with plant density and the average number of cobs per plant. The resulting estimated yield corresponds to the potential yield without locust invasion.

2.2.5 Laboratory analyses

Soil fertility was assessed by measuring pH, total carbon (C), total nitrogen (N) and inorganic nitrogen forms (NO_3, NH_4, NO_2), plant available phosphorus (P) and main cations (K, Ca, Mg, Na, Mn). Soil pH was measured in a 1:2.5 soil:water suspension (v:v) (Allen, 1989). Total C and N were assessed on milled soil with a standard CHN analyser (Dumas method). Because of the absence of carbonates in acidic soils, total carbon represents total soil organic carbon. Extraction solutions were prepared for exchangeable cations (Cobalt-hexamine solution, Co(NH3)Cl3 0.0166 M) and inorganic nitrogen forms (KCl 1 M). All extractions were performed on 10 grams of dry soil with 40 ml of solution, then shaken for one hour at 120 rpm and filtered at 0.45 µm. Exchangeable cations were measured with a plasma atomic emission spectrometer Shimadzu ICPE-9000, whereas inorganic nitrogen forms were analysed colorimetrically using a continuous flow analyser. Phosphorus was measured with an anion-exchange resin. This method has been shown to correlate well with the phosphorus fraction available for the plant (Hedley et al., 1982). Five grams of dry ground soil samples were shaken overnight (16h) with resin membrane strips (bicarbonate charged) in a miliQ solution. Later, resins were eluted with a NaCl-HCl 0.5 M solution to extract phosphorus (Kouno et al., 1995). Phosphorus concentrations were measured colorimetrically using the malachite green method and placing the samples in a Shimadzu 1800 UV-Vis spectrophotometer (Ohno and Zibilske, 1991).

2.2.6 Statistical analyses

Linear mixed effects models were used to determine whether soil chemical properties and plant morphological traits varied with the duration of exploitation of the plots (land-use effect) and the sampling year (climate effect), which were the fixed effects. The models included village and soil sampling depth as random effects nested within sampling year to take into account repeated measurements within each sites (Pinheiro and Bates, 2000). Redundancy analysis (RDA) was implemented to assess the multivariate response of soil and plant variables to the duration of exploitation of the plots (land-use effect) and the sampling year (climate effect). When necessary, values were log-transformed prior to analysis to satisfy the assumption of normality and homogeneity of variance.

To assess the effect of the 2015 extreme rain (Chedza cyclone in January 2015) and other past extreme events (e.g. the Giovanna cyclone in February 2012), we built up pair-wise comparisons for the major plant nutrients in the soil (two N forms, P and K), the plant morphological traits (height, basal diameter, cob length and diameter) as well as plant density and grain yield (Fig. 2.3, Fig. S2.2). Pair-wise comparisons permit disentangling of potential effects of extreme events from land-use effects. T-tests were compiled for pair-wise comparisons and converted subsequently into Cohen's d estimate (mean difference) for effect size measurement (Cohen, 2003). Effect sizes ab1, ab2 and ab3 are related to climate differences, because they describe pair-wise comparisons between fields of same age, but sampled under different climatic conditions. Effect sizes a12, a23, b12, b23 are related to land-use differences, because they are pair-wise comparisons along the chronosequences. However, this last set of effect sizes can potentially also describe legacy effects of past cyclones along the chronosequences, such as the Giovanna cyclone in February 2012 (Fig. 2.3).

Finally, to determine the corn field response to soil fertility, we computed for plant height, plant basal diameter, cob size and grain yield, a full linear model including main plant nutrients: phosphorus, nitrate, ammonium and potassium. Nitrate and ammonium were combined together to analyse plant response to total inorganic N. Then, the full model was simplified by stepwise selection, which consists of removing one by one non-significant variables until the best model is obtained, according to the Akaike Information Criterion (AIC) value (Borcard et al., 2011).

All statistical analyses were performed using R 3.0.1 (R Development Core Team, 2013) using the vegan (Oksanen, 2011), compute.es (Del Re, 2013), nlme (Pinheiro and Bates, 2000) and sciplot packages (Morales, 2012).

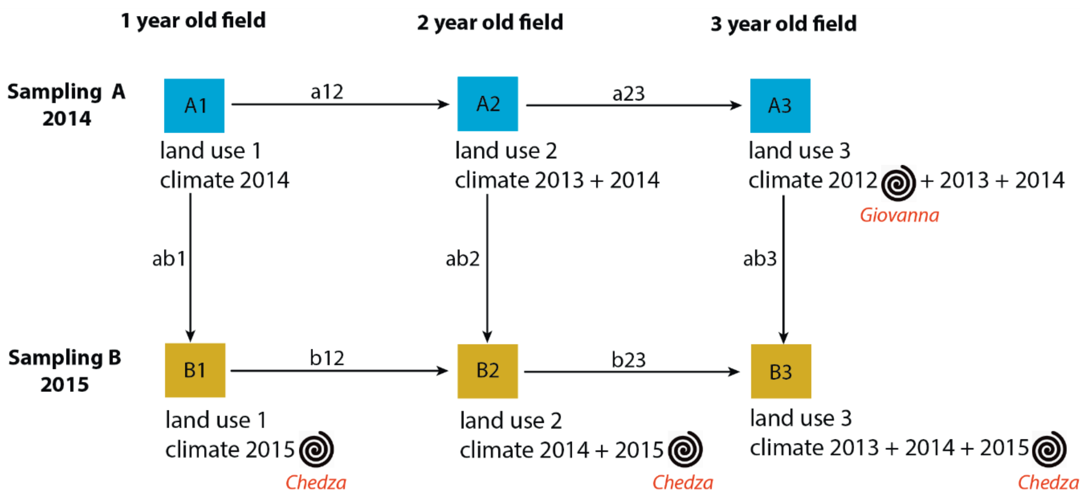


Figure 2.3 *Sampling design with respect to the duration of field exploitation (land-use effect) and the sampling year (climate effect). Capital letters indicate field categories and lower case letters indicate pair-wise comparisons for detecting effect size on response variables. Cyclone icons show the year with a 'cyclonic climate', i.e. when a cyclone hit the coast near the study site during the cropping season.*

2.3 Results

2.3.1 Soil fertility dynamics

Soil fertility decreased along the chronosequences, notably for plant-available phosphorus, nitrate and ammonium (Fig. 2.4, Table S2.2). Nutrient concentration decreased by 50% for phosphorus ($P = 0.008$, Fig. 2.4), by 50% to 80% for nitrate ($P < 0.001$, Fig. 2.4) and by 40% to 80% for ammonium ($P < 0.001$, Fig. 2.4), accounting for both sampling years. Conversely, soil K concentration did not decrease over the years of cultivation, nor did total N, total C and Ca (Table S2.1, S2.2). In 2015, all soil chemical variables had lower values than in 2014 (up to -50%, $0.011 < P < 0.001$), except for pH, which remained stable (c. 7.5; Table S2.1, S2.2). Soil concentrations at the two different depths (0-10 cm and 10-20 cm) showed similar tendencies, however the concentrations were significantly higher for depth 0-10 cm ($P < 0.001$). As a corollary, hereafter we present only figures for depth 0-10 cm, except for RDA graphs (Fig. 2.5, Fig. 2.6).

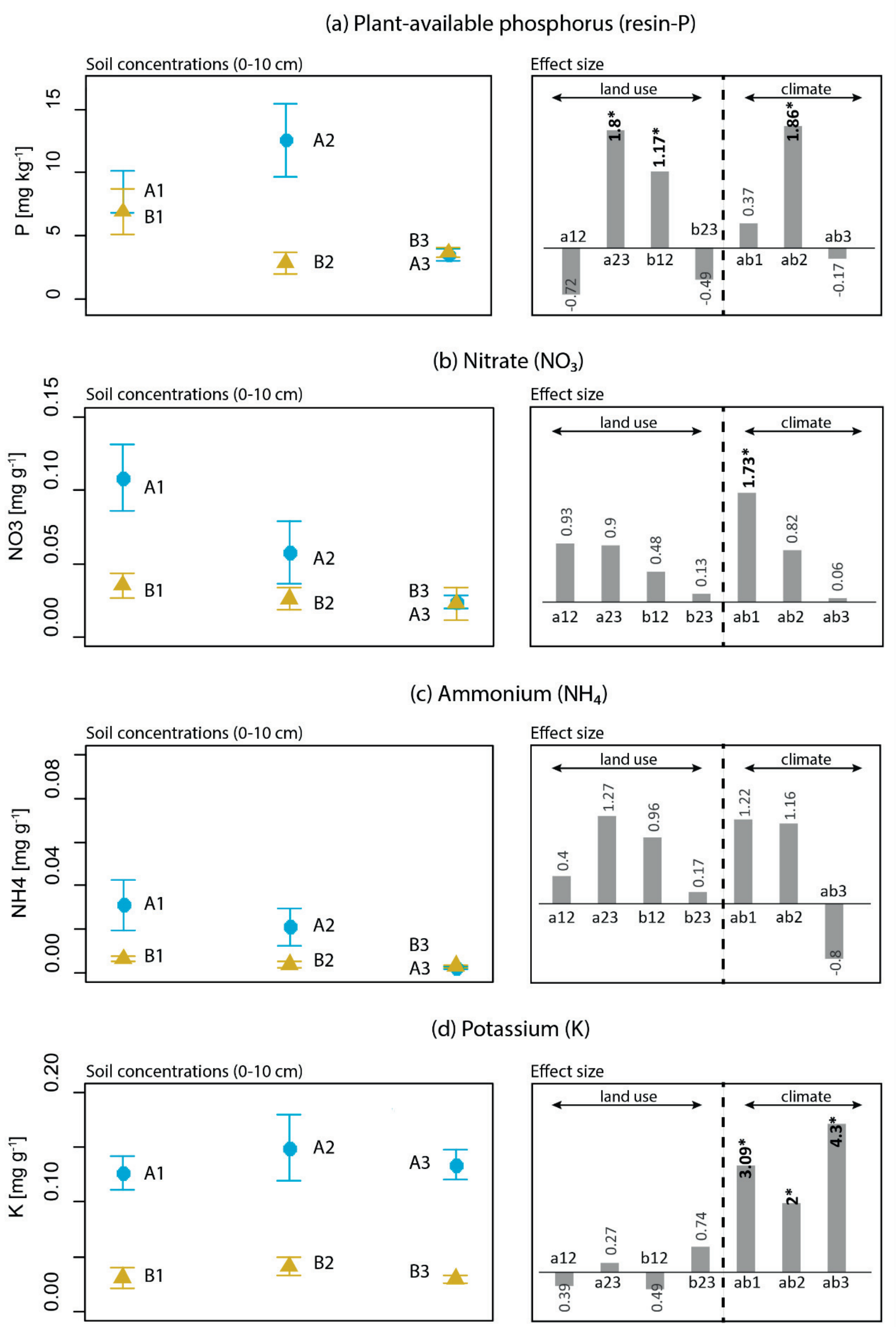


***Figure 2.4** Differences in top-soil (0-10 cm) phosphorus, nitrate, ammonium and potassium concentrations in the sampled plots according to the sampling year (A: 2014; B: 2015) and duration of cultivation (numbers 1, 2 and 3 correspond to fields that have been cultivated during 1, 2 or 3 years). Effect sizes are given according to pair-wise comparisons (see signification of codes in Fig. 2.3).*

Effect sizes for pair-wise comparisons revealed different patterns for distinct nutrients. For phosphorus, effect sizes were significant for two land-use effect relationships (a23 = 1.8, b12 = 1.17) and one climate effect relationship (ab2 = 1.86). For NO_3, only ab1 was significant (ab1=1.73), while for NH_4, no effect sizes were significant. Further, for K, all climate effect sizes relationships were significant (ab1=3.09, ab2=2 and ab3=4.3), while land-use effects were not. For both NO_3 and K, effect sizes related to climate differences (ab1, ab2, ab3) were higher than effect sizes related to land-use (a12, a23, b12, b23). Finally, the effect size for the relationship ab3 was constantly lower than ab1 and ab2 for P, NO_3 and NH_4.

RDA for depth 0-10 cm indicates contrasting relationships according to soil chemical variables and sampling years (Fig. 2.5, Fig. 2.6). Samples are well separated in relation to sampling year along the first axis (41%, $P \leq 0.001$, 2015 against 2014), while the second axis (4.7%, P = 0.021) separates the samples according to the duration of field exploitation, especially in 2014. Together, sampling year and duration of field exploitation explain 44.9% of the variance (adjusted-R2). Older fields are characterized by inferior concentrations of NO_3, NH_4 and phosphorus. Samples of 2015 had generally lower concentrations of most chemical variables. RDA for depth 10-20 cm showed the same trend than RDA for depth 0-10 cm (40.3%, P = 0.001 for 1st axis; 3.7%, P =0.04 for 2nd axis; Fig. 2.6).

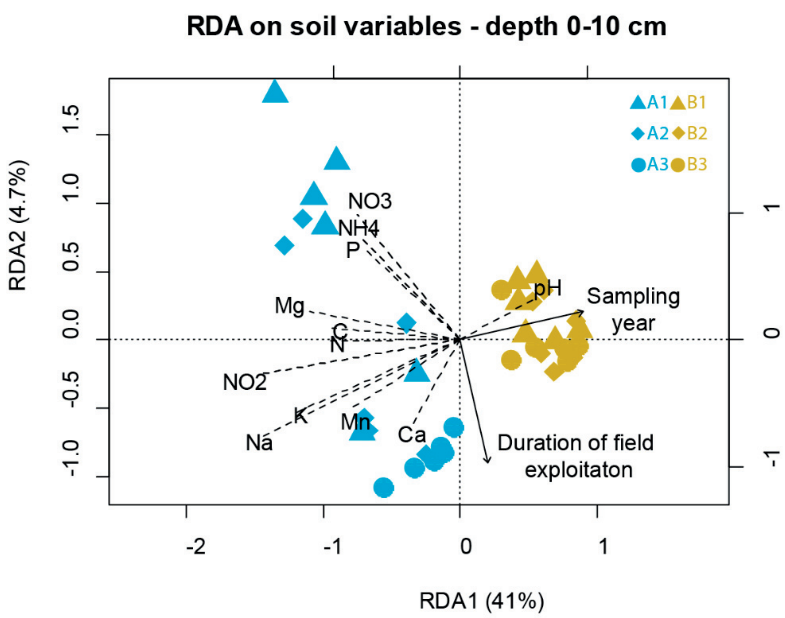


__Figure 2.5__ Redundancy analysis (RDA) of soil samples (0-10 cm) using chemical response variables and two quantitative explanatory variables, sampling year (A: 2014 and B: 2015) and duration of field exploitation (1, 2 or 3 years).

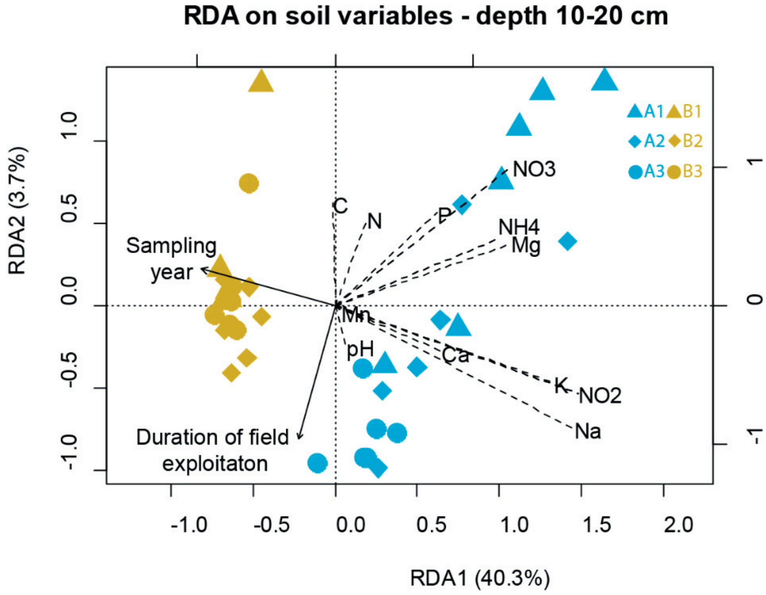


Figure 2.6 *Redundancy analysis (RDA) of soil samples (10-20 cm) using soil chemical response variables and two quantitative explanatory variables, sampling year (A: 2014 and B: 2015) and duration of field exploitation (1, 2 or 3 years).*

2.3.2 Corn fitness and yield

The plant density, as well as the number of cobs per plant, was not affected by land use, neither by climate nor locust plague (Fig. 2.7, Table S2.3). Plant density averaged 1.3 plants m-2 (±0.4), while the plants held a mean of 1.1 cobs (±0.2). Plant height seemed to respond only to land-use, while plant diameter, cob size and grain yield responded only or stronger to climate than to land use (Fig. 2.7, Fig. S2.2, Table S2.3). Plant height decreased from the first year of cultivation to the third year by 20% (from 280 cm to 220 cm, $P < 0.001$) (Fig. 2.7). The decrease was especially strong between the second and the third year of cultivation (18%). Grain yield seemed to decrease also with the duration of field exploitation (Fig. 2.7, Table S2.3). However, while the decrease in grain yield due to the duration of field exploitation reached about 37.5% after three years of cultivation on the same field (from 4 to 2.5 t ha^{-1}, $P = 0.012$), yield decreased up to 75% between 2014 and 2015 (from 4 to 1 t ha^{-1}, $P < 0.001$). Grain yield of 2014 corresponds to the potential yield without the locust invasion. If we considered the attack of the swarms, grains were completely eaten on the fields and yield loss can be considered as nearly 100%. Plant diameter decreased also by about 20% in 2015, in comparison to 2014 (from 2.3 cm to 1.8 cm, $P < 0.001$, Fig. 2.7). Effect sizes related to climate (ab1, ab2, ab3) were higher than effect sizes related to land-use (a12, a23, b12, b23) for plant diameter and grain yield, which were all significant. For plant height, the tendency was opposite and significant effect sizes were related to land-use rather than for climate.

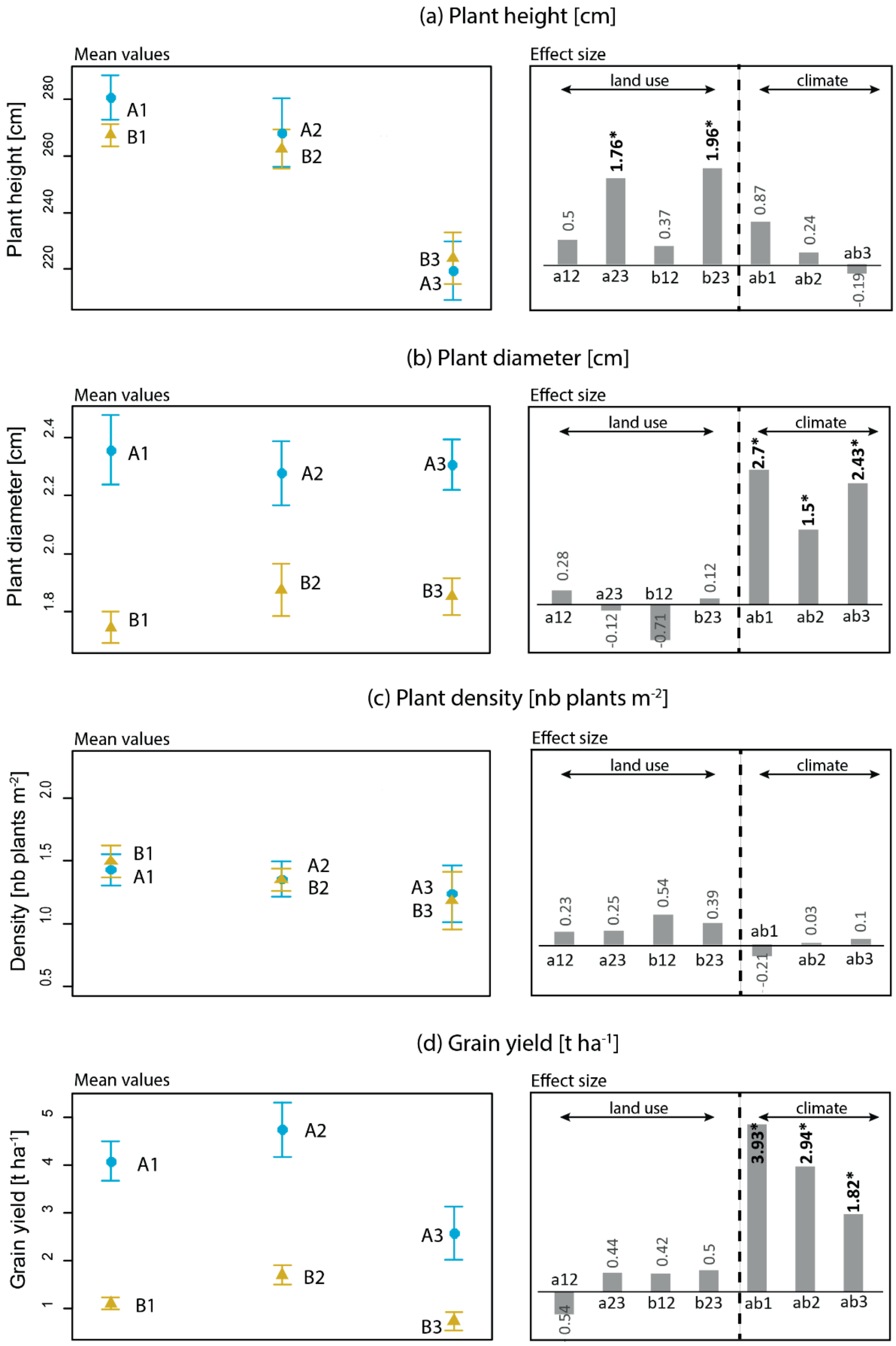


Figure 2.7 *Differences in corn fitness and yield in the sampled plots according to the sampling year (A: 2014; B: 2015) and duration of field exploitation (numbers 1, 2 and 3 correspond to fields that have been cultivated during 1, 2 or 3 years). Effect sizes are given according to pair-wise comparisons (see signification of codes in Fig. 2.3). Corn yield in 2014 corresponds to the estimated yield lost during the locust plague.*

RDA for plant morphological traits and field characteristics shows similar patterns as the RDAs of soil chemical properties (Fig. 2.8). Two clear groups of samples are separated along the first axis (47.7%, P = 0.001) which is defined mostly by the sampling year. Samples are also separated along the second axis (9.6%, P = 0.001) according to the duration of field exploitation. Sampling year and duration of exploitation explain together 66.3% of the variance (adjusted R2). Fields sampled in 2015 are characterized by plants with reduced basal diameter and corn cobs, as well as a lower grain yield, as compared to 2014. Three-year-old fields are characterized by smaller plant heights than younger fields.

Plant response to soil fertility models showed that inorganic N, P and K soil concentrations all had significant effects on the traits (Table S2.4). The optimum models describing plant response to soil fertility, according to AIC, were the full models for plant height and cob length (models with N, P and K) and partial models with only N and K for plant diameter, cob diameter and grain yield. Inorganic N had a significant effect on plant height (P = 0.014), plant diameter (P = 0.003), cob diameter (P <0.001) and grain yield (P <0.001). It had also a marginal effect on cob length (P = 0.071). Phosphorus was significant for plant height (P = 0.039) and had an interaction effect with inorganic N on cob length (P = 0.040). Finally, potassium had a strong influence on plant diameter, cob length, cob diameter and grain yield (P < 0.001).

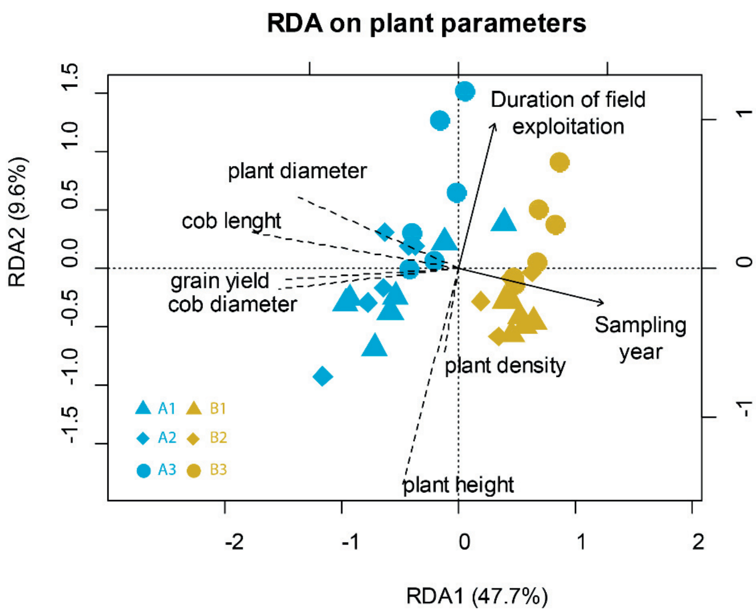


Figure 2.8 *Redundancy analysis (RDA) of corn plants using morphological traits as response variables and two quantitative explanatory variables, sampling year (A: 2014 and B: 2015) and duration of field exploitation (1, 2 or 3 years).*

2.4 Discussion

2.4.1 Land use effect on soil fertility dynamics

N and P soil fertility decreased with the years of field exploitation. While plant available P and inorganic N forms in the soil experienced a strong decrease, K content, however was not affected by land-use. The input of base cations by ashes is high in comparison to P and N inputs (Béliveau et al., 2015; Ohno and Erich, 1990), suggesting that annual burning helps to stabilize base cation concentrations. In Kirindy forest, the biomass of a 40 year old secondary succession reaches about 72 t ha^{-1} (Raharimalala et al., 2012). When this biomass is converted to ashes through slash-and-burn agriculture, about 50% of K and P are lost through wind and rain erosion, as well as nutrient leaching, and 95-98% of N is volatilized during tree combustion (Chadwick et al., 2003). Given so, Raharimalala (2011) estimated the fertilization rate of the ashes to be 17 kg N ha^{-1}, 10 kg P ha^{-1} and 148 kg K ha^{-1}. As the plots of our study came from primary forest remnants instead of old secondary successions, the aforementioned values are probably lower than the real biomass and fertilization rates. Nevertheless, N and P fertilization values are far from meeting corn requirements (50 kg N ha^{-1}, 75 kg P ha^{-1} and 80 kg K ha^{-1}, according to Landon, 1996), which may lead to soil depletion after several years of cultivation.

Studies that compare fire-free techniques to slash-and-burn agriculture corroborate our results on the depletion of nitrogen (Comte et al., 2012; Giardina et al., 2000; Nye and Greenwood, 1960). As underpinned by the effect sizes (a12, a23, b12 and b23), the decrease in N is moderate, yet constant. Furthermore, fire has a direct impact on soil microorganisms. Heat induces lysis of microbial biomass, causing a rapid and short flush of plant-available N (Durán et al., 2008), increasing the risk of N loss by leaching following rainfall events.

Concerning P, its availability in tropical acid soils is mostly controlled by the strong adsorption capacity of iron and aluminum minerals, making it unavailable for plant uptake (Frossard et al., 1995). In slash-and-burn agriculture, the increase in pH due to ash amendment modifies the chemical equilibrium between the different P forms, enhancing the release of phosphorus into the soil solution (DeBano and Klopatek, 1988). The heat of the fire will also increase plant available phosphorus by pyro-mineralization of organic and microbial P forms (Saa et al., 1993). Thermally transformed unavailable P into plant-available forms can even be larger than mineral P contained in the ashes and in the soil in general (Giardana et al., 2000). The trend along the studied chronosequences showed partly this complex geochemical equilibrium. Phosphorus depletion occurred from A1 to A3 and from B1 to B3, but non-significant value for a12 and b23 indicate a steady state from A1 to A2, and from B2 to B3. This non-uniform decrease of P could be due to fire temperatures, pH or an amount of P release from killed microorganisms. Release of P attached to iron and aluminum oxides plays an important role for soil fertility, although it is difficult to quantify and predict.

2.4.2 Climate effect on soil fertility dynamics

The strong effect of sampling year in both effect sizes and in the RDA is most probably due to the cyclone Chedza which occurred in January 2015, at the early stage of crop development when plants were low and the soil was bare. Heavy rainfall has two major effects on soil: rapid leaching of nutrients, and induced soil erosion through surface run-off (Thomaz, 2013; Vezina et al., 2006), leading to a degradation of the nutrient rich top soil (Comte et al., 2012). Vegetation cover decreases with repeated fires and consequently protection against splash-effect caused by raindrops is removed (Vezina et al., 2006). Saint-Laurent et al. (2014) studied the effect of temporary flooding on soil properties and showed that soil organic matter and nutrients concentrations were lower in frequently flooded soils than in non-flooded soils, which mirrors the results of our study.

In the rainy season of 2012, another cyclone (Giovanna) crossed Madagascar in February 2012 near the study site (Fig. 2.2). The occurrence of this phenomenon could have affected our oldest plots, the A3 plots. Indeed, a significant fertility drop occurred from A2 plots to A3 plots and the effect size a23 was systematically significant for NO_3, NH_4 and P. The concentrations of these nutrients in the A3 plots dropped to similar concentrations as in the B3 plots, leading to a non-significant ab3 effect size. Indeed, both A3 and B3 plots underwent a cyclonic event, A3 in 2012 and B3 in 2015. However, this tendency is not found for K as the effect size a23 is not significant, but ab3 is significant. We argue that K is present in high quantity in the ashes (Ohno and Erich, 1990), which is not the case for P and N. Thus, this element can be replenished more easily than N and P. Consequently, cyclonic events might have a strong and long lasting effect on soil N and P fertility, and only a short-term effect on K concentrations.

2.4.3 Effect of cyclones in interaction with soil fertility on corn fitness and yield

Plant height responded more to land-use than to climate, while plant diameter, cob size and grain yield were more impacted by the difference in climate in both years. Plant responses to soil fertility models showed that the decrease of N and P impacted negatively on all morphological traits. However, plant diameter, cob size and grain yield were also strongly impacted by a decrease in K as occurred in 2015 after the cyclone Chedza. Thus, under normal rainfall regime, corn plants may cope with limited soil N and P, while under intense rainfalls, K concentration (and probably other cations too) become also low, which leads to a generalized poor soil fertility and reduces the overall corn performance.

Both N and P have a structural role for plants. N is present in proteins, nucleic acids, chlorophyll, coenzymes, and secondary metabolites (Römheld, 2012). P is also a constituent of nucleic acids and forms adenosine phosphates, which control energy transfers in the plants. Generally it is assumed that soils are P deficient for plants when $P < 15$ mg kg^{-1}, and N deficient when N < 10 mg g^{-1}. Hence, all soils in this study are low in P and N since concentrations are systematically below this threshold. Some varieties of corn can adapt to low N and P concentrations (Gaume et al., 2001). This could be the case in our studied fields as plant height was not different between 2014 and 2015, although concentrations of soil N and P were lower in 2015. These result might be explained because *vonivony* corn variety may be able to cope with limiting N and P in the soil until a very low threshold. This threshold is reached only during the third year of cultivation, creating a strong decrease in plant height for A3 and B3 fields. When P is deficient, the dry matter is significantly reduced (Gaume et al., 2001). Nitrogen deficiency is also known to act both on growth rates and on the timing of growth stages (Zhang et al., 2008a). N fertilization experiments show N addition to lead to taller plants, earlier in the season and advanced plant maturity (Zhang et al., 2008a). Furthermore, P deficiency acts negatively on N concentrations. At low P concentration, an addition of N has little effect on yield, whereas at high P concentration, yield increases (Sumner and Farina, 1986). Indeed, low P concentration reduces the activity of ammonia-oxidizing bacteria and leads to a reduction in plant available N forms (Chu et al., 2007).

Besides N and P effects, the level of soil moisture at the beginning of the dry season might have also impacted plant heights (Çakir, 2004; Payero et al., 2006). In the third year, all trees disappeared after repeated slash-and-burn practice, while in younger fields some trees are still remaining (Dirac Ramohavelo, 2009). As such, older fields do not have shading from remaining trees. Consequently, soil water shortage will be stronger in older fields, and the dry season may start a few days earlier for A3 and B3 fields than for A1, B1 and A2, B2. If drought starts during vegetative or tasseling stages, a loss of 28 to 32% of dry matter weight can result (Çakir, 2004). Plants suffering from water stress stop growing, because N and P uptake is hampered (Sardans and Peñuelas, 2012).

Finally, while decrease in grain yield due to slash-and-burn agriculture reaches about 37.5% after three years of cultivation on the same field, it decreases by 75% after a single cyclonic rainy season. The drastic decrease between years 2014 and 2015 is probably due to a strong N and P limitation, combined with a low concentration of K. Potassium controls plant osmoregulation, which is essential for stomata movement and also for cell extension (Römheld, 2012). However, in a fertilization experiment in Zimbabwe with a similar soil, K did neither improve grain yield, nor had an interaction with N or P for yield (Kurwakumire et al., 2014). In our study, an alternative explanations for the difference in grain yield between 2014 and 2015 might be a multiple soil deficiency in leachable cations such as Mn, Ca or Mg (Saint-Laurent et al., 2014). Also, an excess of humidity might have damaged the plants in 2015, preventing an optimal growth (Rakotobe et al., 2016).

2.4.4 Further considerations on locust swarms

The variability of rainfall distribution, particularly drought episodes, and newly deforested areas favor the development of migratory locusts outbreaks (Locusta migratoria capito) (Lecoq and Sukirno, 1999; Liu et al., 2008). This phenomenon is not recent in

Madagascar where locusts can form huge swarms in the south-western Madagascar around Tulear region (Cooper et al., 1995). Depending on the size of the swarm, it can be a severe threat to corn and rice cultivations, destroying entire fields of smallholder's farms over large areas (Fei and Zhou, 2016). Surprisingly, in 2014, a swarm invaded the Kirindy forest, although this forest was never a locust zone before that year. The effect on corn fields was dramatic, reducing the yield down to zero. The apparition of this new zone is strongly linked with the absence of locust control measures after the political crisis in 2009. Migratory locust swarms were declared as a national threat for the Island in November 2012 and a three-year emergency program has been launched to control this pest between 2013 and 2016 (FAO, 2016). The plague was stopped and a calm locust situation prevails now (FAO, 2016). Locust control goes hand in hand with critical political decisions, and therefore this question would need a broader investigation, beyond the scope of a single ecological study (Lecoq, 2001). Nevertheless, this disaster points out the fragility of the food security situation in western Madagascar.

2.5. Conclusion

Cyclones have a much stronger impact on soil fertility and corn fields than land use. Heavy rainfalls intensify soil nutrient depletion by slash-and-burn agriculture. The soil turns out to be not only N and P deficient, but K concentration is also reduced, and other cation concentrations as well. Overall, this leads to a strong decline in corn performance, and thus yields are reduced by 75% (from 4 t ha^{-1} to 1 t ha^{-1}). However, K is replenished more rapidly in the top soil than N and P, possibly because for K, the yearly fertilization rate is superior to corn requirements. We also detected a legacy effect on soil N and P concentrations of a past cyclone 3 years after its occurrence. Therefore, cyclonic events may have a strong and lasting effect on soil N and P fertility and a short-term effect on K concentration.

Besides our study, a locust pest also damaged half of the corn fields in 2014, driving the corn yield down to zero on those fields. Natural threats such as locust swarms enhance the fragility of rural households, as well as underline the increasing food security instability in south-western Madagascar. Global warming, modification of cyclonic activity and frequency, or prolonged drought periods will ultimately worsen the working conditions of farmers and the soil fertility management. Our findings calls for raising farmers' awareness with respect to more sustainable agricultural practices in order to face future challenges of food security in the context of climate change. Fertilization means that increase organic matter content with slow release of mineral elements should be favored, as well as soil protection against soil erosion and nutrient leaching. Possible alternatives could be mulching, composting or a selective slash-and-burn cultivation where remaining standing trees provides shade, organic matter, shelter against locust invasion and a higher seed bank for quicker forest re-establishment. We would recommend to combine those three alternatives in order to fight actively against soil degradation, deforestation and locust swarms.

Chapter 2 supplementary material

Supplementary figures

Figure S2.1 Regression model between corn cob dimensions (diameter x length) and cob grain weight

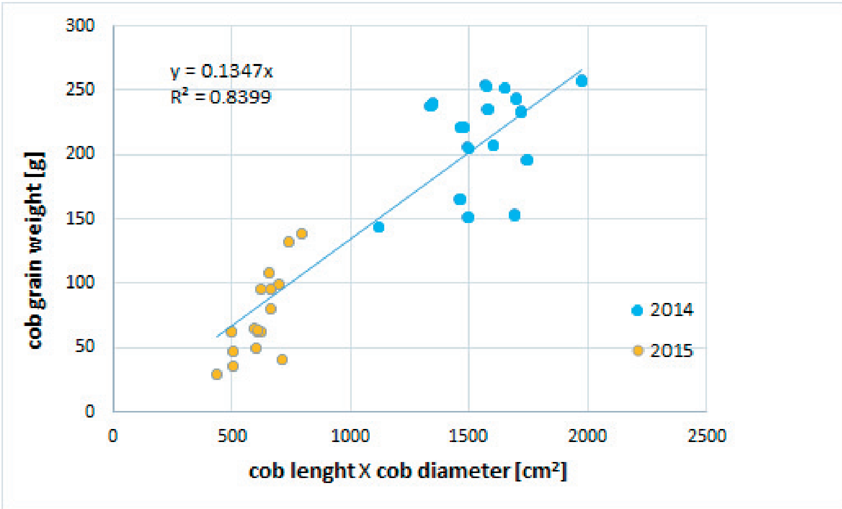
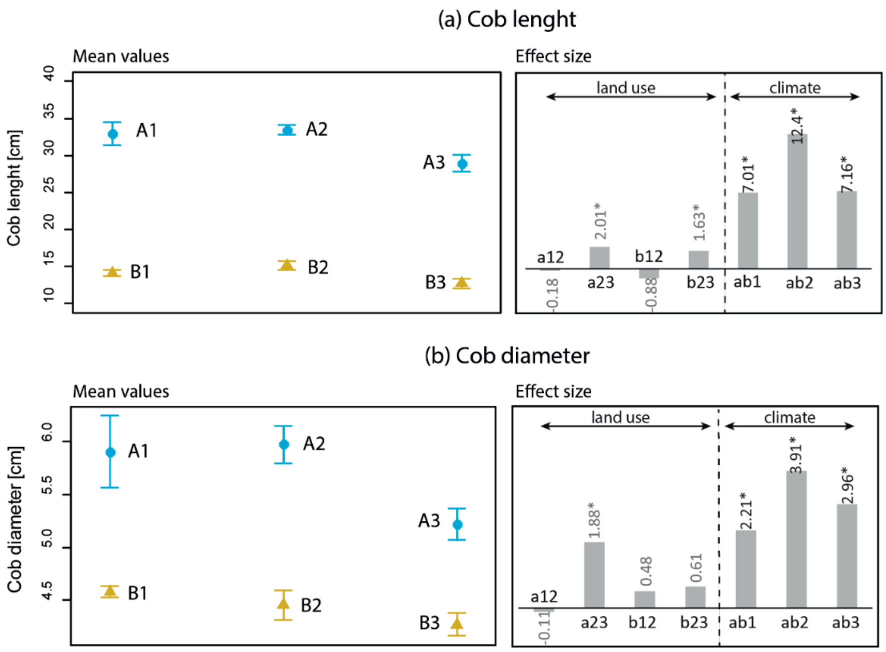


Figure S2.2 Differences in corn cob a) length and b) diameter in the sampled plots according to the sampling year (A: 2014; B: 2015) and duration of field exploitation (numbers 1, 2 and 3 correspond to fields that have been cultivated during 1, 2 or 3 years). Effect sizes are given according to pair-wise comparisons (see signification of codes in Fig. 2.3).



Supplementary tables

Table S2.1 Mean values and their standard deviation for some soil fertility parameters measured within surveyed plots.

Duration of cultivation [year]	Sampling year	Nb plots	pH	Mg [mg kg^{-1}]	Ca [mg kg^{-1}]	Ntot [%]	Ctot [%]
1	2014	6	7.362 (0.340)	0.226 (0.055)	1.599 (0.424)	0.214 (0.038)	2.544 (0.506)
2	2014	6	7.580 (0.267)	0.189 (0.079)	2.352 (0.660)	0.214 (0.033)	2.552 (0.486)
3	2014	6	7.332 (0.347)	0.128 (0.027)	1.856 (0.720)	0.139 (0.030)	1.665 (0.459)
1	2015	6	7.585 (0.250)	0.078 (0.023)	1.484 (0.613)	0.092 (0.054)	1.161 (0.726)
2	2015	6	7.688 (0.171)	0.089 (0.020)	1.413 (0.251)	0.073 (0.038)	0.959 (0.498)
3	2015	6	7.572 (0.163)	0.096 (0.042)	1.772 (0.679)	0.118 (0.103)	1.309 (1.247)

Table S2.2 Summary of linear mixed effect models using soil chemical response variables (2014 and 2015) according to duration of field exploitation (land-use effect), year of sampling (climate effect), soil depth and their cross effects. Significant values are in bold.

	Duration of cultivation (Land-use)		**Sampling year (Climate)**		**Soil depth**		**LxC**		**LxD**		**CxD**		**LxDxC**	
	F	p	F	p	F	p	F	p	F	p	F	p	F	P
N	2.67	0.1120	13.86	**0.0008**	6.16	**0.0185**	5.98	**0.0203**	0.01	0.9169	9.96	**0.0035**	0.52	0.4732
C	3.03	0.0913	13.36	**0.0009**	3.43	0.0731	1.80	0.1886	0.03	0.8531	11.35	**0.0020**	0.04	0.8359
K	0.35	0.5579	143.55	**<.0001**	10.88	**0.0024**	1.07	0.3085	0.02	0.8668	3.24	0.0810	2.82	0.1023
P	7.92	**0.0084**	54.48	**<.0001**	6.07	**0.0194**	0.01	0.8974	2.89	0.0991	0.50	0.4846	1.21	0.2785
Mg	4.72	**0.0375**	52.33	**<.0001**	73.26	**<.0001**	11.92	**0.0016**	1.62	0.2122	0.20	0.6572	1.40	0.2439
Ca	0.17	0.6801	7.38	**0.0107**	318.87	**<.0001**	0.23	0.6324	3.25	0.0805	5.02	**0.0321**	0.49	0.4878
N03	24.20	**<.0001**	29.35	**<.0001**	42.63	**<.0001**	0.75	0.3919	1.11	0.2981	17.25	**0.0002**	0.29	0.5908
NH4	24.20	**<.0001**	29.35	**<.0001**	42.63	**<.0001**	0.75	0.3919	1.11	0.2981	17.25	**0.0002**	0.29	0.5908
pH	0.02	0.8876	1.18	0.2864	0.02	0.8966	0.35	0.5593	0.32	0.5744	5.91	0.0208	0.55	0.4655

Table S2.3 Summary of linear mixed effect models using corn performance response variables (2014 and 2015) according to duration of field exploitation (land-use effect), year of sampling (climate effect) and their cross effect. Significant values are in bold.

	Duration of cultivation (Land-use)		**Sampling year (Climate)**		**LxC**	
	F	*P*	F	*P*	F	*P*
Plant height [cm]	32.696	**<0.001**	0.522	0.475	0.920	0.344
Plant diameter [cm]	0.255	0.6173	50.268	**<.0001**	0.931	0.342
Cob length [cm]	7.695	**0.0094**	544.880	**<.0001**	0.052	0.820
Cob diameter [cm]	8.401	**0.0069**	86.065	**<.0001**	0.475	0.495
Dry grain yield [t ha^{-1}]	7.234	**0.012**	72.30392	**<.0001**	0.847	0.364
Plant density [nb plants m^{-2}]	2.493	0.124	0.00038	0.984	0.142	0.708
Number of cobs per plant	1.790	0.191	1.562	0.221	0.463	0.501

Table S2.4 AIC values for all possible linear models linking plant morphological traits and soil nutrients. Significant values are in bold. N includes both nitrate and ammonium.

	K	**N**	**P**	**K&N**	**N&P**	**K&P**	**K&N&P**
Plant height [cm]	330.3207	325.17	332.31	300.79	314.94	318.27	**271.19**
Plant diameter [cm]	9.3435	24.46	37.09	**-0.76**	36.17	20.30	5.77
Cob length [cm]	217.2762	245.14	253.92	196.17	240.74	211.53	**180.80**
Cob diameter [cm]	63.49159	82.55	86.17	**52.46**	83.54	67.98	56.71
Dry grain yield [t ha^{-1}]	73.05085	82.77	93.04	**58.69**	88.23	79.67	63.05

- CHAPTER 3 -

Local ecological knowledge elicitation helped defining what triggers field abandonment in a slash-and-burn agricultural system

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This work is the outcome of the master thesis of Céline Dillmann, MS student at ETH Zurich, supervised by Prof. Claude Garcia. Justine Gay-des-Combes has helped in organizing field work, advised Céline while she was in the field and co-written the article. The survey design and the methodology were conceived and driven by the ETH team. The manuscript is in preparation.

Picture: Maize harvest in Kirindy village
Justine Gay-des-Combes, 2014

Abstract

Slash-and-burn agriculture is a major driver of forest degradation in the tropics. In Madagascar, this technique is strongly embedded in traditions, resulting in difficulties for the government to initiate a change towards more sustainable practices. Academic research stressed out that this type of cultivation leads to soil degradation and nutrient depletion over the years, which forces the farmers to abandon their fields and continuously re-burn new forest areas. However, the decision-making process in shifting fields has never been verified from farmers' point of view. Thus, this study aims at (1) understanding farmers' decision making processes that lead to abandoning their fields and clearing new forest areas; and (2) giving hints to develop more sustainable agricultural practices. For this, we explore farmers' local ecological knowledge (LEK) on soil management in slash-and-burn systems in Central Menabe, western Madagascar. LEK was captured in a knowledge base constructed with the Agroecological Knowledge Toolkit (AKT). The methods included identification, definition and elicitation of local knowledge through interviews and knowledge base construction using the AKT grammar. Weed invasion and soil fertility were both identified as critical factors in farmer's decision-making process. However, we showed that weed management appeared to be more relevant than soil fertility in a farmers' perspective, which was not highlighted by previous research. Weed invasion represents a work overload for farmers, which subsequently leads to field abandonment. This problem should be addressed first in order to build a socially and environmentally sustainable alternative to slash-and-burn agriculture. We argue that future research in natural resource management needs to widen its scope in order to integrate properly the needs, constraints and aspirations of the local actors, otherwise the real drivers of change in agro-ecosystems might be overlooked. The elicitation of local knowledge is a good point to begin with.

Keywords
Deforestation, ecological knowledge, Madagascar, slash-and-burn agriculture, soil fertility, weed invasion.

3.1 Introduction

Tropical forests hold a large biodiversity, which is threatened by severe deforestation (Geist and Lambin, 2002). The problem is particularly salient in Madagascar (Brinkmann et al., 2014; Green and Sussman, 1990; Waeber et al., 2016), which is pointed out as one of the eight most important biodiversity hotspots in the world in terms of both endemic species and threats (Myers et al., 2000). In the Menabe region, western Madagascar, the forest cover will have disappeared within the next 11 to 37 years if deforestation rates stays unabated (Zinner et al., 2014), and with it, ecosystem services such as nutrition, timber provision, biodiversity conservation or carbon storage (Ramohavelo et al., 2014; Sorg et al., 2003; Waeber et al., 2015). This could have knock-on effects and is likely to negatively impact the livelihood of the rural population (Dirac Ramohavelo, 2009). Slash-and-burn agriculture, a traditional technique during which the forest is transformed to agricultural land by cutting and burning trees, is still practiced in the area. Ashes are spread on the newly cleared land to amend the soil. After a few years of repetitive cultivation on the same surface, crop yield decreases and weeds invade the field. Farmers are then forced to abandon their fields to burn and clear new areas of forest (Styger et al., 2009, 2007).

Since the beginning of the 20th century, constant efforts have been made to change the current slash-and-burn agricultural practices, however they were not successful (Kull, 2004). Even radical measures like anti-fire policies, in place for over one-hundred years, could not stop these practices (Jarosz, 1993). Styger et al. (2007) and van Vliet et al. (2012) explained the persistence of shifting cultivation as a result of farmers' limited access to micro-credits and markets, unsecure land tenure systems and population growth. Yet, the strong social and cultural background is another driving factor (Desbureaux and Brimont, 2015; Jarosz, 1993). Since the beginning of 1900, forest areas were cleared intensively, even after the colonial government imposed a ban on shifting cultivation (Harper et al., 2007). The anti-fire policies have been seen by local population as a deprivation of access to their subsistence and a means to force them to undertake wage labour (Jarosz, 1993). Besides, slash-and-burn agriculture is also linked with spiritual practices, and with the hierarchical organization of the community; thus, losing this practice would be felt as a 'cultural loss' by many forest communities (Desbureaux and Brimont, 2015). As a consequence, alternative approaches that could halt, or at least slow-down, actual deforestation should not aim to suppress slash-and-burn agriculture, but rather modify it to make it sustainable. Indeed, this practice can be sustainable, given the right conditions (Carrière et al., 2002; Kleinman et al., 1995). When the fallow period is kept for a minimum of 10 years, forest can regrow to an optimal stage and the soil can recover sufficiently from past cultivation cycles (Thomaz et al., 2014). Raharimalala et al. (2010) indicate a required fallow time of 20 years for the Menabe region. Maintaining some trees within the fields, instead of burning them all would also help creating a more sustainable system. These trees provide shade, as well as a seed bank for a faster forest recolonization. The roots of the trees also prevent soil erosion and maintain the microbial community (Carrière et al., 2002).

Social research has explained the persistence of slash-and-burn agriculture with its history and traditions in Madagascar, while ecological research points to the importance of soil fertility and the mechanism of forest regeneration (Gay-des-Combes et al., 2017; Raharimalala et al., 2010; Thomaz, 2013). Yet, the decision-making process to abandon cultivated land and burn new forest patches has rarely been studied, even though understanding what triggers field abandonment is the key towards the development of new alternative slash-and-burn techniques. Despite the ecological descriptions of soil fertility loss and weed invasion (Gay-des-Combes et al., 2017; Raharimalala et al., 2010; Thomaz, 2013), the underlying drivers have not been verified from a local farmer's perspective. Hence, local perception and knowledge is an important gap in our understanding of slash-and-burn agricultural systems. Our study aims to (1) understand farmers' decision making processes that lead to abandoning their fields and clearing new forest areas in the context of slash-and-burn agriculture in Madagascar; and (2), to give hints to initiate a change towards more sustainable agricultural practices. For this, we interviewed farmers from villages that have been severely affected by deforestation. Interviews were then processed with the Local Ecological Knowledge (LEK) framework, a tool that allows us to compare local versus scientific knowledge, and to identify opportunities for more sustainable natural resource management (Sinclair and Walker, 1998).

3.2. Methods

3.2.1 Study site

The study site is located in the region of Menabe, on the western coast of Madagascar. The interviews took place around Beroboka village (S19°58', E44°36') in the Kirindy forest, north of the city of Morondava. This forest has been chosen because of its important dry ecosystem biodiversity (Sorg and Rohner, 1996) and the severe local deforestation rate, which is attributed to slash-and-burn agriculture (Zinner et al., 2014). The local climate has a distinct seasonality, typical for the region, with a rainy season between November and March and a dry season between April and October (Sorg and Rohner, 1996). The landscape is composed of primary and degraded dry deciduous forests, wooded grasslands and cultivated land area (Dirac et al., 2006; Waeber et al., 2015). Slash-and-burn agricultural production dominates the landscape with mainly maize, peanuts and rice cultivation (Ramohavelo et al., 2014). The soils are acidic and poor in nutrients, resulting in difficult agricultural growing conditions and low yields (Raharimalala et al., 2010).

3.2.2 Data sampling based on the Local Ecological Knowledge framework

The Local Ecological Knowledge (LEK) framework defines knowledge as people's understanding and interpretation of ecological processes in their particular social and geographical context, based on observation and experience (Joshi et al., 2004; Olsson and Folke, 2001). In this study we applied this approach to gather and analyse the LEK of farmers, specifically knowledge related to soil fertility and other soil properties, and how these factors influence farm management and crop yields. LEK was captured in a knowledge base constructed through the Agroecological Knowledge Toolkit (AKT) developed by Bangor University (http://akt.bangor.ac.uk/index.php.en).

The framework prescribes going through four stages of knowledge elicitation; (i) a scoping phase, (ii) definition phase, (iii) compilation phase and (iv) generalisation phase (Dixon et al. 2001). Scoping allows for creating a general understanding of the study site, the identification of different knowledge holding strata within the local population, and the sources base. The definition phase comprises further interviews conducted within the strata of interest for this study, i.e. the farmers practising slash and burn agriculture around Beroboka village, in order to determine the extent and boundaries of their LEK. The compilation phase is then used to explore the depth of the knowledge, which is done through repeated interviews with a small set of informants (farmers). During this phase, it is important to conduct multiple interviews with the same source. This helps to gain deeper explanatory knowledge, and allows for addressing unresolved questions or concepts from the previous interview. The generalisation phase allows for testing how much other sources within the targeted strata share the detailed knowledge elicited in the compilation phase (Dixon et al., 2001; Sinclair and Walker, 1998, 1994).

The knowledge was evaluated and analysed via the AKT software package. The knowledge representation in the software builds upon the abstraction of the informants' narrative, using a formal grammar (AKT grammar). The articulated knowledge is translated and codified into unitary statements. The knowledge is represented with single phrases or is expressed as a conditional or causal relationship between objects, processes or actions (Dixon et al., 2001). Details of structure and application of this toolkit are available in Dixon et al. (2001).

We carried out 40 interviews with 17 informants during the dry season of 2015. This was the most favourable time for conducting interviews, because farmers have less work in their field and thus are more ready to participate. To favor a positive contact and a confident atmosphere with the local farmers (Jones et al., 2011), introduction to the community was made via an esteemed and locally respected farmer. The translations of the interviews were then provided by Auréla Nasoa Malalaniaina who has already been working in the region. The set of informants was carefully chosen on the basis of three key criteria: (i) owning their fields; (ii) cultivating their fields themselves; (iii) residency in the area for more than 3 years, and was assumed to be a representative of the farmer's community of interest to this study. The third criteria was added to avoid including nomadic groups who are transiting from one village to another in the sources base, whom might have different practices than resident farmers. The informants were gender-balanced and distributed within the age range of 20 to 75 years. To understand decision-making processes in the agricultural system, the interviews focused on (i) the general description of slash-and-burn agriculture (ii) farmers' understanding of soil fertility (iii) current techniques used to maintain the soil fertility and crop yields. The interviews were semi-structured and each lasted between 40 minutes to 1.5 hours, resulting in a total of 38 hours of interview time. Each interview was recorded with the informant's consent. Generally, this research abides to the ethical code of conduct by Wilmé et al. (2016). With each informant, two or three repeated interviews were conducted, with an average of 38 unitary statements per interview. The interviews recorded in the knowledge base amounted to a total of 753 statements.

3.3 Results

3.3.1 Slash-and-burn cultivation system in the Menabe

The forests in the Menabe regions are converted to maize fields by cutting and burning bushes and trees (Fig. 3.1). According to the farmers, maize is cultivated for two or three years, before they switch to peanut cultivation, sometimes intercropped with maize or cassava. After a cultivation period of 4 to 6 years, the yields decrease and fields are left in fallow (statement S247, Table 3.1, Fig. 3.1). At this point, farmers either transform a new forest patch into a maize field, or they re-cultivate old fallows which have recovered from a previous cultivation cycle. The cultivation season takes place during the rainy season, between December and May. At the start of each cultivation season, the field is weeded and burnt to remove remaining trees, weeds and crop residues. According to the farmers, highest yields can be obtained in the second year of cultivation (S723, Table 3.1). During the first year, the clearing and burning process causes a thick layer of ashes (Fig. 3.2) which induces high soil temperatures and consequently lower yields (S365, 542, 731, Table 3.1). From the third year on, yields decrease, in particular for maize (S410, Table 3.1), because weeds increase in number and density (S60, Table 3.1). This increase of weeds goes together with an increase of field work and time spent for weeding and field maintenance (S577, Table 3.1). Finally, to complete the cycle, 20 to 30 years are necessary for abandoned fields to regenerate into a forest (S580, Table 3.1).

Table 3.1 *Selection of farmers' statements from the Knowledge Base (KB). Identification numbers (ID) indicate the position of the statement in KB. They are expressed as recorded in the AKT software (cf. Dixon et al. (2001) for details about the knowledge recording and codification) and are either causal (CAUSES) or conditional (IF).*

Topic	ID	Statement
Cultivation cycle	365	burning of tree duration is between 3 and 4 days CAUSES ash quantity is too high
	542	ash quantity is too high CAUSES soil temperature is too high
	723	yield of the first year cultivation is greater than yield of the second year cultivation
	731	soil temperature of first year cultivation is greater than soil temperature of the second year cultivation
	410	field cultivating duration increases CAUSES maize yield decreases
	577	weeding the field effort is high CAUSES abandoning of field motivation is high IF tsipotika [a bad weed] location is on the field
	580	abandoning of the field duration is 30 years CAUSES forest growing location is on the field
Soil fertility	669	soil fertility is low CAUSES colour of crop leafs is red
Soil temperature	640	soil temperature increases CAUSES soil humidity decreases
	699	soil temperature increases CAUSES major crops yield decreases
Soil humidity	173	soil fertility is high IF soil humidity is high
	619	soil humidity decreases CAUSES crops growth decreases
Soil solidity	132	soil fertility is low IF soil solidity is hard
	570	fire passing duration increases CAUSES soil solidity increases
Burning	240	weeding of the field method is by burning the weeds IF weed density is high
	298	burning of weed location is on the field CAUSES weed re-growing occurrence is low
	691	burning of tree location CAUSES soil temperature is high
Fallowing	247	field abandoning duration is between 2 and 3 years
	277	an increase in field cultivation duration CAUSES a decrease in soil fertility
	623	field abandoning CAUSES weed rotting location is on the field
	655	weed growing is occurring CAUSES soil renewing occurrence is high IF field abandoning is occurring and field abandoning duration is 2 years
	696	major crops yield decreases CAUSES field abandoning
Tilling	180	field abandoning is not necessary IF field is tilled
	360	field cultivating duration is more than 2 years CAUSES major crops yield doesn't decrease IF field is tilled
Weeds	60	weed growing density is low IF field type is hatsa-bao [1-2 years old field]
	100	weed growing location is on the field IF field cultivating duration is more than 2 years
	174	soil fertility is high IF good_weed location is on the field
	440	weed growing location is on the field CAUSES weed out-competing maize occurrence is high
	660	not weeding the field CAUSES maize yield decreases
	621	weed decomposing to fertiliser CAUSES soil fertility increases
Fertiliser	572	fertiliser application location is on the field CAUSES soil solidity is soft
	697	zebu manure application effort is high CAUSES farmer motivation is low IF zebu manure application location is on the field

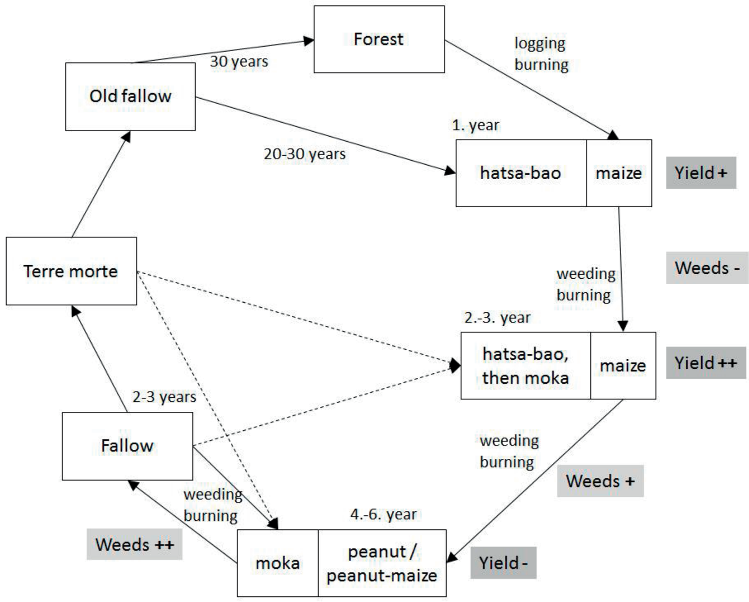

Figure 3.1 Overview of the cultivation cycle of a field. Solid arrows indicate traditional field transformations by the farmers. Dotted arrows indicate possible transformations, however uncommon. Legend: + medium amount, ++ high amount; - low amount.

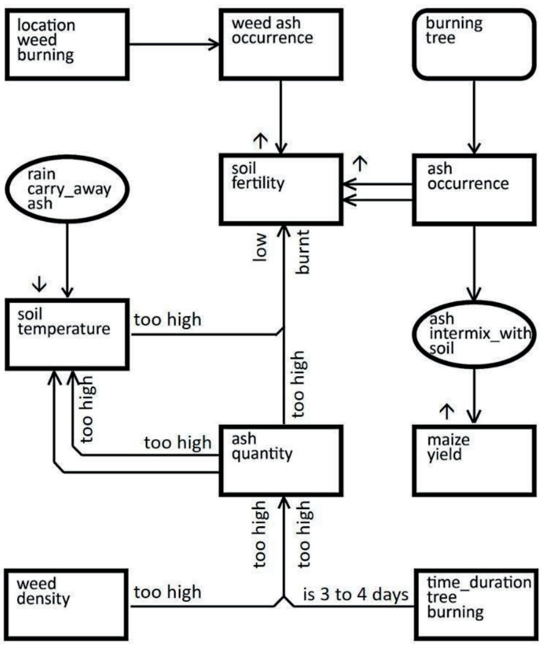

***Figure 3.2** Diagram output from the KB (adapted), showing all direct causes and effects related to the term object 'ash' in the KB. Legend: Rectangular nodes are objects and their attributes; rectangular nodes with soft edges are human induces processes, ellipses are natural processes. Arrows indicate a causal relationship between two nodes. Double arrows indicate that there are two relationships between the nodes. Upwards arrows indicate an increase, downwards arrows a decrease.*

3.3.2 The farmers' perception of soil fertility

The Malagasy word for soil fertility ('*tsiron' tany*') literally means 'taste of the soil'. We observed through the interviews that soil fertility was a difficult concept to describe for the farmers. They generally used words like 'fat' or 'new' to describe fertile land, and 'dead' for infertile soil. It remained unclear to which extent farmers are aware of soil nutrient's quantity and quality, as there was no distinct word for nutrients in their language. To assess the soil fertility, the farmers use different indicators, such as productivity and crop yield (Table 3.1). Farmers described the soil as fertile when the yield was high and crops grew well (tall plants, nice general aspect, dark green leaves). However, other indicators such as soil solidity (soft, hard), consistency (sandy, sticky, dusty), moisture (moist, dry), temperature (warm, cool), and the quantity of weeds as well as the presence of some species can be used to describe soil quality (Table 3.1).

Farmers associate fertile soil with cool soil temperature and higher moisture. Soil moisture and soil temperature are often used in a similar context and interchangeably. Fire, high sun exposition and low rainfall are mentioned by farmers as reasons for high soil temperatures and low moisture, damaging the plants and leading to poor yields (S542, S619, S691, S699, Table 3.1). Soft soil is also an attribute for fertility while farmers are concerned about hard soil. Factors related to increased soil solidity are for instance high sun exposition, presence of grass-type weed species and rain-induced soil erosion. Weeds are used by the farmers as indicator plants to assess soil fertility.

3.3.3 Farmers' current techniques to improve soil fertility

In the study area, farmers mention weeds as an important factor with regard to yield and soil fertility management. They blame weeds for harmful effects on crops because they outcompete them (S440, Table 3.1). Weeding is therefore an essential part of the agricultural work. Insufficient ability to weed can impair crops health and lower the yields (S440, S660, Table 3.1). After weeding, uprooted weeds are left on the field or turned belowground during tillage, which is done mostly by using a zebu (cattle); the natural process of rotting and decomposition of weeds is perceived to have a fertilizing effect on the soil (S621, Table 3.1). Thirteen of the 17 informants mentioned this soil fertility management technique. They referred to tillage as another way to increase soil fertility and stressed that tilling also facilitates subsequent weeding. Nevertheless, tillage is not common and, most of the time, limited to small patches around future maize plants.

Fallow allows also to recover soil fertility. According to eight of the farmers, abandoning a field results in a renewing of the soil, making it suitable for re-cultivation, largely due to the decomposition process of weeds on the field (S655, Table 3.1). Fire is not primarily used for obtaining ashes as a fertilizer. Farmers explain that fire is mainly used as a tool for weed management, although they are aware that ashes may lead to an increase in soil fertility. According to the farmers, fire can have both positive and negative effects on the soil or on its productivity (Fig. 3.2). Negative effects of ashes on soil fertility can result from thick ash layers and the related high soil temperatures that lead to lower yields (S365, S542, Table 3.1). Positive effect comes from a better weed control (S298, Table 3.1) and facilitated field work such as subsequent tilling and weeding. Farmers know different kinds of fertilizers like animal manure or chemical fertilisers. In the study area fertilizers are rarely used though. Farmers name a lack of money or transportation facilities, as well as a high handling effort and lack of time as most important constraints for fertilizer use (S697, Table 3.1).

The relative relevance of the different factors or terms are represented in the knowledge base (KB), depending on how often a term, i.e. a word in the KB was used in a statement. The term soil fertility is used in 82 statements out of 753 statements in total. Further terms are soil moisture (in 47 statements), tilling (44 statements), burning (43), soil solidity (39), soil temperature (35), fertilizer (22), and abandoning a field [=fallowing] (20). The terms ‘weed’ or ‘weeding’ were found in 146 statements.

3.4 Discussion

3.4.1 Local knowledge is key for improving management

Competing land uses are increasingly putting pressures on landscapes. To reach a sustainably managed landscape, the concurrent addressing and balancing of agricultural demands and biodiversity conservation needs is required. To achieve a social license, local land use rights and needs need to be taken in consideration (Sayer et al., 2013). The involvement of local people in the management process is vital in this respect (Dirac Ramohavelo, 2009). For example, the coffee agroforestry systems in the Western Ghats in India or the slash-and-burn system in Panama are examples for the integration of agricultural landscapes and conservation perspectives (Garcia et al., 2010; Tschakert et al., 2007). For a successful conservation and for sustaining the rural livelihood, the early inclusion of local stakeholders is seen as essential, especially when the interests of the farmers might differ or even be opposing the conservation objectives (Garcia et al., 2010). It is therefore necessary to look at farmers’ rationality and perception in order to get a better understanding of their needs and constraints in their decision-making process (Kull, 2000). This also includes the understanding of the knowledge on which farmers base their management decisions (Joshi et al., 2004).

3.4.2 Soil fertility is perceived by farmers in a number of ways

Soil fertility is fundamental for farmers as it constrains the quality of their livelihood (Joshi et al., 2004). Farmers use different strategies to maintain soil fertility, such as tillage or the incorporation of uprooted weeds into the soil. Farmers have a multisided perception of soil fertility (Corbeels et al., 2000). Indeed, a suitable crop production depends not only on chemical soil properties, but also on its physical properties. Thus, high yields are obtained not only with the right soil nutrient concentration, but also with a suitable soil moisture, temperature, and consistency and with a control of weeds (Corbeels et al., 2000). Similarly to our findings, in Ghana, farmers use crop growth as an indicator of fertile soils (Joshi et al., 2004; Moss, 2001) and denote them as "land that crops do well on" (Joshi et al., 2004). They also associate fertile soils with cool soil temperatures and soft soil, and use the terms soil moisture and soil temperature interchangeably, like the farmers in our study; they also recognize different plant species as indicators of fertile and infertile soils. They say that on fertile soil weeds are less present than on infertile soils, thus less work is required to remove them. The farmers list 'decomposing weeds', 'leaf litter' and 'fertilizers' as factors that increase soil fertility (Joshi et al., 2004; Moss, 2001). In Ethiopia, soil fertility is assessed by farmers based on yields and crop performance (e.g. if the crops are wilting) (Corbeels et al., 2000). These farmers perceive soil's water-holding capacity as a characteristic of fertile soil, since rainfall is a limiting factor. They also refer to soil depth—with deep soil being more fertile than shallow soil—and to soil topography, color, texture and stone content. The farmers identify problems with soil nutrient status by the presence of certain weed species (Corbeels et al., 2000). These congruency between different studies in different regions of the world also support the argument of Joshi et al. (2004) that although local knowledge is local in the sense that it has been collected in a small and restricted area with terms being specific for this particular area, the underlying natural processes and the way farmers explain these processes show regularities across agro-ecosystem and cultural boundaries.

3.4.3 Weed management outweighs fertility issues

Previous research in the study area with a focus on secondary forest dynamics and soil properties have shown that soil degradation can be considerable under cultivation (Raharimalala et al., 2010). This suggests that soil fertility depletion might be the main trigger which forces farmers to leave their fields. Soil fertility depletion may thus drive deforestation. Our findings show that soil fertility is a relevant aspect in farmer's decision-making. Farmers are aware of soil fertility, and they use diverse cultivation techniques that contribute to maintain yields and longer cultivation periods—such as fallowing and the use of natural fertilizers. They also recognize the negative impact of burning the forest. In spite of this knowledge, many farmers prefer to slash-and-burn forests to obtain new fields; they rarely use fertilizers to increase soil fertility on old fields. This appears to be an incongruence between knowledge and practice. Yet, from a farmer's perspective, our study suggests that the main factor—i.e. the ones forcing farmers to abandon their fields—is weed management rather than soil fertility. Farmers argue that weeds (i) are outcompeting the crops, (ii) can be difficult to remove and thus hard labour is required, and (iii) can make the soil harder; also, (iv) burning facilitates subsequent weeding; (v) the presence of weeds make tilling more difficult; (vi) there are only few or even no weeds on freshly cleared fields compared to older fields, and that (vii) cultivating more than three years on the same fields comes at the cost of having more 'bad weeds' and thus necessitates heavy weeding labour. These arguments point out that cultivation on a freshly cleared field is more attractive for farmers. The relative importance of weeds is also reflected in our knowledge base. With 146 statements, the terms ‘weed’ or ‘weeding’ are clearly more represented than other key words.

Milleville et al. (2001) and Styger et al. (2007) have identified weeds as a central aspect in the context of field abandonment in other parts of Madagascar, and Moody (1975) has described weed management as the major limiting factor to extend the cultivation period on the same fields in the tropics. A recent example from shifting cultivation in the Amazon supports the finding that weed management is critical in the decision making process (Junqueira et al., 2016). Based on local knowledge, Junqueira et al. (2016) explained how Amazonian farmers balance labour requirement and other factors when deciding over field abandonment and opening of new fields. Their study also showed how the farmers take their decisions based on a combination of socioeconomic and biophysical factors. Quantitative measurements in previous studies in the Kirindy forest showed the nutrient depletion of the soil, suggesting that there is a lack of natural capital (Gay-des-Combes et al., 2017; Raharimalala et al., 2010), which might prevent farmers from longer cultivation on the same field. Insights also indicate that farmers perceive constraints in human capital (labor requirement for weeding, time), financial capital (money for fertilizers, or for zebu) and physical capital (transportation, zebu). In their decision-making farmers weight these constraints against the lack of natural capital. Thus, the implementing of alternative management strategies will likely not be successful if they do not address what local actors perceive to be the key limiting factors.

3.5 Conclusion

Our findings confirm with a social perspective what previous ecological research described as drivers to field abandonment: the decline in soil fertility and the weed invasion. But it also shows that weeds have to be considered as a priority if we want to change the practices and find feasible alternatives for the long term cultivation. Indeed, weed invasion leads quickly to high demands on labour and subsequently to a work overload and field abandonment. Farmers’ worries concerning soil fertility seems less important. Consequently, a selective slash-and-burn technique as proposed by Carrière (2002) or a longer fallow time (Thomaz et al., 2014) will not be sufficient measures for reducing the surface of new burnt areas if the problem of weed invasion is not solved beforehand. We suggest to explore possibilities for mulching and soil coverage since these techniques can potentially both increase soil fertility and help keeping weeds under control.

By conducting a LEK elicitation process, the study paved the way for a more inclusive and meaningful dialogue between farmers and scientists in the future. Listening to farmers to understand their decision-making processes is crucial. There is no technical fix that could overcome barriers to implementation as long as we ignore the local knowledge. The combination of scientific and local knowledge has the potential of achieving the social license towards the adoption of more sustainable alternative slash-burn cultivations. Therefore, future research in natural resource management should possibly integrate needs, constraints and aspirations of the main stakeholders; eliciting local ecological knowledge can be a good entry point.

- CHAPTER 4 -

Tropical soils degraded by slash-and-burn cultivation can be recultivated when amended with ashes and compost

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In press in Ecology & Evolution

Picture: Maize field experiment in Kirindy forest
Justine Gay-des-Combes, 2013

Abstract

In many tropical regions, slash-and-burn agriculture is considered as a driver of deforestation; the forest is converted into agricultural land by cutting and burning the trees. However, the fields are abandoned after few years because of yield decrease and weed invasion. Consequently, new surfaces are regularly cleared from the primary forest. We propose a reclamation strategy for abandoned fields allowing and sustaining re-cultivation. In the dry region of south-western Madagascar, we tested, according to a split-plot design, an alternative selective slash-and-burn cultivation technique coupled with compost amendment on 30 years old abandoned fields. Corn plants (*Zea mays* L.) were grown on four different types of soil amendments: no amendment (control), compost, ashes (as in traditional slash-and-burn cultivation) and compost + ashes additions. Furthermore, two tree cover treatments were applied: 0% tree cover (as in traditional slash-and-burn cultivation) and 50% tree cover (selective slash-and-burn). Both corn growth and soil fertility parameters were monitored during the growing season 2015 up to final harvest. The amendment compost + ashes strongly increased corn yield, which was multiplied by 4 to 5 in comparison to ashes or compost alone, reaching 1.5 t ha^{-1} compared to 0.25 and 0.35 t ha^{-1} for ashes and compost, respectively. On control plots, yield was negligible as expected on these degraded soils. Structural equation modeling evidenced that compost and ashes were complementary fertilizing pathways promoting soil fertility through positive effects on soil moisture, pH, organic matter and microbial activity. Concerning the tree cover treatment, yield was reduced on shaded plots (50% tree cover) compared to sunny plots (0% tree cover) for all soil amendments, except ashes. To conclude, our results provide empirical evidence on the potential of recultivating tropical degraded soils with compost and ashes. This would help mitigating deforestation of the primary forest by increasing lifespan of agricultural lands.

Keywords
Crop yield, deforestation, microbial activity, organic matter, soil fertility, structural equation model

4.1 Introduction

Tropical forests support a large and unique biodiversity, but are threatened worldwide by rapid deforestation due to their conversion into agricultural lands. Deforestation rates are particularly alarming in Madagascar, a country which is pointed out as one of the eight leading global biodiversity hotspots in terms of endemic species (Myers et al., 2000). On the south-western coast of the island, in Menabe region, deforestation annual rate of the dry deciduous forest has been estimated at 2.6% between 2008 and 2010, i.e. a loss of 1’820 ha per year (Zinner et al., 2014). At that rate, the forest and most, if not all, its endemic species, will have entirely disappeared by 2050 (Zinner et al., 2014).

In Madagascar, slash-and-burn agriculture is the main driver of deforestation (Dirac Ramohavelo, 2009; Genini, 1996). In this traditional, widespread technique, forest is converted to agricultural land by cutting and subsequently burning trees, the ashes being used to amend the soil. After few years (between 2 to 4 years, depending on the regions) of repetitive cultivation, crop yield decreases whilst weeds invade the agricultural fields. Farmers then generally abandon their fields and convert new surfaces of primary forest into agricultural fields. As a consequence, the primary forest area decreases progressively, while degraded land increases. In Madagascar, extreme measures like anti-fire policies were applied for over one-hundred years without much success in putting halt to deforestation (Jarosz, 1993; Kull, 2002). Farmers still practice shifting cultivation, even against the law, because it is most convenient to them (Kull, 2002), but also because this method is embedded within a strong spiritual and social background (Desbureaux and Brimont, 2015; Hume, 2006; Jarosz, 1993; Scales, 2012).

Slash-and-burn agriculture modifies the physico-chemical properties of the soil (Are et al., 2009; Béliveau et al., 2015; Demeyer et al., 2001; Thomaz et al., 2014). Ashes are strongly alkaline, which reduces soil acidity, boosts microbial activity and increases soil nutrient availability (Ohno and Erich, 1990). This is particularly useful in tropical acid soils, as it favours plant growth. The effects on the soil nutrients are, however, short-term for some highly soluble elements subject to leaching, like for example potassium (K), calcium (Ca) or magnesium (Mg) (Demeyer et al., 2001; Ulery et al., 1993). Additionally, ashes push the stoichiometry of soil nutrients towards nitrogen (N) limitation, as after combustion, the nitrogen contained in tree-leaves is volatilized (Ohno and Erich, 1990). Hence, ashes fertilization is not appropriate for long term cultivation, occasioning soil nutrient exhaustion after repetitive cultivation during few years (Folberth et al., 2013). Also, by cutting and burning the trees, field surface remains bare, with no protection against strong winds and rains. Tropical heavy rains can lead to soil saturation and the formation of free water on the surface, which further causes soil erosion even on slightly sloping terrains. Such soil erosions are problematic for maize cultivations as a single cyclonic storm can reduce corn yields by more than 75% (Gay-des-Combes et al., 2017).

Regeneration of the forest on most tropical degraded soils requires a minimal of 10 years of fallow period (Thomaz et al., 2014). However, in western Madagascar, it happens that the soil never recovers from such degradation, leading to large abandoned areas where the ecosystem shifts from forests to savannahs (Raharimalala et al., 2010). Clearly, re-cultivating the abandoned surfaces is urgent and would safeguard agricultural land, while simultaneously reducing the pressure on the primary forest. However, to be successful, the re-cultivation needs alternative techniques that both slow down, or even stop, soil degradation and leave intact the socially and cultural embedded practice of slash-and-burn techniques. Indeed, maintaining the use of fire when developing alternative techniques might be non-negotiable to convince farmers to change their agricultural practices. In this context, the use of biochar, as an alternative to the ashes, could be a promising solution in terms of soil amendment with burnt wood. Biochar contains 'black carbon' which are residues of incomplete combustion of organic material. Its structure, composed of aromatic cycles, is chemically and microbiologically stable, leading, when amended to soils, to the formation of persistent organic matter over years (Glaser et al., 2001). Thus, biochar amendment boosts the overall quality of soil by improving its nutrient status, its water holding capacity and its microbial activity (Hass et al., 2012; Laird et al., 2010; Mitchell et al., 2015). However, biochar is hardly reproducible on a frequent-basis as its efficiency strongly depends from its final polyaromatic structure determined by the type of material used and its combustion temperature (Butnan et al., 2015; Reed et al., 2017). Furthermore, farmers in developing countries are not always willing to accept, let alone being able to pay, the costs for the application of biochar (Cernansky, 2015).

Although ashes and biochar are closely related material and could have similar effects on the soil fertility (Reed et al., 2017), the main problem of traditional wood ashes compared to biochar is the absence of solid structure stabilizing nutrients in the soil. Here, we suggest that an addition of organic matter, such as compost, to wood ashes could play this role (Bougnom et al., 2010). Compost enhances both water- and nutrient holding capacity of the soil (Zhang et al., 2016). Therefore, combining compost and ashes may play a significant role for tropical soil security by mitigating nutrients leaching (Agegnehu et al., 2016). Besides, compost is also known to increase plant yield through the addition of nutrients (Abdel-Sabour and El-Seoud, 1996; Mbau et al., 2014; Zhang et al., 2016). Additionally, letting some trees within the fields could also rise the soil organic matter content through littering (Nair, 2013). Furthermore, trees prevent soil erosion and contribute to maintaining soil microbial community (Carrière et al., 2002b). Thus, we tested a selective slash-and-burn agriculture (where some trees are intentionally not cut), coupled with compost amendment. We believe that this system could lead to significant improvements of soil fertility and crop yields yields, while respecting traditional slash-and-burn method. We specifically aimed at answering two questions addressing the effects of the aforementioned technique. First, do a partial remaining tree cover and compost amendment increase corn yield, as compared to traditional slash-and-burn agriculture? Second, what are the respective contributions of tree cover, ashes and compost to soil organic matter, its nutrient status and microbial activity?

We hypothesized that compost amendment and tree cover will increase organic matter, microbial biomass, as well as N and P contents of the soil. Ash, on the other hand, should rise soil pH, which in turn promotes the mineralization of organic matter. Because of soil fertility improvement, we also predicted that corn amended with both ashes and compost will show the highest yield.

4.2 Materials and methods

4.2.1 Study site

Field sampling was conducted in the dry deciduous forest of Kirindy (central Menabe) near the village of Beroboka (20° 00’22.3’’S, 44° 35’06.1’’E). The nearest large city is Morondava, located 30 km south. Beroboka was selected because it is strongly affected by deforestation due to slash-and-burn cultivation (Dirac Ramohavelo, 2009) and it offers a large area (about 1000 ha) of abandoned fields, thus allowing experimentations on degraded soils. The climate is tropical, but with a long dry season from April to September. Mean annual rainfall is about 800 mm, but varies from 250 to 1400 mm depending on the year and cyclonic events (Sorg and Rohner, 1996). Temperatures are high year-round and average at 24.7°C (Sorg and Rohner, 1996).

4.2.2 Plot selection and experimental design

Three sites, 300 m distant from each other, were selected on 30-years-old abandoned fields with comparable vegetation structure, mainly small shrubs and a few tall trees. The soils at the three sites were ferruginous soils, corresponding to the Lixisols after the World Reference Base for Soil Resources (Raharimalala et al., 2010). The soils had similar nutrient concentrations (Table 4.1), were yellowish red (5YR 5/8, Munsell color code) and composed of about 15% clay, 10% silt and 75% of sand. On half of the surface in each site all vegetation was removed (0% tree cover; treatment ‘sunny’), and on the other half shrubs and some trees were removed (50% tree cover, treatment ‘shaded’). Within each tree cover treatment, four 3 × 3 m plots were allocated randomly to one of the following treatments: control (Ctr), ashes (Ash), compost (Comp) and ashes mixed with compost (CoAs). This led to a split-plot design with 8 plots in each experimental site (4 per tree cover treatment), 24 in total. The treatments containing ashes (Ash, CoAs) were prepared with the help of local farmers, in order to follow closely the traditional slash-and-burn practices, in particular the quantities per surface unit. They resulted from gathering and burning the wood from the cut trees at each desired plot location, and subsequent application of a 1.5 cm ash layer on the soil.

At the start of the rainy season, on 27th December 2014, three corn seeds were buried 10 cm deep at 10 different spots within each plot. We used the main local corn variety called "*vonivony*", with a growth cycle of 110 days. At a later stage, a thinning took place and only one plant was left in each plantation hole, leaving 10 plants per plot, i.e. 1.1 plant m-2, comparable to usual field density in the region. In the compost treatments (Comp and CoAs), 1 L of compost was added in each plantation hole when burying the seeds. The compost was produced and matured during the 8 months prior to the experiment with an equal volume of branches and leaves coming from three local trees (*Poupartia sylvatica, Tarenna sericea* and *Fernandoa madagascariensis*). Only small branches were collected in order to leave the trees undamaged. Besides, these tree species were chosen because they have a high content of nutrients and are very abundant in secondary forest successions, preventing further degradations of the primary forest (Raharimalala, 2011; Raharimalala et al., 2012).

4.2.3 Soil and corn sampling

Soil moisture was measured at 10 cm in each plot halfway the growing season (i.e. 15th March 2015), using a TDR probe (FieldScout 100). On 29th March, at the end of the growing season and before plant senescence started, plant final heights were measured. On 27th April, once plants started to dry, shoot and bulk grains were collected. Shoot and grains were sun dried during 3 days, until constant weight, and measured. As the plant density in the experimental plots was similar to the density found in surrounding corn fields (Gay-des-Combes et al., 2017), dry weight of bulk grains per plot was converted to grain yield per ha. Finally, in the same time than corn harvest, on 27th April, three soil samples (c. 100g) were collected, within each plot (0-10 cm depth), pooled together to reduce heterogeneity, sun dried during 3 days, until constant weight, and finally sieved at 2 mm.

4.2.4 Laboratory analyses

Plant nutrient content and uptake

Nitrogen (N), phosphorus (P) and potassium (K) content of the corn leaves and grains were assessed by digesting the plant samples as described by Wolf (1982). Potassium (K) was determined by atomic absorption spectrophotometry (Solaar 969, ThermoOptek). Total nitrogen (N) and phosphorus (P) concentrations were determined by, respectively, the blue-indophenol method and the molybdovanadate method using a continuous flow autoanalyser (FlowSys, Systea). Plant uptake in aerial parts was calculated as the sum of the product of leaf and grain nutrient content and respective leaf and grain dry weight.

Soil, ashes and compost parameters

All measures were performed on the initial soil of the experimental sites before the experiment started, the ashes and compost (at maturation) used in the experiment, and soil samples collected after the experiment. Total C and N were measured on milled soil with a standard CHN analyser (Dumas method). The pH was assessed in a 1:2.5 soil:water suspension (v:v) (Allen, 1989). Cation exchange capacity (CEC), exchangeable K and inorganic nitrogen (NO_3 and NH_4) were measured by extraction: CEC and K with Cobalt-hexamine solution ($Co(NH_3)Cl_3$ 0.0166 M) and inorganic nitrogen with KCl (1 M). Later, inorganic nitrogen forms were analysed colorimetrically using a continuous flow analyser. CEC and exchangeable K concentrations were read on a plasma atomic emission spectrometer (Shimadzu ICPE-9000). Soil phosphorus availability was assessed on anion-exchange resins (Hedley et al., 1982) and the concentrations were measured colorimetrically using the malachite green method and placing the samples in a Shimadzu 1800 UV-Vis spectrophotometer (Ohno and Zibilske, 1991). Finally, organic matter was measured through loss of ignition at 450°C.

Microbial biomass and soil enzyme activity

Microbial C biomass was measured with a chloroform fumigation followed by 0.5 M K_2SO_4 extraction (Vance et al., 1987). As a proxy for soil activity, we measured the activity of four enzymes involved in C, N and P cycling (Sinsabaugh et al., 2008). We quantified the relative activity (i.e. enzyme activity under optimal and saturating substrate conditions) of extracellular enzymes responsible for the hydrolysis of one peptide (Leucine amino-peptidase, LAP, N cycle), two carbohydrates (β-glucosidase, BG; Chitinase, CHI, C and N cycle, respectively), and one phosphatase (alkaline phosphatase, AP, P cycle; all substrates supplied Sigma-Aldrich Switzerland). Enzymes were determined on 1 g (wet weight) aliquots of soil and analysed in microplates following (Jassey et al., 2016).

4.2.5 Statistical analyses

The effects of ashes, compost and tree cover on soil parameters and plant morphological traits were analysed using Split-Plot analysis of Variance (ANOVA). The effect of the different treatments was tested while the site effect was corrected by adding ‘site’ as a random variable (block). Tukeys post hoc analyses were used to determine the differences among amendment treatments. When required, values were log-transformed before the analyses to satisfy the assumption of normality and homogeneity of variance. These analyses were performed in R (R Development Core Team, 2013).

The analyses described above assess well the responses of soil descriptors and plant traits to amendment treatments. However, the underlying drivers of corn yield need to be determined. To investigate whether the tree cover, compost and ashes directly drive the soil fertility and consequently corn yield, we established a structural equation model (Grace et al., 2012, 2010). Following current concepts of microbial processes and soil fertility, we built an a priori conceptual model of hypothesized causal relationships within a path diagram (Table S4.2; Grace et al., 2014). Microbial stock and activity were represented by carbon microbial biomass as it was strongly correlated to acid phosphatase ($r = 0.63$, $P = 0.0012$), beta-glucosidase ($r = 0.88$, $P < 0.001$), as well as chitinase activity ($r = 0.86$, $P < 0.001$). To increase model stability, the variables 'ash' and 'tree cover' were removed from the model, as ash and pH were strongly correlated (r = 0.77, $P < 0.001$), and tree cover and humidity too (r = 0.55, $P = 0.005$). The adequacy of the model was assessed using chi-square tests, root mean square error of approximation index (RMSEA), Akaike value (AIC), standardized root mean square residual index (SRMR), and good fitness index (GFI). Adequate model fits showed non-significant differences when comparing the predicted and observed correlation matrices (chi-square tests with $P > 0.05$), and are indicated by RMSEA < 0.05, by lower AIC, SRMR < 0.05 and GFI > 0.95 (Grace et al., 2010). The structural equation model was achieved with the R package sem (Fox, 2006).

4.3 Results

The soils of the experimental sites were moderately acid (pH = 5.8) and had a limited content of organic matter and a low CEC (O.M. = 57.2 g kg^{-1}, CEC = 5.1 cmol kg^{-1}, Table 4.1). The ashes and the compost used as soil amendments in the experiment contained about 5 and 20 times more nutrients than the control soil, respectively (Table 4.1). Ashes were basic (pH = 8.6), while compost was close to neutral (pH = 7.5, Table 4.1). Although, ashes are generally mostly mineral, they still contained 37% of organic matter (Table 4.1).

Table 4.1 Mean values with standard deviations for some chemical parameters of the soil found in the experimental fields and for the ashes and compost used in the experiment.

Material	Density [kg dry wt/L]	pH	CEC [cmol/kg]	O.M. [g/kg]	Ctot [g/kg]	Ntot [g/kg]	Ninorg [mg/kg]	Ptot [mg/kg]	P resin [mg/kg]	K ex [mg/kg]
Control soil	1.4 ± 0.1	5.8 ± 0.2	5.1 ± 0.8	57.2 ± 4.2	10.7 ± 2.9	0.95 ± 0.03	2.1 ± 1.0	71.9 ± 5.1	2.3 ± 0.5	64.2 ± 3.3
Compost	0.6 ± 0.1	7.5 ± 0.1	36.8 ± 0.5	685.8 ± 35.4	253.9 ± 20.5	18.2 ± 1.2	189.0 ± 12.3	1553.9 ± 106.1	162.9 ± 12.0	4331.2 ± 153.8
Ashes	1.1 ± 0.2	8.6 ± 0.2	15.2 ± 1.1	371.7 ± 25.2	123.6 ± 5.7	7.4 ± 0.4	29.0 ± 3.1	640.0 ± 23.2	11.9 ± 1.3	2630.0 ± 65.1

4.3.1 Corn growth, yield and nutrient allocation

While plant height and yield were similar between compost and ash amendments (Ash, Comp) for both sunny and shaded conditions, yield was multiplied in the compost and ash mixture (CoAs) under sunny conditions, i.e. the dry bulk grain weight, by six (from 0.25 to 1.5 t/ha) and increased plant height by 60 % (from 150 to 240 cm) compared to traditional slash and burn method (Ash) (Fig.4.1). 'CoAs' treatment also led to a three-fold increase in grain yield, as compared to 'Comp' treatment (from 0.5 t ha^{-1} to 1.5 t ha^{-1}), whilst plant height increased by 26% (from 190 to 240 cm). Lower plant heights and corn yields were found on the shaded part of the experiment, except with 'Ash' treatment. In the latter case, plant height increased by 20% (from 155 to 185 cm) and corn yield almost doubled (from 0.25 t ha^{-1} to 0.4 t ha^{-1}; Fig.4.1).

Tree cover did not affect plant height, nor yield by itself. Yet, the interaction between tree cover and soil amendment was significant (plant height, P = 0.0367; corn yield, P = 0.051, Table S4.1). On control plots (Ctr), corn yield was close to zero for both sunny and shaded conditions (Fig.4.1). We observed similar trends for the nutrient uptakes. The plant uptake was the largest on sunny 'CoAs' plots, where levels raised up to 55 kg N ha^{-1}, 6 kg P ha^{-1} and 33 kg K ha^{-1} (Table 4.2, Table S4.1). 'Comp' and 'CoAs' treatments showed higher plant uptake on the sunny plots, while for 'Ash' plant uptake was doubled on the shaded plots (Table 4.2). For 'Ctr' plots, the uptake was also slightly higher in the shaded plots.

Table 4.2 *Mean values with standard deviations for plant uptake in shaded and sunny plots*

	Shaded plots			Sunny plots		
Treatment	N uptake [kg/ha]	P uptake [kg/ha]	K uptake [kg/ha]	N uptake [kg/ha]	P uptake [kg/ha]	K uptake [kg/ha]
Compost	5.77 ± 0.74	0.63 ± 0.05	4.15 ± 0.19	18.13 ± 3.00	2.01 ± 0.17	11.69 ± 0.43
CoAs	25.93 ± 2.69	3.07 ± 0.65	16.20 ± 1.18	55.62 ± 4.94	6.40 ± 0.42	33.08 ± 3.55
Ash	17.49 ± 1.00	2.05 ± 0.24	12.34 ± 0.97	9.40 ± 1.05	1.02 ± 0.13	6.24 ± 0.45
Control	8.30 ± 0.77	0.58 ± 0.15	6.57 ± 1.18	6.12 ± 2.11	0.47 ± 0.25	4.93 ± 0.72

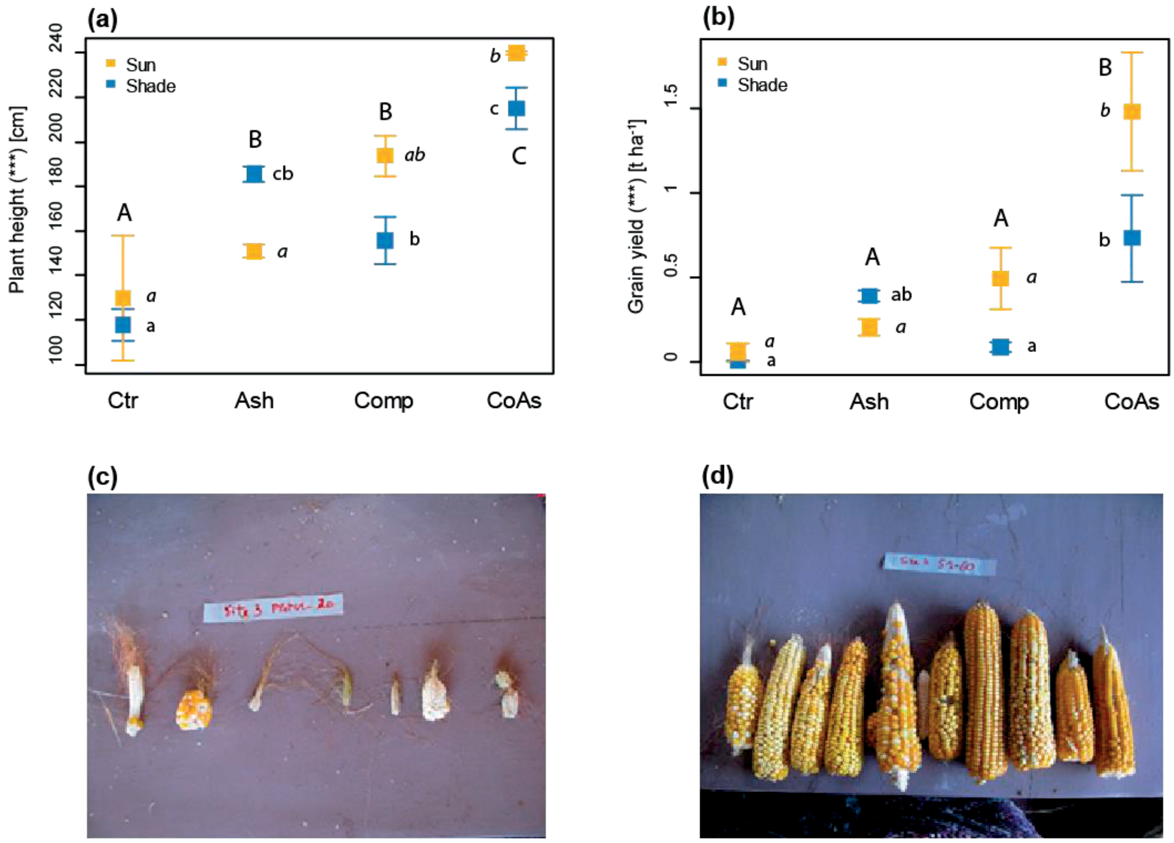


Figure 4.1 *Mean (± standard errors) plant height (a) and grain yield (b) at harvest for each soil amendment treatment on both sunny and shaded plots of the experiment. Asterisks indicate significance in the variable variation according to the treatments (P < 0.001 = ***; P < 0.01 = **; P < 0.05 = *; P < 0.1= ·). Different letters denote significant differences between soil amendment treatments (Tukey tests, P ≤ 0.05). Capital letters stand for the overall treatment; normal lower case letters for the shaded plots and italic lower case letters for the sunny plots. c) Harvested corn cobs on a sunny 'Ctr' plot. d) Harvested corn cobs on a sunny 'CoAs' plot.*

4.3.2 Soil physico-chemical fertility and microbial activity

After corn harvest, the different soil amendments did not display significant differences in soil nutrient concentrations, except for K concentration which was higher in 'Comp' and 'CoAs' plots (Fig. S4.1, Table S4.1). The amendment of soil with ash and compost changed its acidity from moderately acid in the 'Ctr' plots to slightly acid in 'Comp' plots to neutral in 'Ash' and 'CoAs' plots (Fig. 4.2). No difference in soil pH was found between the shaded and sunny plots (Table S4.1). Soil moisture, microbial biomass and organic matter were significantly higher in shaded plots than in sunny plots ($P \leq 0.05$, Table S4.1). 'Comp' and 'CoAs' treatments resulted generally in a significantly higher soil moisture, carbon microbial biomass and organic matter, compared to 'Ash' and 'Ctr' treatments. 'Comp' treatment increased soil moisture by 15 to 35% and organic matter by 50%, as well as multiplied microbial biomass by 4 to 5 times compared to 'Ash' and 'Ctr' plots. 'CoAs' treatment exhibited slightly lower soil variables than 'Comp' treatment, however the difference between the two treatments was not statistically significant.

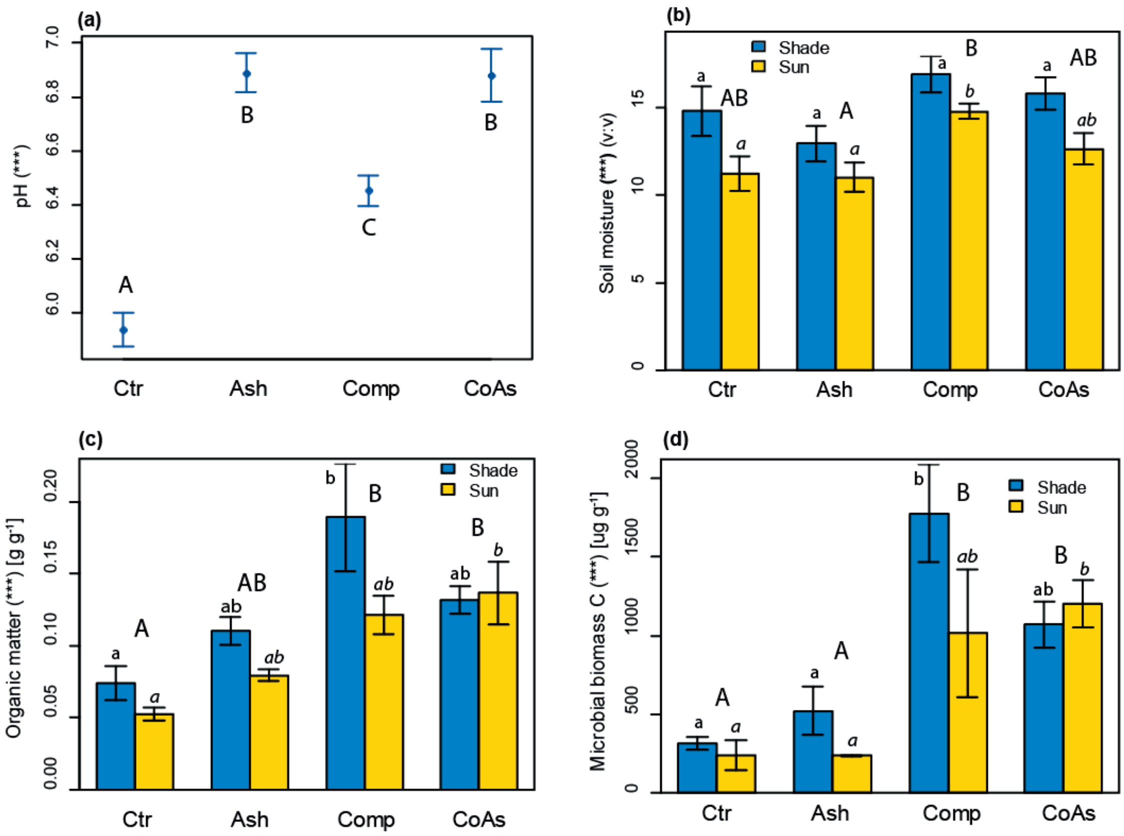


Figure 4.2 *Mean (± standard errors) soil pH (a), moisture (b), organic matter (c) and microbial biomass (d) according to the different treatments. For abbreviations, asterisks & letters, cf. fig. 4.1. Results for shaded and sunny plots are confounded for (a) because the effect was not significant.*

The enzymatic activities indicate a generally higher microbial activity in 'Ash' and 'Ctr' plots. Enzymatic activities significantly differed according to the soil amendment treatments (Fig.4.3, Table S4.1), except for CHI ($P > 0.05$). AP ($P \leq 0.001$) and LAP ($P = 0.015$) activities were generally higher in the 'Ctr' and 'Ash' plots while BG showed only a significantly higher value for the 'Ctr' plots compared to other soil amendments ($P = 0.012$). Moreover, AP and LAP were correlated to P uptake ($r = 0.44$, $P = 0.03$) and N uptake ($r = 0.52$, $P = 0.012$), respectively.

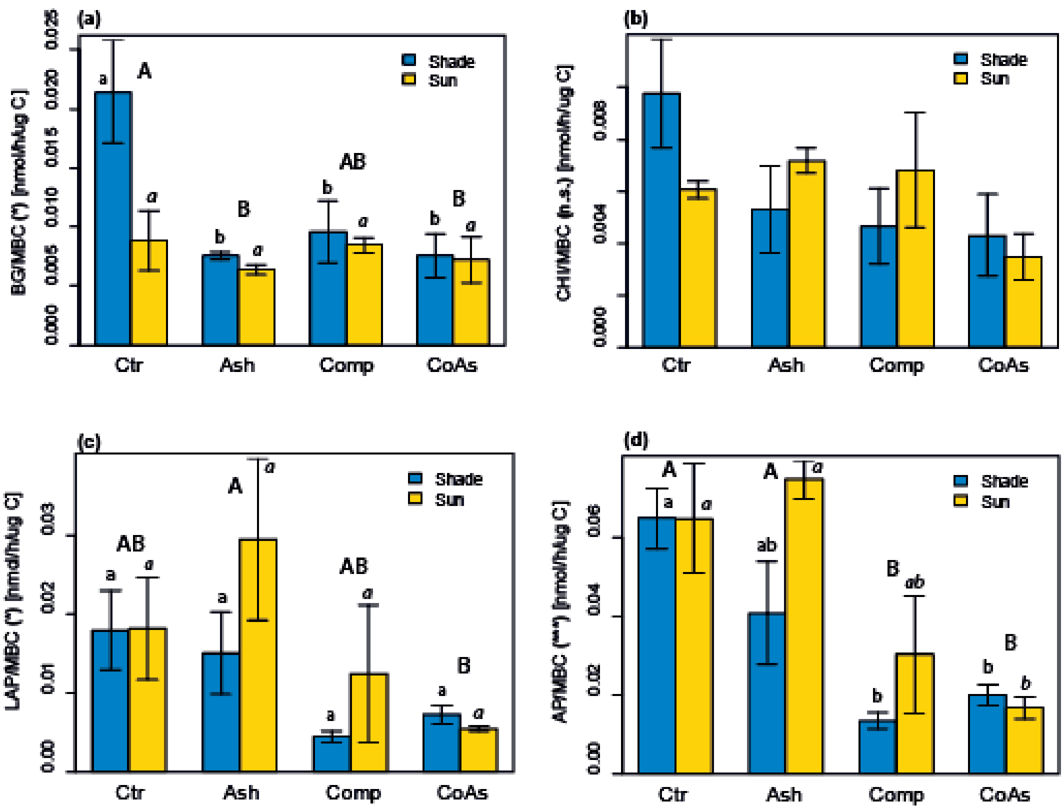


Figure 4.3 *Mean (± standard errors) enzymatic activities normalized by carbon microbial biomass (MBC) according to the different soil treatments, a) beta-glucosidase (BG), b) chitinase (CHI), c) leucine aminopeptidase (LAP), d) acid phosphatase (AP). For abbreviations, asterisks & letters, cf. Fig. 4.1.*

4.3.3 Underlying relationships between crop yield and soil fertility drivers

Independently of tree cover, structural equation modeling showed that two distinct pathways explained corn yield (r2 = 0.61; Fig. f.4). The first pathway was driven by compost amendment that directly increased both soil moisture (path = 0.57) and carbon microbial biomass (path = 0.61). Increasing soil moisture also promoted carbon microbial biomass (path = 0.30) but in a lesser extent that the direct effect of compost (Fig. f.4). Carbon microbial biomass positively and strongly increased soil organic matter (path = 0.69), which in turn promoted corn yield (path = 0.40). The second pathway highlighted the direct effect of increasing pH due to ash amendment on corn yield (path = 0.58). In sum, our model showed that high organic matter content and a rise of pH from moderately acid to neutral were the main drivers of corn yield.

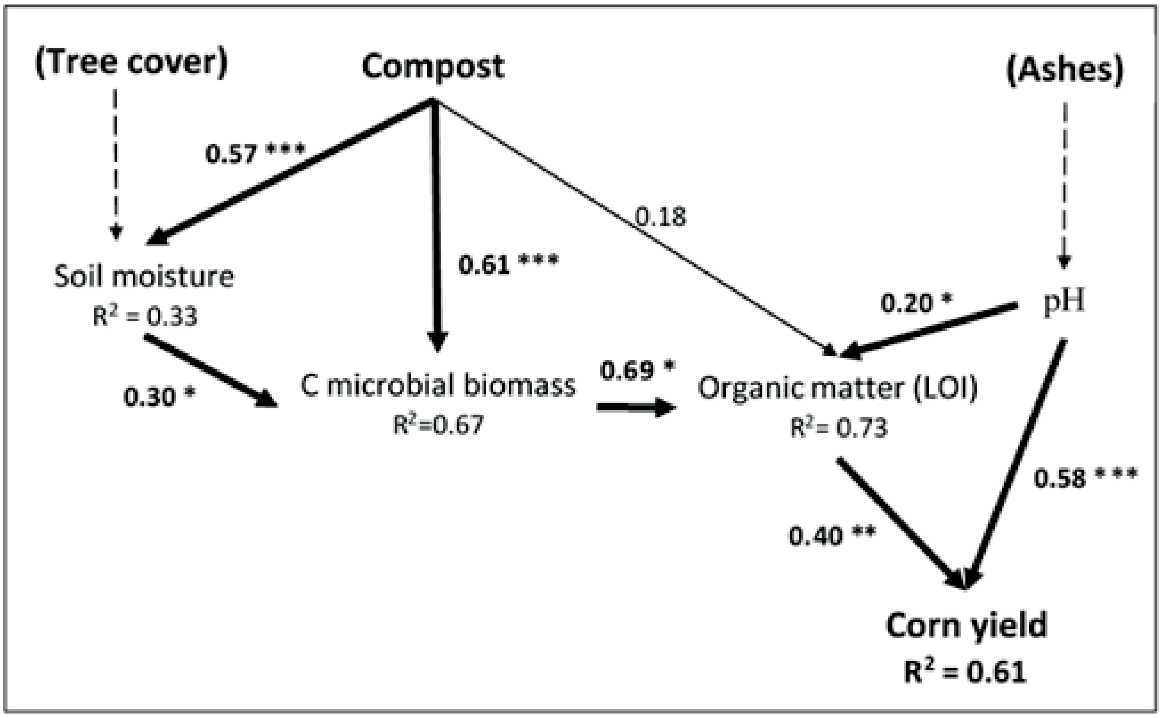


Figure 4.4 *Structural equation model for the effect of compost and ash on corn yield. Bold arrows show significant relationships (pathways) between variables (for asterisks, cf. Fig. f.1), the thin arrow indicates a non-significant relationship, and numbers next to arrows show standardized parameter estimates (i.e. standardized regression weights). Dotted arrows indicate existing relationships which have not been integrated in the model for stability reason. Squared multiple correlations (R2) for the predicted/dependent factor are given below the dependent variables. All model fit indices were good: chi-square = 7.65, P = 0.36, GFI= 0.91, RMSEA= 0.06, SRMR= 0.07 and AIC = 35.6.*

4.4 Discussion

Our findings show that a combined soil amendment of ashes and compost multiplies corn yield by four to five compared to compost or ash alone, respectively. Our analysis based on structural equation modeling allowed interpreting the complex interactions between compost and ashes on soil fertility processes driving corn yield. Although ultimate causality could not be established with this method, it, however, highlights that each amendment enhances distinct, but complementary, properties of soil fertility, resulting in a multiplicative effect on corn yield

4.4.1 The ashes' pathway

Ash amendment is known for its alkalinity properties which rise the soil pH (Demeyer et al., 2001). In our study, ash pH was moderately basic, being of 8.6, while in other conditions it could attain values up to 13.5 (Etiégni and Campbell, 1991). Wood, at the center of the pile, burns at higher temperatures and longer than wood on the edges, which influences the alkalinity of the ashes; higher temperatures produce more alkaline materials (Demeyer et al., 2001). Then, the modification of soil pH following ash amendment changes soil nutrient availability, in particular phosphorus. In tropical acid soils, P availability is mostly controlled by the strong adsorption capacity of iron and aluminum minerals, which tend to occlude phosphorus (Frossard et al., 1995). An increase in pH favors the release of those occluded phosphorus forms into the soil solution and increase phosphorus availability (DeBano and Klopatek, 1988).

We found that the ratio enzyme activity to microbial biomass increased in ash-alone amendment and controls, especially for LAP and AP. Enzyme activities are indicators of differences in soil conditions and response to modification of nutrient supply (Wallenstein et al., 2009; Weedon et al., 2012). LAP is linked with N soil supplies, while AP is linked with P soil supplies (Sinsabaugh et al., 2008). Microorganisms require an appropriate nutrient supply to uphold essential physiological processes for their survival, like the synthesis of proteins or nucleic acids. When one or several nutrients become limiting, microorganisms focus their activity towards the acquirement of these nutrients for their survival, rather than their multiplication (Liao and Xie, 2007). Hence, in our system, enzymatic activities suggest that in 'Ctr' and 'Ash' treatments, the soil is particularly depleted into available N and P for microbes and plants as compared to the treatments 'Comp' and 'CoAs'.

4.4.2 The compost pathway

Compost enhanced soil moisture, organic matter, microbial biomass and also N and P leave content in 'Comp' and 'CoAs' treatments compared to the 'Ctr' and 'Ash' treatments. By selecting three local tree species with a very high nutrient content (Raharimalala, 2011), we produced an efficient compost. This suggests that the effects of compost on soil properties could be reduced with the use of other composting material, as reported by Lima et al. (2004)

who showed that compost made with thoroughly selected vegetal waste increased by 80% the biomass of corn plants compared to a non-selected compost.

Using compost in agriculture usually helps in preserving long term soil fertility with the improvement of soil microbial biomass and activity, as well as, providing slow-released nutrients in accordance with crop requirements (Mbau et al., 2014; Zhang et al., 2016). However, despite the observed enhancements of soil fertility through compost, crop yields remained similar between ‘Ash’ and ‘Comp’ treatments. Only ‘CoAs’ treatment led to significantly greater corn yields with 1.5 t ha^{-1} instead of instead of 0.25 t ha^{-1} for ashes and 0.35 t ha^{-1} for compost. These findings show that, on acid soils, compost amended with ashes improves significantly both soil fertility and plant growth. This synergic effect is probably due to the pH elevation effect of ashes on both organic matter content amended by compost and corn yield, as supported by the SEM. Indeed, Kuba et al. (2008) and Bougnom et al. (2010) found similar results in other systems and demonstrated that compost amended with industrial ashes on acid and nutrient-deficient soils resulted in better plant cover and soil microbiological properties, due to the positive effect of ashes on pH (Gabhane et al., 2012). Consequently, our results suggest that a continuous application of compost in combination with ashes could be a suitable method for the reclamation of most abandoned fields in Madagascar.

4.4.3 Trees double-game

Trees play simultaneously a role of soil protector and light competitor. The first role benefits corn plants, while the second prevents their growth. This double effect is revealed in our study, by the contrasting results found between ‘Ash’ treatment and the other treatments. Indeed, yield was decreased on shaded plots (50% tree cover) compared to sunny plot (0% tree cover) for all treatments, except ‘Ash’. Ashes, because of their black color, diminish soil albedo and increase soil temperature (Usowicz et al., 2016). Thus, on sunny plots, soil moisture was reduced while on shaded plots, soil moisture has probably been retained longer at the end of the rainy season, increasing potentially the corn growing season for a while (Çakir, 2004; Payero et al., 2006). Indeed, plants suffering from water stress cease their growth because nutrient uptake is not possible anymore (Sardans and Peñuelas, 2012). At the opposite, for the other treatments, the shade of the trees impacted negatively corn growth by probably preventing an optimum photosynthesis. When intercropping trees and corn, Reynolds et al. (2007) assessed a significant reduction of solar radiation, associated with a reduced yield, for corn plants growing at 2 m of the trees. Tree cover should be therefore kept to a minimum and corn plants should be planted at a higher distance. Carrière et al. (2002) showed in South Cameroon that 3 to 7 trees for a field of 0.8 ha are enough to improve the slash-and-burn agricultural system.

4.4.4 Further considerations on up-scaling

A violent storm occurred during the time of our experiment: from 17th to 19th January 2015, heavy rains flooded the Kirindy forest due to the cyclone Chedza. Such an extreme event may have affected the results of the experiment and considerably reduced the expected grain yield of the different treatments. Gay-des-Combes et al. (2017) showed that such storm can decrease the grain yield from 4 t ha^{-1} to 1 t ha^{-1} and lower the nitrogen and phosphorus soil concentrations by at least 50%. Given what precedes and considering that the study was done over only one year and on one particular type of soil, the proposed reclamation strategy needs to be checked over longer periods, and multi-sites before the results could be generalized. However, because of the cyclone, our experiment faced one of the worst-case scenarios in terms of nutrient depletion. Thus, most probably, similar or better outcomes would be reached if the proposed cultural method is re-tested in better conditions in terms of soil fertility or climate.

On the long term, the increase in labor requirement, due to the compost fabrication and maintenance, may halt that technique to be endorsed by the farmers. However, compost is very demanding in labor only on a short period of time, namely for green material collection and preparation. If that task can be performed at the beginning of the rainy season, when maize has been sown, it may suit with farmer's cultural calendar. One might also argue that improved production in shifting cultivation will not reduce deforestation, but rather accentuates deforestation to increase production over a larger scale. We observed that for one day of work invested in compost production, only c. 700 m2 of crop field can be amended with compost (Gay-des-Combes, unpublished data). Considering that most farmers possess 1 to 2 ha (Dirac Ramohavelo, 2009), they would need about 14 to 35 days to produce enough compost to cover their entire fields. In consequence, to limit labor constraints and to avoid further damage on the primary forest, we would rather recommend compost as a tool to sustain cultivation on the most degraded fields, rather than a solution for large scale fields.

As a follow up of this research, composting workshops have been performed with farmers in Beroboka and two other neighboring villages (Marofandilia and Kirindy) between May 2015 and December 2016. As slash-and-burn agriculture is embedded in traditions and spirituality, the developed methodology, which stays close to traditional practices, was expected to meet a high social acceptance (Desbureaux and Brimont, 2015; Jarosz, 1993). Indeed, five hundred farmers participated to the workshops, corresponding to about 13% of the population of the villages. This local interest called for further social and ecological research on the refinement and validation of that alternative slash-and-burn practice.

4.5. Conclusion

A combination of wood ashes and compost seems to be a good solution for recovering tropical degraded soils but requires further investigation before generalization. In our experiment, it increased corn yield by 4 to 5 compared to traditional slash-and-burn agriculture. Thus, the proposed solution is original because it considers the deeply socially rooted slash-and-burn practice as an acceptable solution if it is well matched with soil organic matter enrichment, whereas it is usually dismissed as destructive. Recognizing this type of agriculture as a cultural heritage and trying to modify it to make it sustainable paves the way towards a more integrative vision of traditional agriculture along with tropical forest management.

Chapter 4 supplementary material

Detailed methodology for the laboratory analyses

Plant nutrient content and uptake

Nitrogen (N), phosphorus (P) and potassium (K) content of the corn leaves and grains were assessed by digesting the plant samples as described by Wolf (1982). In short, c. 0.05 g of air-dried and ground (0.1 mm) plant biomass was digested in 3 mL of H2SO4, using selenium (Na2SO4Se) as catalyst, and heated up to 420°C for 15 min. The volume of extract was diluted with distilled water and then used for determination of NPK in plant biomass. Final nutrient concentrations were corrected for the dry weight of the plant biomass obtained after drying a sub-sample at 105 °C for 24 hours. Further, potassium (K) was determined by atomic absorption spectrophotometry (Solaar 969, ThermoOptek). Total nitrogen (N) and phosphorus (P) concentrations were determined by, respectively, the blue-indophenol method and the molybdovanadate method using a continuous flow autoanalyser (FlowSys, Systea, Anagni, Italy). Standard reference material (NIST Citrus leaves 1572, National Bureau of Standards) was analysed along with the samples in order to ensure accuracy within 5% of known K, N and P concentrations. Plant uptake in aerial parts was calculated as the sum of the product of leaf and grain nutrient content and the respective leaf and grain dry weight.

Soil, ash and compost parameters

Total nitrogen (N) and carbon (C) were measured on milled soil with a standard CHN analyser (Dumas method). The pH was assessed in a 1:2.5 soil:water suspension (v:v) (Allen, 1989). Cation exchange capacity (CEC), exchangeable K and inorganic nitrogen (NO_3 and NH_4) were measured by extraction: CEC and K with Cobalt-hexamine solution ($Co(NH_3)Cl_3$ 0.0166 M) and inorganic nitrogen with KCl (1 M). The extractions were done on 10 g of dry soil with 40 ml of solution. Then, they were shaken for one hour at 120 rpm and filtered at 0.45 µm. Cation exchange capacity and exchangeable potassium were read on a plasma atomic emission spectrometer (Shimadzu ICPE-9000). Inorganic nitrogen forms were analysed using a continuous flow analyser. Plant phosphorus availability was measured with an anion-exchange resin (Hedley et al., 1982). Five grams of dry ground soil samples were shaken during the night (16h) with resin membrane strips (bicarbonate charged) in a miliQ solution. Further, resins were eluted with a NaCl-HCl 0.5M solution to extract phosphorus (Kouno et al., 1995). Phosphorus concentrations were measured with the malachite green method and by inserting the samples in a Shimadzu 1800 UV-Vis spectrophotometer (Ohno and Zibilske, 1991). Lastly, organic matter was measured through loss of ignition at 600°C. All measures were performed on the initial soil of the experimental sites before the experiment started, on the ashes and compost (at maturation) used in the experiment, and on soil samples of every plot at the end of the experiment.

Soil respiration, microbial biomass and soil enzyme activity

Microbial C biomass was measured with a chloroform fumigation followed by 0.5 M K2SO4 extraction (Vance et al., 1987). Shortly, soil samples were divided in two 5g sub-samples. One of each set of sub-samples was chloroform fumigated in a desiccator over 24 hours in the dark, while the other sub-samples remained in similar conditions but without chloroform. Then, an extraction was done on both sets of sub-samples. After addition of 25ml 0.5M K2SO4, all samples were shaken at 120 rpm during 1 hour. Samples were finally filtered at 150mm, and C concentration was measured on a Shimadzu TOC-V analyzer. Microbial biomass was calculated by the difference between chloroform fumigated and control samples and corrected with Kc factor (Kc=0.45,Beck et al., 1997).

As a proxy for soil activity, we measured the activity of four enzymes involved in C, N and P cycling (Sinsabaugh et al., 2008). We used substrates labelled with the fluorophores 7-amino-4-methylcoumarin (MUC) or methylumbelliferone (MUB) to quantify the relative activity (i.e. enzyme activity under optimal and saturating substrate conditions) of enzymes responsible for the hydrolysis of one peptide (Leucine amino-peptidase, LAP), two carbohydrates (β-glucosidase, BG; Chitinase, CHI), and one phosphatase (acid phosphatase, AP; all substrates supplied Sigma-Aldrich Switzerland). Extracellular enzymes were extracted following (Criquet et al., 2000) and analysed in microplates. For each sample, 4 pseudo-replicate wells were included in a 96 well microtiter plate. Four pseudo-replicate wells containing boiled extracts (3h at 90°C) were also performed as a control to take into account the quenching effect (Burns et al., 2013). Each wells received 38 µL of enzyme extract and 250 µL of substrate. Microplates were then incubated at 25°C for 3h. Fluorescence was monitored spectrophotometrically with an excitation wavelength of 365 nm and emission detection at 450 nm (Biotek, SynergyMX). All enzymatic activities were converted to nanomoles per gram dry weight per min ($nmol.min^{-1}.g^{-1}$ DM).

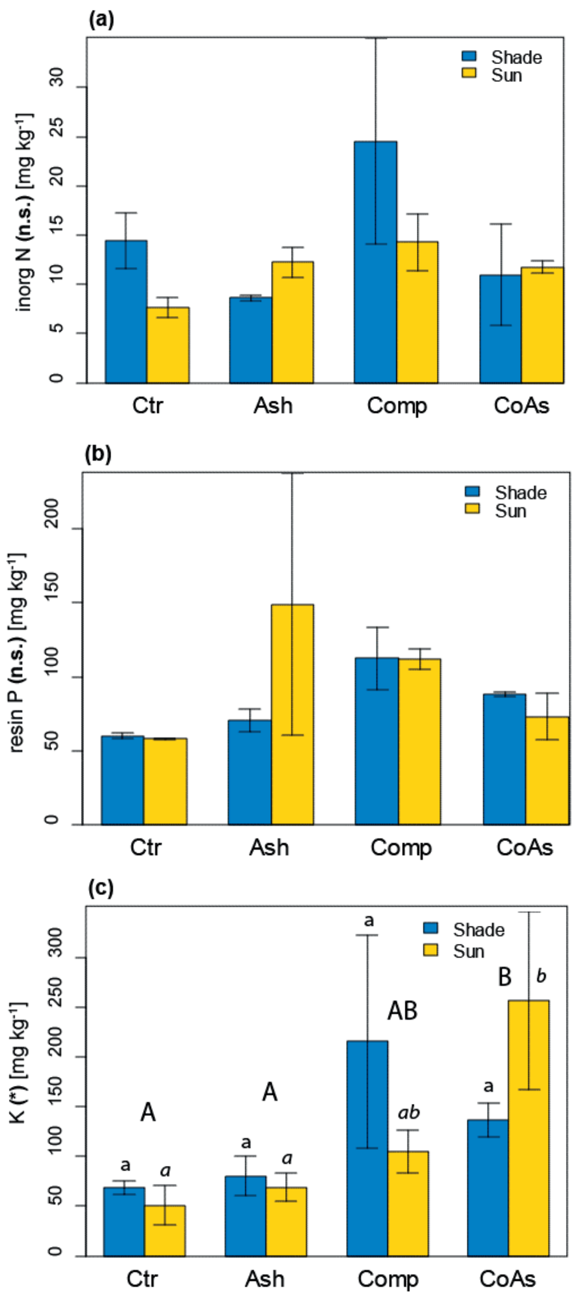
Table S4.1 Summary of split-plot models. Significant values are in bold.

	Tree cover, shade (S)		Soil amendment (T)		SxT	
Parameter	F	*P*	F	*P*	F	*P*
Height	0.727	0.484	28.055	**<0.001**	3.918	**0.037**
Grain yield	1.782	0.314	17.998	**<0.001**	3.471	**0.051**
Plant K uptake	0.478	0.498	5.070	**0.037**	0.013	0.910
Plant N uptake	0.405	0.533	5.715	**0.028**	0.050	0.825
Plant P uptake	0.223	0.642	8.046	**0.011**	0.027	0.872
pH	0.22	0.68	20.82	**<0.001**	0.72	0.56
Soil moisture	27.617	**<0.001**	10.478	**<0.001**	0.614	0.617
Organic matter	106.7	**0.009**	11.170	**<0.001**	0.933	0.455
Soil inorg. N	4.855	0.158	1.381	0.296	1.188	0.355
Soil resin P	4.856	0.158	1.381	0.296	1.188	0.355
Soil ex K	1.74	0.32	4.31	**0.028**	2.22	0.139
Microbial biomass C (MBC)	58.92	**0.017**	18.773	**<0.001**	2.246	0.135
Activity AP/MBC	4.998	**0.045**	16.503	**<0.001**	2.306	0.128
Activity LAP/MBC	3.365	0.092	5.275	**0.015**	1.478	0.270
Activity BG/MBC	3.598	0.082	5.613	**0.012**	2.512	0.108
Activity CHI/MBC	0.002	0.965	2.040	0.162	1.136	0.374

Table S4.2 Components of hypothesis represented by structural equation model of Fig. 4.3

Path	**Hypothesized mechanisms based on *a-priori* knowledge (cf. table S4.1)**
Compost -> Soil moisture	Compost increases soil moisture.
Compost -> Microbial biomass	Compost increases microbial biomass.
Tree cover -> Soil moisture	Tree cover increases soil moisture.
Soil moisture -> Microbial biomass	Soil moisture increases microbial biomass.
Compost -> Organic matter	Compost provides organic matter to the soil.
Microbial biomass ->Organic matter	Microbial biomass degrades litter and increases organic matter.
Organic matter -> Corn yield	Organic matter increases plant available nutrients and thus enhances corn yield.
Ash -> pH	Ash rises soil pH.
pH -> Organic matter	pH enhances organic matter.
pH -> Corn yield	pH favors plant growth when optimal.

Figure S4.1 Mean (± standard errors) of soil inorganic N, resin P and exchangeable K concentrations after corn.harvest.



- CHAPTER 5 -

Combined use of compost and wood ashes enhances maize growth and nutrient availability in poor tropical soils

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Under review in Basic and Applied Ecology

Picture: Maize growth experiment in pots, Morondava
Justine Gay-des-Combes, 2015

Abstract

In Madagascar, slash-and-burn agriculture is seen as an important driver of deforestation; the forest is transformed into agricultural land by cutting and burning the trees. Yet, the fields are abandoned after a few years because weeds start to invade them and yield decreases due to the decline of soil fertility. The fertility decrease is due to both plant nutrient uptake and a strong nutrient leaching, as well as erosion, because of the rains. Consequently, new areas are frequently cleared from the primary forest. We tested an alternative slash-and-burn agriculture, consisting of adding compost to the fields, for sustaining re-cultivation. We aim at assessing 1) how the performances of maize plants are modified by amending the soil with wood ashes and compost compare to traditional slash-and-burn agriculture and 2) how that combination affects the nutrient retention capacity of the soil. We performed a maize growth trial and a nutrient retention laboratory experiment with three treatments: a) ashes, b) compost and c) a mixture of ashes and compost. Combining ashes and compost increased maize growth rate by 20% and advanced phenology stages for 25% of the plants, leading to 20% taller plants with 50% higher cob weights, compare to traditional agricultural practices. This combination also helped dealing with nutrient soil deficiencies by mitigating their leaching during rain events. After a rain simulation, stocks of nitrogen, phosphorus and potassium were 30 to 50% higher in the mixture of ashes and compost than in other substrates. Moreover, recognizing slash-and-burn agriculture as a cultural heritage and trying to optimize it in order to make it sustainable is the starting point towards the incorporation of traditional agriculture within conservation strategies of tropical forests.

Keywords
Organic matter, fertilization, leaching, deforestation, slash-and-burn agriculture, maize phenology

5.1 Introduction

Slash-and-burn agriculture is widely used in the tropics, and is the main driver of deforestation in Madagascar, where more than 80% of its population is depending directly on the agricultural sector (Desbureaux and Brimont, 2015; Genini, 1996; Poudyal et al., 2016). Typically, on the south-western coast of the island (i.e. the Menabe region) a striking 2.6% of forest was lost annually between 2008 and 2010 (Zinner et al., 2014). At such a rate, the Malagasy western forest biome will disappear by 2050 (Zinner et al., 2014). Briefly, forests are converted to agricultural land by cutting and burning trees. After a few years of repetitive cultivation on the same field, crop yield decreases already (Milleville et al., 2001) and farmers are forced to abandon their fields and seek to burn new areas of forest (Dirac Ramohavelo, 2009; Styger et al., 2009). In Madagascar, a complex network of political, social and ecological stakes had proven to thwart the transition towards a more sustainable agricultural system (Scales, 2012). Limited access to micro-credits and markets, unsecure land tenure systems, population growth, as well as a strong social and cultural background strengthen the persistence of slash-and-burn agriculture in Madagascar (Desbureaux and Brimont, 2015; Hume, 2006; Jarosz, 1993; Styger et al., 2009; van Vliet et al., 2012).

Traditional slash-and-burn practice relies on wood ashes as soil amendment. Wood ashes are strongly alkaline (i.e. they increase soil pH), and favour microbial activity (Jokinen et al., 2006). Hence, ash amendment enhances the quantity and the availability of soil nutrients when spread on acid tropical soils (Demeyer et al., 2001). Nevertheless, that effect is short lived. After few cultivation cycles, nutrient deficiencies tend to appear in the soil because of an imbalance between plant nutrient uptake and soil fertilization. Indeed, large inputs of wood ashes pushes the soil macronutrient stoichiometry towards nitrogen (N) limitation, as ash is generally N-poor. Nitrogen limitation can become even more problematic as maize (Zea mays L.), after rice the most cultivated crop in Madagascar, is a high-nitrogen-demanding plant. A lack of nitrogen impacts on crop phenology by delaying its maturity, as well as decreasing its growth rate, leading to smaller plants and reduced yields (Zhang et al., 2008a, 2008b). In western Madagascar, maize yields can be up to 4 t ha^{-1}, but can drop to 2.5 t ha^{-1} after three years of cultivation on the same field (Gay-des-Combes et al., 2017). Besides, the high pH of slashed-and-burnt soils increases nutrients solubility, which may lead to enhanced nutrient loss through leaching (Béliveau et al., 2015; Nye and Greenwood, 1960). In turn, this can lead to an even stronger decline in maize yield than repetitive cultivations, as demonstrated by Gay-des-Combes et al. (2017) who measured a yield drop from 4t ha^{-1} to 1t ha^{-1} after an intense tropical storm.

Acknowledging the difficulty to suppress slash-and-burn agriculture because of the complex socio-political situation, and considering that it progressively engenders soil nutrient deficiency, we suggest to optimize this agricultural practice with adequate amendments. As chemical fertilizers are unaffordable for most rural households, compost could be a solution to enhance the soil nutrient status, and to overcome N deficiency. Compost is low cost and enhances both the capacity of the soil to hold water and nutrients (Zhang et al., 2016). Such soil improvement may subsequently enhance crop yield (Abdel-Sabour and El-Seoud, 1996; Mbau et al., 2014; Zhang et al., 2016). There is a growing awareness on the benefit of mixing compost and ashes for agriculture (Bougnom et al., 2009; Brod et al., 2012; Gay-des-Combes et al., in press; Juárez et al., 2015; Kuba et al., 2008). It has been suggested that the high pH of ashes accelerates the mineralization of compost, releasing on the short-term a larger quantity of macro-nutrients in the soil (Smebye et al., 2016). That effect would be beneficial in tropical rural agriculture in order to grow plants like maize which needs a high concentration of rapidly available nutrients. However, combining compost and ashes could also play a significant role in tropical soil protection by increasing the soil potential to retain nutrients during heavy rains, because of compost high retention capacity (Agegnehu et al., 2016). The few existing studies focused mostly on using the ashes to accelerate the maturation of compost, or on soil quality improvement. None studied the potential of that technique on nutrient-demanding plants like maize, nor its potential implication for nutrient leaching prevention. Here, we seek to fill those particular knowledge gaps in the context of slash-and-burn agriculture. The present study demonstrates 1) how the performances of maize plants are modified by amending the soil with wood ashes and compost compare to traditional slash-and-burn agriculture and 2) how that combination affects the nutrient retention capacity of the soil. Using a variety of mesocosm experiments, we assessed the effect of ashes, compost, and their mixture on the growth and yield of maize plants under natural environmental conditions, and we tested the effects of these treatments on the capacity of soils to store nutrients. We hypothesized that i) a mixture of compost and ash increases maize growth rate and accelerates plant maturity, leading to higher plants at the end of the growing season; ii) Mixing compost and ashes allows to decrease nutrient leaching compared to ash or compost alone, thus improving the soil nutrient stocks.

5.2 Material and methods

5.2.1 Material collection for experiments

We conducted our experiment in the dry deciduous forest of Kirindy (central Menabe) near the village of Beroboka (20° 00’22.3’’S, 44° 35’06.1’’E), 30 km north of the city of Morondava. This region was selected as it is severely affected by deforestation due to slash-and-burn agriculture (Dirac Ramohavelo, 2009). In southwestern Madagascar, the climate is tropical, but with a long dry season from April to September. Mean annual rainfall is about 800 mm, but varies between 250 and 1400 mm (Sorg and Rohner, 1996). Temperatures are high year-round and average at 24.7°C (Sorg and Rohner, 1996).

In order not to disturb the primary forest, we selected a forest site located on a 30 years old secondary forest. The soil of the site was a ferruginous soil, corresponding to the Lixisols after the World Reference Base for Soil Resources (Raharimalala et al., 2010). It was yellowish red (5YR 5/8, Munsell color code) and composed of about 75% of sand, 10% silt and 15% clay. Vegetation, dominated mainly by *Poupartia sylvatica, Tarenna sericea and Fernandoa madagascariensis* trees, as well as some lower shrubs, was removed and the cut wood was piled-up and burnt, yielding a 1-2 cm ash layer. For the experiments, the ashes were collected, as well as the underlying burnt soil (0-5 cm) and the 10-20 cm horizon of the soil called "deep yellow soil". These different soil layers were used, together with the compost, for assembling the different soil substrates in the two mesocosm experiments. Characteristics of the different soil layers were assessed (Table 5.1).

Table 5.1 *Properties of the substrates used for the mesocosm experiments. Chemical determination was assessed using the same protocol described at sub-chapter 2.3.2.*

Material	Density [kg dry wt/L]	pH	CEC [cmol /kg]	Ctot [g/kg]	Ntot [g/kg]	N inorg [mg/kg soil]	Ptot [mg/kg soil]	P resin [mg/kg soil]	K ex [mg/kg soil]
Compost	0.6 ± 0.1	7.9 ± 0.2	43 ± 3	239 ± 20	14 ± 1	310 ± 13	1257 ± 25	117 ± 7	348 ± 21
Ashes	1.1 ± 0.1	11.2 ± 0.1	6 ± 2	24 ± 5	1 ± 0.3	4 ± 1	647 ± 15	3 ± 0.5	637 ± 35
Burnt soil	1.3 ± 0.1	10.4 ± 0.1	2 ± 1	9 ± 1	1 ± 0.2	11 ± 1	275 ± 12	14 ± 1	1559 ± 48
Deep yellow soil	1.4 ± 0.1	5.8 ± 0.2	5 ± 1	11 ± 3	1 ± 0.3	2 ± 1	72 ± 5	2 ± 0.5	64 ± 3

Eight month prior to the experiment, compost was made with an equal volume of *Poupartia sylvatica, Tarenna sericea* and *Fernandoa madagascariensis* biomass, collected adjacent to the slash-and-burn site. These trees are frequent in the secondary forest, are rather productive, have high nutrient contents, and have been shown to be appropriate for composting (Raharimalala et al., 2011, 2012). Furthermore, these species are not used by villagers for any traditional work. Branches (< 2 cm diameter) and leaves were collected and all plant material was crushed into 1–2 cm chips, after which all material was put in a 1m3 pit for eight months composting. The pit was protected from direct sunlight and watered once a week with 15 L of water from the local well. Furthermore, every fortnight the material in the pit was thoroughly mixed. Similarly, to the ashes and the soil, we assessed the characteristics of the compost at the end of the composting period (Table 5.1).

5.2.2 Maize growth experiment

Experimental design

A pot experiment was installed in an open-air plant nursery at the Centre National de Formation, d'Etude et de Recherche en Environnement et Foresterie (CNFEREF) in Morondava. A total of 80 pots (23×28×31 cm) were prepared, and filled with four soil substrates (17L.; n = 20). Pots were filled with deep yellow soil and received on top one or several layers of amendments, as follows: control (Ctr): deep yellow soil (17 L); ash (Ash): deep yellow soil, burnt soil, and ashes (12 L, 4 L, 1 L, respectively); compost (Comp): deep yellow soil and compost, (16 L, 1 L, respectively); ash + compost (CoAsh): deep yellow soil, burned soil, ashes, and compost. (11 L, 4 L, 1 L, 1 L, respectively). Treatments were allocated randomly to the pots, which were buried into the soil to prevent lateral solar radiation.

In December 2014, after the first rain event of the rainy season, three maize seeds (variety *vonivony*; commonly used in the region with a growth cycle of about 110 days) were placed in the center of each pot. Once the seedlings appeared, plants were thinned as to leave only one plant per pot. Pots received natural precipitation throughout the experimental period (December 2014 - March 2015). Precipitation was recorded with a pluviometer installed in the plant nursery. Cumulative rainfall during the growing period reached 2140 mm. Rain occurred approximately every two days throughout the experimental period, with an average amount of 45 mm per rainfall event. Maximum rain for a single rainfall event reached 250 mm on 7th February. To avoid soil splashing out of the pots during rain events, the pots were filled 5 cm lower than their actual maximal capacity (about 20 L) and small holes were perforated at the bottom of each pot to ensure water drainage out of the pot.

Plant variable measurements

For each plant, total height was assessed every week. The reproductive stages of the plants were assessed 60 and 90 days after seeding. Days 60 and 90 correspond to tassel emergence and dough stage of the variety, respectively. On March 30, 2015, when plants were matured, the first leaf above the upper cob was collected and its chemical content was analyzed. Nitrogen (N), phosphorus (P) and potassium (K) contents were assessed by digesting the samples as described by Wolf (1982). Potassium (K) was determined by atomic absorption spectrophotometry (Solaar 969, ThermoOptek). Total nitrogen (N) and phosphorus (P) concentrations were determined by the blue-indophenol method and the molybdovanadate method, respectively, using a continuous flow autoanalyser (FlowSys, Systea). Finally, at the start of senescence (April 20, 2015), plant height was measured, as well as the dry weight of the shoot, of the cobs and of the roots. Bulk grain weight was not measured as the final cobs were small and not filled entirely with grains. The roots were separated from the soil in two steps: the largest roots were removed by hand and the finest roots were collected after sieving the soil at 2 mm.

5.2.3 Nutrient retention laboratory experiment

Experimental design

A column experiment was performed in the laboratory where only the amendments (i.e. compost and ashes) were tested, without plants (Table 5.1). Neither burnt soil, nor deep yellow soil were used, because we were interested in singling out the chemical interactions between compost and ashes. Although we are aware that amendments interact with the soil, that particular design permits to draw conclusions on compost and ash amendments, which may also apply in other types of soils than yellow soils. Altogether we had 12 columns (PVC tubes, 5.8cm diameter), which we filled with ashes (*Ash*; 100%, v), compost (*Comp*; 100%, v), or ashes + compost (*CoAsh*, 50%-50%, v,v) (n = 4). Here (and in the figures), italic letters for the abbreviated names of the treatments permit to differentiate them to the treatments of the pot experiment that include soil. The columns were closed with a plastic grid at the bottom and a 100µm Nitex mesh. A layer of 2 cm of sand was added at the bottom to accomodate drainage. To fill the columns, the substrate for each treatment was added by small increments of 0.5 cm and the columns were gently shaken to obtain an homogeneous filling (Colombani et al., 2015). Another 100µm Nitex mesh was placed at the top of the substrate and covered with 2 cm of sand to protect the substrate from erosion (Li et al., 2015). The columns were then slowly saturated from the bottom with water, so as to avoid building-up of preferential channels during the subsequent rain simulation from top (Li et al., 2015; Sun et al., 2001). After 2 hours, all the columns were drained by gravity for 3-4 hours. At water holding capacity, the water content was 19% for *Ash*, 20% for *Comp* and 22% for *CoAsh*. The columns were then weighted. These values served as a reference to keep a constant level of soil moisture throughout the experiment. Columns were incubated during one week to reactivate the microbial community. To simulate rain, Milli-Q water has been used. Watering was performed with a slow dripping technique using a multi-tips tube. The rain was drained by gravity after each rain simulation (Escudey et al., 2015; Ro et al., 2016). The columns were watered 3 times a week with the equivalent of 4.5 cm of water (i.e. 119 ml for each column), which corresponded to the average rain height for a single event in Morondava during the 2015 rainy season.

Laboratory analyses

At the end of the pot experiment and at both the start and end of the column experiment, the following variables were measured on the substrates: pH, CEC, inorganic nitrogen forms (NO_3, NH_4), plant available phosphorus, exchangeable K, total carbon, total nitrogen and total phosphorus. Soil pH was measured in a 1:2.5 soil:water suspension (v:v) (Allen, 1989). Extraction solutions were prepared for CEC and exchangeable potassium (Cobalt-hexamine solution, $Co(NH_3)Cl_3$ 0.0166M), as well as for inorganic nitrogen forms (KCl 0.5M). All extractions were performed on 5 g. of dry substrate with 40 ml of solution, then shaken for one hour at 120 rpm and filtered at 0.45µm. Exchangeable potassium was measured with a plasma atomic emission spectrometer SHIMADZU ICPE-9000, whereas inorganic nitrogen forms were analysed colorimetrically using a continuous flow analyser. Plant-available phosphorus was extracted with an anion-exchange resin. This method has been shown to correlate well with the phosphorus fraction available for the plant (Hedley et al., 1982). Five grams of dry ground soil samples were shaken overnight (16h) with resin membrane strips (bicarbonate charged) in a miliQ solution. Later, resins were eluted with a NaCl-HCl 0.1M solution to extract phosphorus (Kouno et al., 1995). Plant-available phosphorus concentrations were measured colorimetrically using the malachite green method and placing the samples in a Shimatzu 1800 UV-Vis spectrophotometer (Ohno and Zibilske, 1991). Finally, total C and N were assessed on milled soil with a standard CHN analyser (Dumas method) while total phosphorus was obtained by microwave digestion with H_2O_2/HNO_3 and subsequent analysis of the extract with the malachite green method.

5.2.4 Statistical analyses

For the maize growth pot experiment, linear regressions were fitted for maize plant heights over time. The explanatory variable time was included in the error structure, plant replicates being nested within time to account for the correlation between the repetitive measurements. The intercepts of the linear regressions were constrained to zero to build a realistic ecological model. Further, the slopes were extracted from the regressions and the effects of the soil treatments on the slopes, i.e. maize plant growth rates, were analyzed using an analysis of variance (ANOVA) and Tukey post hoc tests. Because the reproductive stages of the plants were expressed as binary variables, they were analyzed according to generalized linear models from the binomial family and post hoc tests based on contrast analyses. Final leaf nutrient concentrations (NPK), final height, dry shoot weight, root weight and cob weight were analyzed with analyses of variance (ANOVA) and further with Tukey post hoc tests to determine the differences among amendment treatments. When necessary, values were log-transformed prior to analysis to satisfy the assumption of normality and homogeneity of variance. For the column experiment, nutrient stocks in the columns before and after rain simulation were compared. Analyses of variance (ANOVA) and Tukey post hoc tests were performed on those response variables. All analyses were performed in R (R Development Core Team, 2013).

5.3 Results

5.3.1 Maize response variables

The combined addition of compost and ash (CoAsh) to the soils considerably increased the growth rate of maize plants compared to other treatments (Fig. 5.1, Table S5.1, $P < 0.001$). CoAsh amendment increased plant growth rates by 50% as compared to the control treatment, and by 20% compared to single compost and ash amendment. The latter two treatments did not results in differences in plant growth rate.

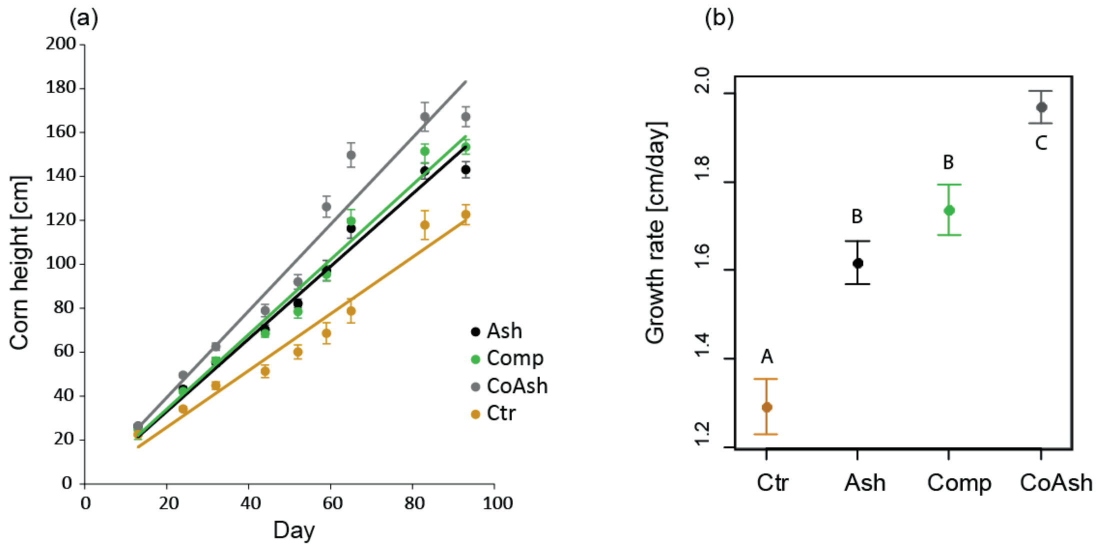

Figure 5.1 *a) Relationship between mean plant height (± SE) and time for the different soil treatments. Linear regression lines are given for each soil treatment. b) Growth rate of the maize plant over the experimental period, assessed as the slope of the linear regressions. Different letters denote significant differences between soil amendment treatments (Tukey tests, P ≤ 0.05).*

On day 60, 85% of the plants which received a combination of compost and ashes were at tasselling stage. When compost or ashes were added as a single treatment, 60% and 50% of the plants, respectively, were at tasselling stage, while only 20% of the control plants were at that stage (Fig. 5.2, Table S5.1, $P > 0.001$). This trend carried over to the dough stage (day 90); 50% of the plants in the combined compost and ash amendment treatment were at dough stage as compared to 45% and 30% for the single compost and ash amendments, respectively (Fig. 5.2, Table S5.1, $P > 0.001$). None of the plant grown in the control soils reached dough stage.

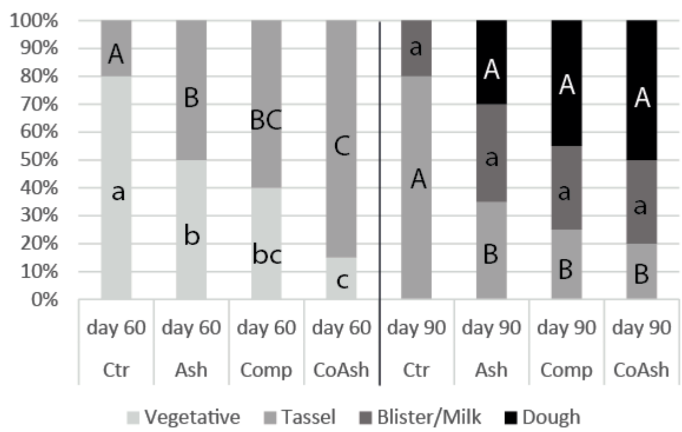

Figure 5.2 *Percentage of the maize plants reaching a particular reproductive stage according to the different soil treatments and two periods (day 60 and day 90) during the growing phase. Different letters denote significant differences between soil amendment treatments (Contrast tests, P ≤ 0.05).*

Maize leaf nitrogen (N) and phosphorus (P) content were highest when compost and ash were added to the soil together, and lowest in the control treatment (Fig. 5.3, Table S5.1). Similar as observed for plant growth rates, leaf N and P concentrations did not differ between plants grown in the compost or ash amendment treatments. For leaf potassium (K) content, we observed an opposite pattern with the highest value in the control treatment and lowest value in the combined compost and ash treatment. Again, leaf K content in the single compost and ash treatments did not differ (Fig. 5.3).

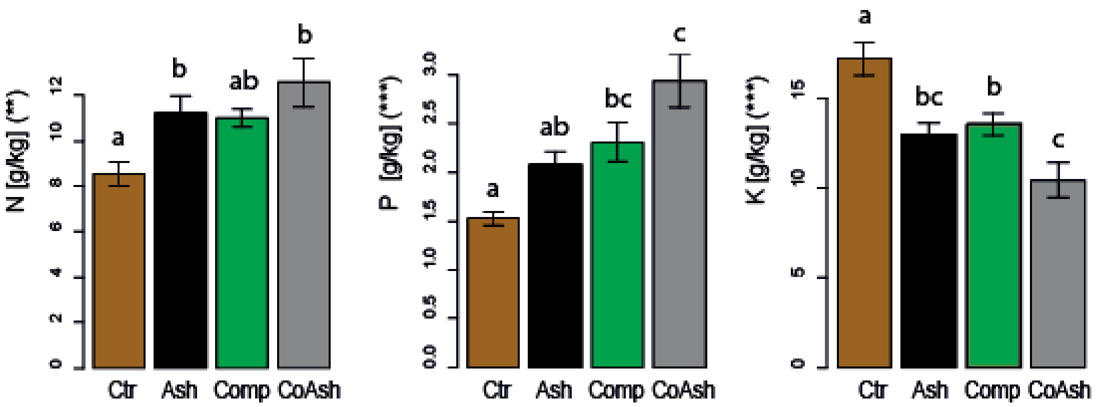

***Figure 5.3** Mean values (± SE) for maize leaf nutrient contents according to the different soil treatments, at the end of the growing season. Asterisks indicate significant effect of treatments (P < 0.001 = ***; P < 0.01 = **; P < 0.05 = *; P < 0.1= ·). Different letters denote significant differences between soil amendment treatments (Tukey tests, P ≤ 0.05).*

At the end of the growing season, plant height and shoot weight were significantly higher for combined compost and ash treatment as compared to the other treatments (Fig. 5.4, Table S5.1, $P < 0.001$). Plants were 15 % to 20 % taller and shoots were 50% heavier in the combined compost and ash treatment as compared to their single amendment counterparts (Fig. 5.4). No difference in plant and shoot weight was found between plants grown in the two single amendment treatments. Root weight increased with compost and ash single amendments, but was only significantly different form the control in the combined amendment. Cob weight also increased with compost and ash single amendments, but was not significantly higher in the combined treatment as compared to the single amendment treatments (Fig. 5.4, Table S5.1).

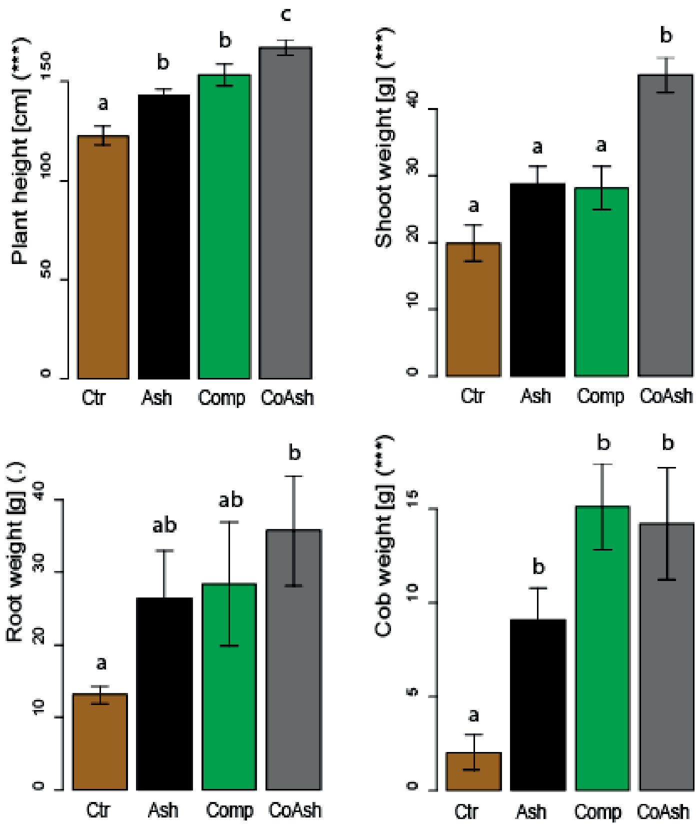

Figure 5.4 *Mean values (± SE) for plant traits according to the different soil treatments, at the end of the growing season. Asterisks indicate significant effect of treatments (P < 0.001 = ***; P < 0.01 = **; P < 0.05 = *; P < 0.1= ·). Different letters denote significant differences between soil amendment treatments (Tukey tests, P ≤ 0.05).*

5.3.2 Nutrient retention laboratory experiment

After the column experiment, the pH was decreased significantly in *Ash* and *CoAsh* substrates (Fig. 5.5, $P < 0.05$). No decrease was recorded for *Comp* substrate ($P > 0.05$). The pH was reduced to more than 1.5 unit for *Ash* and of about 1 for *CoAsh*. The final value of pH was the highest in *Ash* (pH=9.8), the lowest in *Comp* (pH=7.8) and intermediate in *CoAsh* (pH=8.5, Table S5.2, $P < 0.001$).

Initial values for CEC showed that *Comp* substrate held a CEC between 4 to 7 times higher than *CoAsh* and *Ash*, respectively (Fig. 5.5). CEC was about 43 cmol kg^{-1} for *Comp*, while it was 6 cmol kg^{-1} for *Ash* and 11 cmol kg^{-1} for *CoAsh*. Rain simulation decreased CEC values significantly only for the *Comp* substrate (Fig. 5.5, $P < 0.05$, from 43 to 35 cmol/kg), while final CEC values of the two other substrates were almost the same than initial values.

Resin phosphorus stock (i.e. total weight of resin phosphorus in the column) was the highest for *Comp* substrate before rain simulation (Fig. 5.5, 14 mg), but decreased significantly after rain simulation (6 mg, $P < 0.05$). At the opposite, resin P stock increased significantly for *Ash* and *CoAsh* substrates (from 0.5-1.5 mg to 5-8 mg, respectively). Final stock values were the highest for *CoAsh* (8 mg), and the lowest for *Ash* (5 mg, Table S5.2, $P < 0.01$).

Quantity of lost potassium was the highest for *Ash* substrate (from 140 mg to 40, Fig. 5.5), while the potassium stock in *Comp* substrate was not affected. Final potassium stock value was the highest for *CoAsh* substrate (65 mg), while *Ash* and *Comp* were approximately at similar levels (40-45 mg, Table S5.2, $P = 0.012$).

Difference of values for inorganic nitrogen before and after rain simulation revealed that *Comp* and *CoAsh* substrates lost more than 95% of their inorganic N content (Fig. 5.5). *Comp* substrate lost the highest stock of nitrogen (from 35 mg to 0.8 mg, Fig. 5.5). On the other side, *Ash* substrate barely lost inorganic nitrogen, but initial stock was negligible (0.5 mg). With respect to final values, inorganic nitrogen stock was the highest in *CoAsh* (1.2 mg).

Finally, concerning total carbon, nitrogen and phosphorus stocks, no significant difference were found between initial and final values for all substrates (Fig. S5.1, $P > 0.05$). *Comp* substrate had the highest content in total C and total N, while *Ash* had the highest content in total P (Table S5.2, $P < 0.001$).

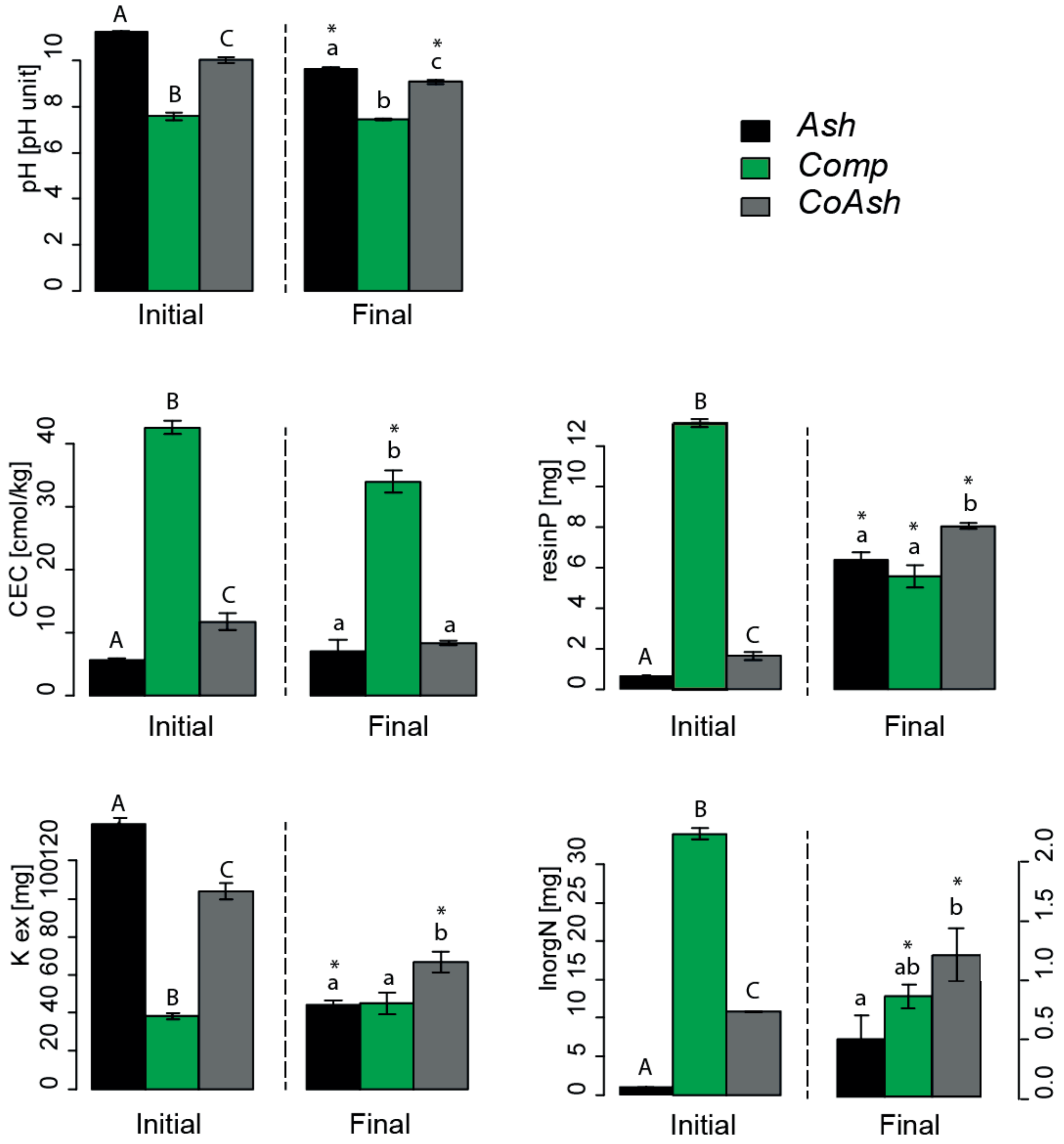

Figure 5.5 Mean values with (± SE) for soil chemical variables in the column experiment, according to the different substrates. Phosphorus, potassium and inorganic nitrogen are expressed as stocks (total weight in the column). Different letters denote significant differences between soil treatments within initial (capital letters) or final (lower case letters) conditions and asterisks represent a significant difference within one treatment between initial and final conditions (Tukey tests, $P \leq 0.05$).

5.4 Discussion

5.4.1 Synergistic effect of ash and compost on maize growth & development

Our results showed that mixing ashes with compost increased significantly maize growth rate and accelerated the phenological development of the plants. Indeed, plants growing on compost and ash mixture reached tassel emergence earlier. Furthermore, these plants had significantly higher root, shoot and maize cobs dry masses. Zhang, Blackmer and Blackmer (2008) demonstrated that the differences in maize plant height growing on soils with different nitrogen concentrations increased until tasseling stage, and then diminished as the plants approached their terminal height. Deficiencies of N can also delay crop maturity, as well as reduce the rate of growth within any given growth stage (Zhang et al., 2009). Under the control treatment, but to some extent also under ash and compost single amendment treatments, the lower N and P concentrations in leaves indicates that those nutrients may have induced deficiencies in crop maturity (Duru et al., 1992; Fig. 5.3). P deficiency most probably also exacerbates N deficiency. At low P concentrations, an addition of N has almost no effect on yield, whereas when P is present in sufficient concentrations, yield increases with N inputs (Sumner and Farina, 1986). In fact, low P concentrations decrease the activity of ammonia-oxidizing bacteria in the soil, which provokes, in turn, a decline in plant available N forms (Chu et al., 2007).

Generally, using compost as a soil amendment enhances long term soil fertility with the increase of soil microbial biomass and activity, as well as, by providing plant mineralizable nutrients (Mbau et al., 2014; Zhang et al., 2016). Most likely, the acidity of the soil in our experiment, plays a role in reducing the efficiency of compost amendment by a decrease in its nutrient mobility. Kuba et al. (2008) and Bougnom et al. (2010) found comparable outcomes in other systems and proved that compost amended with industrial ashes on acid and nutrient-deficient soils resulted in better plant cover and soil microbiological properties, due to the positive effect of ashes on pH. Indeed, the alkaline pH of ashes is known to foster organic matter mineralization (Gabhane et al., 2012). This synergy between ashes and the organic matter of compost can trigger plant-available nutrient release from the organic matter. Also, by selecting three local tree species with leaves having a high nutrient content (Raharimalala, 2011), we produced an efficient compost. This suggests that the effect of compost on soil properties could be enhanced with the use of adapted composting material, as reported by Lima et al. (2004) who showed that compost made with thoroughly selected vegetal waste increased by 80% the biomass of maize plants compared to a non-selected compost. Finally, values obtained for maize plants at the end the experiment were smaller than found usually in field conditions (Fig. 5.4, Gay-des-Combes et al., 2017). We believe that the pots limited partially maize growth because of the restricted space allocated for root expansion.

A complementary second pot experiment was run in 2016 on a smaller number of plants. In that experiment, we doubled the amount of ashes and compost in the single amendments (cf. Supplementary material). Despite a higher quantity of nutrients compared to the first experiment in 2015, the plants who grew on single ash or compost amendments remained smaller than the ones on the mixture of compost and ash (Fig. S5.2, Fig. S5.4, Table S5.3). In that second experiment, maturity stages were also more advanced for compost and ash mixture (Fig. S5.3, Table S5.3). This confirms the observation made in 2015 and backs the principle of a synergistic effect of ash and compost. Each amendment enhances differently, but complementarily, properties of soil fertility, resulting in a multiplicative effect on maize yield. Climate was drier in 2016 (375 mm in 2016 versus 2140 mm in 2015), which explains the lower growth rate and height of plants as compared to the precedent year. The climate in 2016 amplified also the differences among treatments. This second experiment suggests that CoAsh treatment could improve yield stability against climate hazards and help mitigating either heavy rains like in 2015, or hot and dry weather like in 2016.

5.4.2 Compost added to ashes play an important role in preserving the nutrient stocks

The combination of compost and ashes had a 30 to 50% higher contents of potassium, phosphorus and nitrogen at the end of the rain simulation experiment, compared to the other treatments (Fig. 5.5, Table S5.2). That substrate decreased K leaching and soil acidification, while it increased plant-available P stock (Fig. 5.5). It did also affect nitrogen leaching in a least extent (Fig. 5.5). Compost is known to lose substantial amounts of nitrates through leaching (Wong et al., 2017), whereas K is the principal element lost by wood ashes (Steenari et al., 1999). The concentrations of elements in ashes are likely to be controlled by dissolution/precipitation reactions. Solubility of elements such as K, tend to be higher under basic pH (Escudey et al., 2015). A mixture of compost and ashes ultimately retains more cations such as K, than only ashes, because the pH is lowered and CEC increased. However, it also helps simultaneously to mineralize organic nutrients, such as organic P and N, because of the dissolution of organic matter at the contact of ashes (Smebye et al., 2016). Therefore, coupling ashes and compost application provides an optimal combination of the properties of both materials. The same applies for the phosphorus. Its higher availability in the compost and ashes mixture compared to the compost alone can be related to the increased activity of microbes, which may have mineralized some of the organic P in the compost. The addition of ashes is known to trigger soil organic matter mineralization (Khanna et al., 1994), due to the pH increase and the release of dissolved organic carbon (Augusto et al., 2008).

Total nitrogen, phosphorus and carbon were preserved within the columns. We could expect that result to be different in the field, which is subjected to rains and winds (Gay-des-Combes et al., 2017). Indeed, in our experiment, the simulated rain was gently poured on the column, preventing any erosion and maintaining the structure of the soil. Erosion could then lower the fertilizing effect of compost and ashes. However, a field trial demonstrated that despite heavy rains, maize yield were still multiplied by 5 on plots cultivated with ashes and compost compared to traditional slash-and-burn agriculture (0.25 t ha^{-1} to 1.5t ha^{-1}; Gay-des-Combes et al., in press). This suggests that compost added to ashes play an important role in preserving the nutrient stocks, even from erosion.

Finally, it was established that a mix of compost and biochar enhances the leaching of almost all elements, in particular K, P, organic C, nitrogen and some cations, after an incubation period of one month (Sorrenti and Toselli, 2016). As biochar and ashes share similar alkaline properties, they can be compared on the effects deriving from those properties. In our study, the incubation period was reduced to one week. Therefore, increasing the duration of the contact between ashes and compost may increase the quantity of dissolved organic matter and the amount of lost nutrients. Thus, in the context of field application, applying compost superficially onto the soil rather than mixing it with the top-soil, might be a good way to avoid excessive nutrient leaching.

5.5 Conclusion

To conclude, a combination of wood ashes and compost for soil amendment seems to be a good avenue for increasing crop yield on tropical acid soils. It helps dealing with phosphorus and nitrogen soil deficiencies by releasing nutrients in the soil and mitigating their leaching during heavy rain events. Furthermore, by increasing maize growth rate and advancing phenology stages, it reduces plant maturation time and thus the exposure to climate hazards. This could potentially help to cope with shortened rainy seasons in the context of climate change. Nevertheless, further experiments should be carried out to test the long-term outcome of such a practice, along with the potential for implementation in local communities. In optimizing slash-and-burn agriculture, better yields could be targeted, which in turn would allow to sustain longer the cultivation on the fields. The perspective of optimized slash-and-burn practice to make it sustainable is the starting point towards the integration of traditional agriculture within conservation strategies of tropical forests.

Chapter 5 supplementary material

Table S5.1 Summary of linear regression models for the maize growth pot experiment in 2015, using maize response variables according to the different soil treatments. Significant values are in bold.

Slopes	**Treatment**	
	F	*P*
Regression slopes for growth rate	28.85	**<0.001*****
Day 60	7.259	**<0.001*****
Day 90	9.047	**<0.001*****
N leaf content	5.239	**<0.01 ****
P leaf content	10.18	**<0.001*****
K leaf content	11.91	**<0.001*****
Plant height [cm]	17.3	**<0.001*****
Root weight [g]	3.318	0.0569.
Shoot weight [g]	9.714	**<0.001*****
Cob weight [g]	6.716	**<0.001*****

Table S5.2 Summary of linear models for the column experiment, using soil chemical response variables according to the different substrates.

Response variable	**Treatment - start**		**Treatment - end**	
	F	*P*	F	*P*
CEC [cmol/kg]	389.2	**<0.001*****	112.5	**<0.001*****
pH [-]	223.1	**<0.001*****	263.1	**<0.001*****
K [mg/g]	3026	**<0.001*****	7.42	0.0125 *
InorgN [mg/g]	1586	**<0.001*****	3.768	0.0648.
Resin P [mg/kg]	15330	**<0.001*****	10.66	**<0.01 ****
Ptot	9286	**<0.001*****	892.4	**<0.001*****
Ctot	1620	**<0.001*****	243.1	**<0.001*****
Ntot	393.6	**<0.001*****	365.1	**<0.001*****

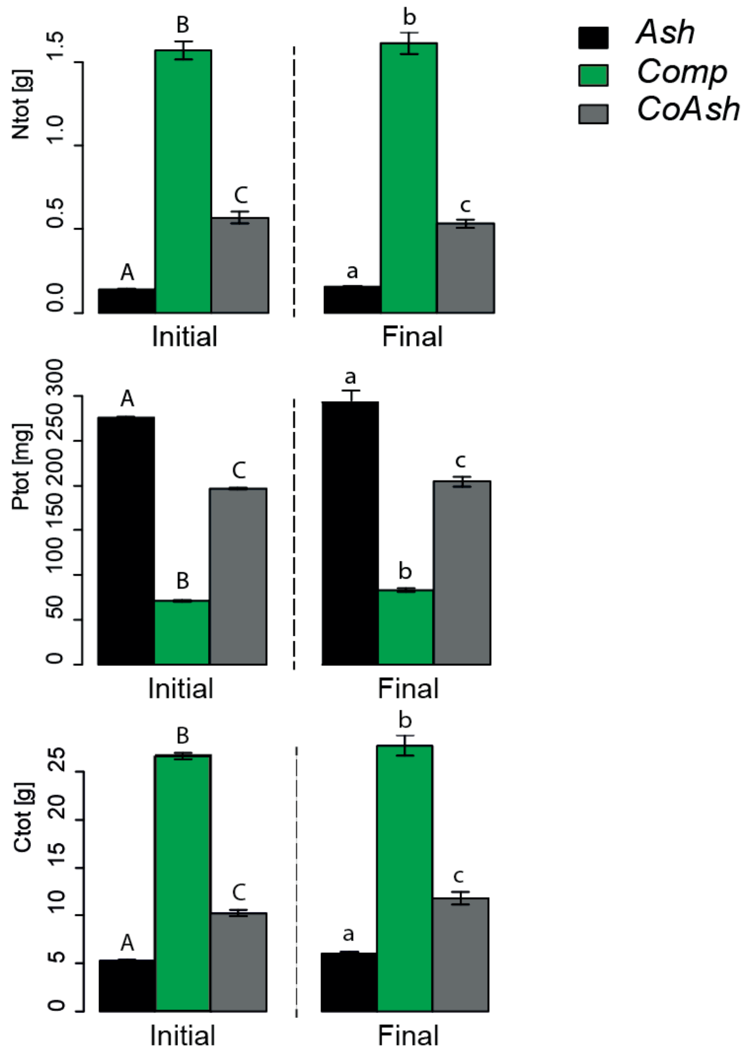

Figure S5.1 Mean values (± SE) for for total carbon (Ctot), total nitrogen (Ntot) and total phosphorus (Ptot) in the column experiment, according to the different substrates and expressed as stocks (total weight in the column). Different letters denote significant differences between soil treatments within (capital letters) or final (lower case letters) conditions and asterisks represent a significant difference within one treatment between initial and final conditions (Tukey tests, $P \leq 0.05$).

Maize growth experiment in 2016

Experimental design & measurements

In 2016, a second pot experiment was carried out in the same open air plant nursery, at the Centre National de Formation, d'Etude et de Recherche en Environnement et Foresterie (CNFEREF), in Morondava. The protocol for material collection was exactly the same as in 2015. A total of 15 pots containing 17 L of soil substrate, with 5 replicates per treatment, were prepared. Pots were filled with deep yellow soil and received on top one or several layers of amendments, as follows: i) ash (2xAsh): deep yellow soil, burned soil, and ashes (7 L, 8 L, 2 L, respectively); ii) compost (2xComp): deep yellow soil and compost,(15 L, 2 L, respectively); ash + compost (CoAsh): deep yellow soil, burned soil, ashes, and compost. (11 L, 4 L, 1 L, 1 L, respectively). Treatment CoAsh was the same as in 2015, whereas the volume of ashes and compost was doubled for the treatments 2xAsh and 2xComp, in comparison of 2015. Treatments were allocated randomly to the pots, which were buried into the soil to prevent lateral solar radiations. Maize sowing followed the same protocol as in 2015. Precipitations were recorded with a pluviometer, installed in the plant nursery. Cumulative rainfall during the growing period reached 375 mm. A minimal irrigation was provided to the plants to avoid them to die (1 L every second days). Maize measurements were done similarly as in the protocol 2015. Statistical analyses were identical as in 2015.

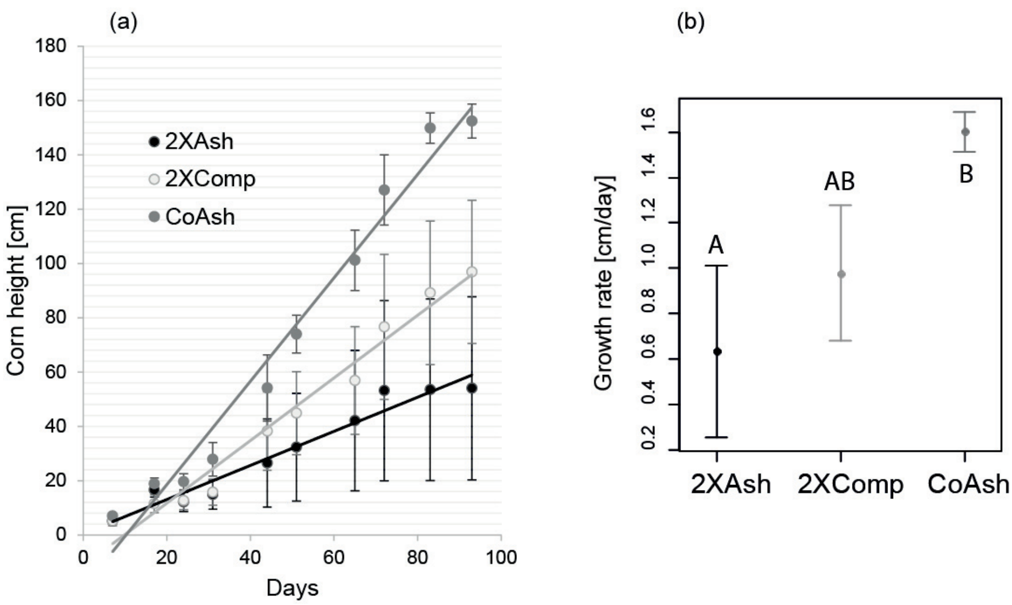

Figure S5.2 a) mean maize height (according to the different soil treatments and growing periods. Linear regression lines are given for each soil treatment. b) Growth rate, assessed as mean values for the slopes of the linear regressions. Different letters denote significant differences between soil amendment treatments (Tukey tests, $P \leq 0.05$).

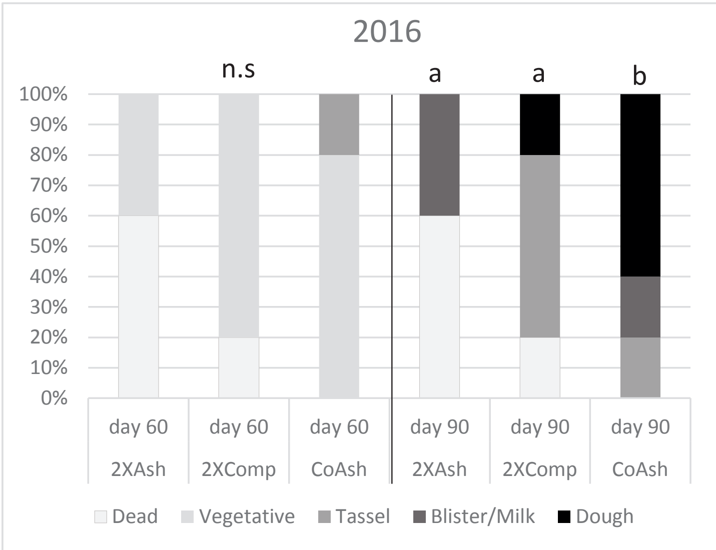

Figure S5.3 Percentage of the maize plants reaching a particular reproductive stage according to the different soil treatments and two periods (day 60 and day 90) during the growing phase. Different letters denote significant differences between soil amendment treatments (Contrast tests, $P \leq 0.05$).

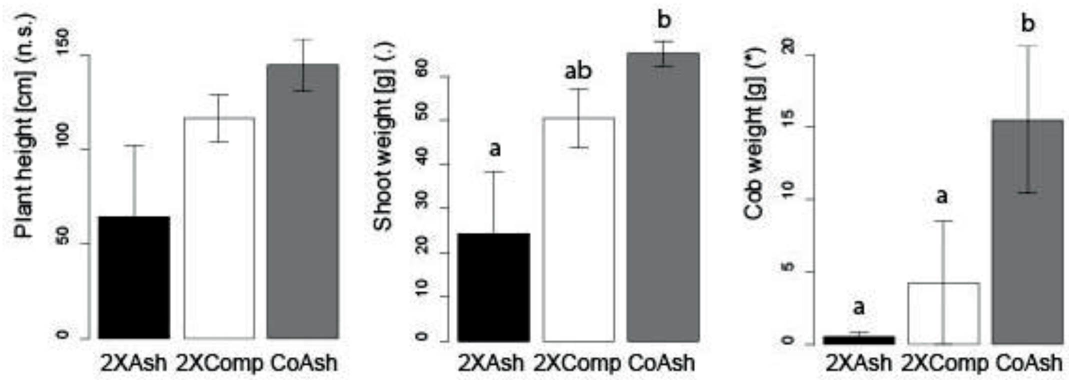

Figure S5.4 Mean values (± SE) for maize plant traits according to the different soil treatments, at the end of the growing season. Asterisks indicate significant effect of treatments ($P < 0.001$ = ***; $P < 0.01$ = **; $P < 0.05$ = *; $P < 0.1$= ·). Different letters denote significant differences between soil amendment treatments (Tukey tests, $P \leq 0.05$).

Table S5.3 Summary of linear regression models for the maize growth experiment in 2016, using maize response variables according to the different soil treatments. Significant values are in bold.

Slopes	**Treatment**	
	F	*P*
Regression slopes for growth rate	2.955	**0.0905.**
Day 60	1.385	0.268
Day 90	7.609	**0.00239 ****
Plant height [cm]	3.006	0.1
Shoot weight [g]	4.066	**0.0552.**
Cob weight [g]	6.206	**0.0202***

- CHAPTER 6 -

Implementation perspectives of a new soil fertility management in traditional slash-and-burn cultivation in Madagascar

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In preparation

Picture: Teaching composting techniques in Kirindy forest
Leia Falquet, 2014

Abstract

In Kirindy forest, on the western coast of Madagascar, farmers have practiced slash-and-burn agriculture for generations. Yet, since 50 years, important human migrations have led to a highly populated region, with concomitant increase of pressure on the forest. The fallow periods were reduced from 8 to 4 years with negative impacts on the forest cover and the soil fertility. Thus, finding alternatives to slash-and-burn agriculture and new strategies for soil fertility management become urgent. This study draws mainly from a sociological approach and is supported in a later stage by agro-ecological measures. We specifically a) assess farmer's actual knowledge, interest and adoption potential of composting techniques, b) investigate the possible fit of the tasks of compost production compare to farmers' cultivation calendar along with the quality of the composts achieved. We performed a Rapid Rural Appraisal (RRA) to understand farmer's knowledge on soil fertility techniques, and we conducted ten participating workshops with a total of 500 farmers (13% of the villages population) to determine how composting practices could be uptaken by the population. Then, an experiment was set up to assess the maturation rapidity and the quality of composts composed of three common tree species, each species separately, as well as mixed together. We demonstrated that the existing barriers to implement such soil fertility management were linked mostly with watering constraints for compost maintenance, and also conflicts with other daily tasks. At the same time, results showed that mixing green residues from different local tree species can lead to equilibrated, fast maturating, composts.

Keywords
Shifting cultivation, rural households, tropical forest, plant nutrient, compost quality, rapid rural appraisal

6.1 Introduction

Slash-and-burn agriculture is widely used in the tropics, and represents a main driver of deforestation in Madagascar, where more than 80% of its population are depending directly on the agricultural sector (Waeber et al., 2015). On the western coast of Madagascar, in Kirindy forest, important human migration have led to a highly populated region, with concomitant increase of pressure on the forest. The fallow periods were reduced from 8 to 4 years with negative impacts on the forest cover and the soil fertility (Jarosz, 1993). The deforestation rate strikes now at an annual 2.6%, which corresponds to a loss of 1’820 ha per year (Zinner et al., 2014). At that speed, the forest may have entirely been replaced by agricultural lands by 2050 (Zinner et al., 2014). In slash-and-burn agriculture, forest is transformed to agricultural land by clearing a forested area and burning the slashed trees. Due to yield decrease and weed invasion, farmers generally abandon quickly their parcels to move further in the primary forest and convert new areas into agricultural lands. As a result, the primary forest disappears gradually, whereas large degraded land areas appear.

Restricted political and economic resources have hindered Madagascar Government from regulating the intrusion of agriculture in forested areas, although slash-and-burn agriculture, or *tavy* in malagasy, is formally forbidden since 1881 (Brimont and Karsenty, 2015). In fact, since that date, multiplied strategies were employed to halt that practice with almost no success (Desbureaux and Brimont, 2015; Poudyal et al., 2016; Zinner et al., 2014). Those strategies varied from very strict measures like the complete ban of fires during the colonial times (Jarosz, 1993) to modern approaches like Community-Based Natural Resource Management (CBNRM; Dressler et al., 2010, Rasolofoson et al., 2015), Payment for Environmental Services (PES; Brimont and Karsenty, 2015) or REDD+ conservation actions (Networks for reduction of carbon emissions from deforestation and forest degradation; Poudyal et al., 2016). Two main reasons were advanced for their successive failures in preserving the forest: first, an insufficient involvement of local farmers, especially during the development steps of new resource management schemes (Marie et al., 2009; Rives et al., 2013), and second the non-recognition of the cultural importance of *tavy* for the indigenous communities (Desbureaux and Brimont, 2015; Hume, 2006; Scales, 2012). Indeed, from the perspective of local households, slash-and-burn practices are associated with rituals which permit to manage soil fertility, while in the same time, satisfy gods and ancestors (Hume, 2006; Scales, 2012).

To start a smoother and socially more acceptable shift in the agricultural practices, an alternative initiative, and not much studied, would be to modify slash-and-burn cultivation and making it sustainable in a first step, rather than suppressing it (Desbureaux and Brimont, 2015). This could potentially work in Kirindy forest where farmers declare willing to test alternatives, especially natural fertilization means, like manure or compost amendments (Dirac Ramohavelo, 2009). Compost enhances both water- and nutrient holding capacity of the soil (Zhang et al., 2016). It has been shown to increase plant yields in numerous studies

(Abdel-Sabour and El-Seoud, 1996; Mbau et al., 2014; Zhang et al., 2016). A field experiment in Kirindy demonstrated the efficiency of amending the soil with a combination of compost and wood ashes (from slash and burn agriculture) to sustain corn production on tropical acidic soils (Gay-des-Combes et al, in press). Compost mixed with ashes enhanced corn growth rates, advanced plant maturity and increased final corn yields by 4 to 5 times compared to traditional slash-and-burn agriculture (Gay-des-Combes et al, in press). In order to obtain a suitable compost amendment, two key tasks should be performed by the farmers: first, the collection and preparation of leaves and branches and second, the compost maintenance throughout its maturation by mixing and watering the green material. Compost maturation can last about 6 to 18 months depending on the surrounding humidity and temperature and is obtained once compost physicochemical properties are stabilized (Albrecht et al., 2008).

However, implementing new soil management techniques, such compost amendment, can be sometimes slow in rural communities, because of various physical and psychological barriers such time constraints, general community interest, conflicts with other tasks in the field, fear of change, peer pressure, etc. (Fleskens and Jorritsma, 2010). As compost maintenance requires a weekly work during a consequent period of time, farmers have not only to be interested to adopt this strategy, but also to be willing to accept to invest time in composting. Therefore, given the agronomical and ecological benefits that could be brought through compost amendment, but also the uncertainties surrounding its implementation perspectives, the present study aims to: a) assess farmer's actual knowledge, interest and adoption potential of composting techniques, b) test the possible fit of the tasks of compost production compare to farmers' cultivation calendar along with the quality of the compost achieved. To reach those objectives, a Rapid Rural Appraisal approach (RRA) was used, followed by several composting workshops with local farmers and finally, an agro-ecological experiment of compost maturation with different combination of tree species.

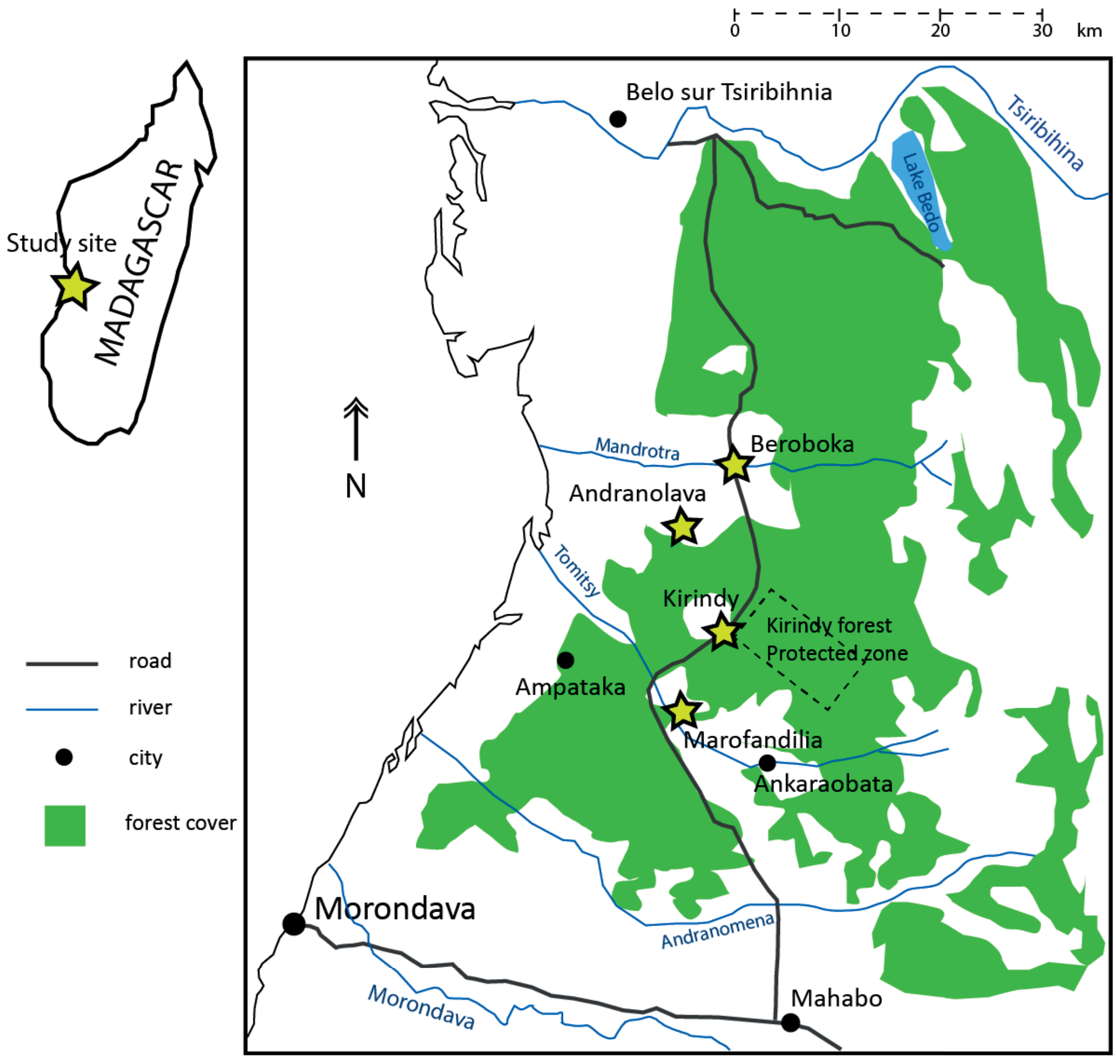


Figure 6.1 *Geographical location of the studied villages in the Kirindy forest, Central Menabe (Gay-des-Combes et al., 2017, originally adapted from Scales, 2012)*

6.2 Methodology

6.2.1 Study site

This study took place in the Menabe region, more precisely in the Kirindy forest, one of the ultimate large remnant of dry forest in Madagascar (Zinner et al., 2014). The research activities were conducted in and around the villages of Marofandilia (20°07’11.07’’S; 44°33’23.97’’E), Kirindy (20° 00’22.3’’ S – 44° 35’6.1’’ E), Beroboka (20° 00’22.3’’ S – 44° 35’06.1’’ E) and Andranolava (19° 59’39.3’’ S – 44° 35’15.8’’ E). The largest nearby city is Morondava, located on the coast, at the northern forest border (Fig. 6.1). Those four villages were chosen because they are the centre of large deforested areas caused by slash-and-burn agriculture (Dirac Ramohavelo, 2009). The climate of Central Menabe is classified as tropical dry with 2 distinct seasons, a rainy (November to March) and a dry season (April to October), and with an average annual temperature of 26°C (Sorg and Rohner, 1996). Average total precipitation is around 800 mm per year, concentrated between November and March. Vegetation is dominated by dry deciduous forests of various types as described in (Koechlin et al., 1997). Farmers mainly cultivate corn (Dirac Ramohavelo, 2009) with a cultivation calendar following the rainy season (Table 6.1; Gay-des-Combes et al., 2017).

6.2.2 Social appraisal using Rapid Rural Appraisal methods

Rapid Rural Appraisal methods (Chambers, 1981; Schut et al., 2015) were used to determine 1) farmers knowledge and interest for compost amendments, 2) the cultural cultivation calendar in Kirindy forest. The investigation was performed between March and April 2015.

First, preliminary semi-structured interviews were conducted with 40 random households in Andranolava (11 households), Beroboka (15 households) and Kirindy (14 households) villages. We chose the household as unit of the study because the work organization and the economic decisions are usually carried out within that unit (Becker, 1991). Households were constituted by 3 to 10 people, leading to a number of 250 participants. Men and women were equally represented. Each interview were carried out according to the ethical framework described by Wilmé et al. (2016) with prior consent of each participant and ensuring their anonymity. The three villages were chosen because, although they vary by their size and their ethnic groups, farmers commonly practiced slash-and-burn agriculture. Together, they represent well the local communities of Kirindy forest. Also, they are all easily accessible by the road and receive regular visits from NGOs, tourists and visitors in general, making the interviews easier to perform.

The semi-structure interviews were performed according to a list of broad questions about the local farming system and the farmer’s current knowledge and interest about natural fertilization methods. Farmers were first asked to answer by ‘yes’ or ‘no’ to 6 broad questions and then to freely detail their farming practices in the frame of each question (Table S6.1, Supplementary material). Later, farmers had to rank four reasons why they would use compost (Fig. 6.2). Points (from 1 to 4) were given for the first (4 points) to the last (1 point) reason ranked by each household. The overall ranking was calculated by summing the scores given by each household and standardizing the result on a scale from 0 to 100.

About 1h was taken for each interview. The interviews were translated by a Malagasy student and supervised by a respected senior farmer of the region. He introduced each household to the interviewing team to ensure a smooth and confident atmosphere during interviews. In a second step, he played also the role of key informant to cross-check the results of the surveys. Finally, to ensure that both the interviews and the translations were correctly done and understood, direct observations were made through village and field walks to visually confirm what was declared earlier during the interviews.

6.2.3 Composting workshops

Composting workshops were performed in villages in order to double-check farmer's willingness in adopting compost amendments from the RRA outcomes and to verify for social or technical barriers for implementation.

Five workshops were undertaken in Beroboka and four in Kirindy. Several workshops were carried out in the same place to establish a deeper trust between the teaching group and the village community, as well as to reach a good understanding of the needs and motivations of the farmers (Sinclair and Walker 1998a, Dixon et al. 2001). In addition, a single workshop was also conducted in Marofandilia village. The workshops were usually announced one week before in each village. The information was given to the president of the village, as well as knowledgeable and public people (such as local guides, shop keepers, member of the local farmer association), who were responsible to relay the information to farmers.

As a general rule, the workshops were taught directly by Malagasy people to avoid translation work and favor a better takeover of the knowledge by locals. The focus of the workshops was on compost and corn yield. In a first step, people were invited to describe and touch the compost, and to observe the differences of corn cobs grown in slashed-and-burnt fields with those grown in slashed-and-burnt fields amended with compost (obtained from the experiment described in Gay-des-Combes et al., in press). Compost production and use were then explained to the assembly. Posters and booklets were distributed to support the training. Those documents were written in Malagasy (Fig. S6.1). Each workshop lasted about 45 minutes to 1 hour. Farmers were free to interrupt, ask questions and express their opinion during the workshop. It was proposed to build, the following day, compost pits with motivated farmers. For each workshop, the number of participants was recorded, as well as the number of built compost pits. We also recorded the time taken to create a pit, collect the composting material and the volume attained.

Path analyses for abandoned pits

After 7 months, the number of maintained pits was recorded. When compost pits were no longer maintained, we elicited the cause of the abandonment with the farmers. To understand the main mechanisms leading to compost pit abandonment, we established a structural equation model (SEM; Grace et al. 2010, 2012). First, we summarize the answers into binary variables which focused on the causes and reasons why compost pits were abandoned. Then, we transformed the resulting matrix into a similarity matrix using Jaccard index and used it as a co-variance matrix to perform the SEM. We built an a priori conceptual model of hypothesized causal relationships within a path diagram (Fig. 6.3; Table S6.2; Grace et al. 2014). The adequacy of the model was determined using chi-square tests, standardized root mean square residual index (SRMR), root mean square error of approximation index (RMSEA), Akaike value (AIC) and good fitness index (GFI). Adequate model fits are indicated by non-significant differences when comparing the predicted and observed correlation matrices (chi-square tests with $P > 0.05$), by lower AIC, RMSEA < 0.05, SRMR < 0.05 and GFI > 0.95 (Grace et al., 2010). The structural equation model was performed with the R package sem (Fox, 2006).

6.2.5 Composting experiment

A composting experiment was run to measure the maturation efficiency over four months of different compost combinations, as well as their quality. Building on previous experiments in Kirindy forest which demonstrated the positive impacts on the soil of a compost made with three tree species (Gay-des-Combes et al., in press), we use the same species here. We tested them both individually and together. The species used were *Poupartia sylvatica*, *Tarenna sericea* and *Fernandoa madagascariensis*.

Experimental design

The tree material for the compost was collected mid-November 2015. Branches (< 2 cm in diameter) and leaves from *Poupartia sylvatica*, *Tarenna sericea* and *Fernandoa madagascariensis* were harvested in the secondary forest near the village of Andranolava (20° 00’22.3’’ S – 44° 35’06.1’’ E). Further, plant material was cutted in pieces of 1 to 2 cm length. Subsequently, 4 types of compost were made with 3 replicates for each type: i) only residues from *Poupartia sylvatica* (designated as P compost further in the text), ii) only residues from *Tarenna sericea* (T compost), iii) only residues from *Fernandoa madagascariensis* (F compost), iv) mixtures of residues from the three species (M compost). At the end, a total of 25 L of green residues was disposed in 12 wooden boxes open at the bottom so that the compost was in contact with the soil. The boxes were disposed, according to a randomized design, in a garden in the city of Morondava, under a roof to protect them from direct sunlight and heavy tropical rains. They were watered once a week with 3 L of water. Further, every fortnight the material in the pit was thoroughly mixed.

Compost maturation assessment

Compost fertility parameters were measured after four months of maturation. A sub-sample of 500g of each compost was taken for laboratory analyses. The samples were sun-dried and sieved at 2mm. The fractions of coarse (>2mm) and fine (<2mm) material were weighted after sieving. Soil pH was measured in a 1:2.5 soil:water suspension (v:v) (Allen, 1989). A standard CHN analyser served to measured Total C and N on crushed soil (Dumas method). Extraction solutions were prepared for exchangeable cations (Cobalt-hexamine solution, Co(NH3)Cl3 0.0166 M) and inorganic nitrogen forms (KCl 0.5 M). Both extractions were performed on 10 grams of dry compost with 40 ml of solution, then shaken for one hour at 120 rpm and filtered at 0.45 µm. Inorganic nitrogen forms were assessed colorimetrically using a continuous flow analyser. Exchangeable cations were measured with a plasma atomic emission spectrometer SHIMADZU ICPE-9000. Finally, phosphorous was extracted with 0.03 N Ammonium fluoride (NH_4F) and 0.025 N hydrochloric acid (HCl) as proposed for acidic soils (Bray and Kurtz, 1945). We used 3 g of soil with 20 ml of NH_4F/HCl solution. After shaking for 15 minutes, extracts were filtered. Phosphorous concentration in the extracts was measured by colorimetry with an ammonium paramolybdate - stannous chloride dehydrate colorimetric reagent. Absorbance was measured with a UV/VIS spectrometer at 660 nm.

Statistical analyses

Maturity parameters (ratio C/N, pH, ratio of fine material vs coarse material, CEC) of the compost combinations, as well as their final contents, were analyzed to assess whether differences exist between the different combinations. First, we used an analysis of variance (ANOVA) to check if the parameters were globally different. Then, Tukey post hoc tests were run to assess pairwise differences. Some values were log-transformed before analysis to fulfil the assumption of normality and homogeneity of variance. The analyses were achieved in R (R Development Core Team, 2013).

6.3 Results

6.3.2 Rapid Rural Appraisal

Interviews and field walks permitted to establish a cultivation calendar for the main cultivated crops in Kirindy forest (Table 6.1). Planting of the various crops mainly occurs around 15th December, just before the rainy season, whereas slash-and-burn work takes place during the dry season over the summer. Only the months of January and February have no particular task assigned. However, they are also the months where tropical cyclones can occur, flooding roads and fields and making them impassable and inaccessible (Gay-des-Combes et al., 2017). Between September and November, the works is also reduced, constituting only in burning the dry accumulated wood to prepare the fields.

***Table 6.1** Kirindy cultivation calendar adapted and amended from* (Gay-des-Combes et al., 2017)*)*

	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Rainy season							■	■	■	■		
Cyclone peak period								■	■			
Tree slashing	■	■	■	■								
Tree burning					■	■						
Corn seeding							■					
Corn harvest	■											■
Groundnut seeding							■					
Groundnut harvest										■	■	
Cassava planting							■					
Cassava harvest		■	■									

When surveying about fertilization means apart from slash-and-burn agriculture, most villagers knew about zebus manure and its potential to increase crop yields. Hence, concerning compost, most people had no knowledge about that technique, neither its associated benefits (Fig. 6.2). In general, villagers declared themselves interested to acquire knowledge on compost techniques (Fig. 6.2). They were also open in investing extra labor in compost production if it would allow them to have higher yields (Fig. 6.2). However, they declared that food security is of first importance, before biodiversity and forest protection. Thus, they would use compost to improve their yields in priority (Fig. 6.2). In general, farmers wish to improve their agriculture techniques, but state to have no knowledge to do it. Critics were especially formulated towards some former research/conservation projects in the region, which had not disseminated properly the results, neither ensured a follow-up at the population level. Farmers were aware of studies having been done on their livelihoods, but could not explain the scope, nor the outcome of those studies. Thus, most villagers are currently skeptical about the engagement of conservation NGOs and scientists in helping them.

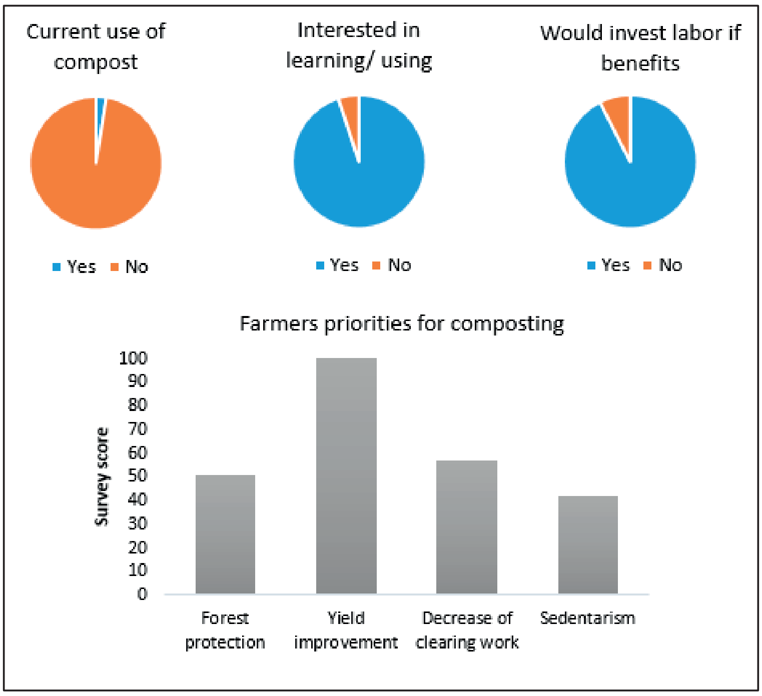


Figure 6.2 *Household survey in Beroboka and Kirindy village (March 2015). Number of positive and negative answers for some questions for a total of 40 households and farmers priorities for composting.*

6.3.2 Workshop outcomes

The number of attendees varied between 30 to 70 people for each workshop, reaching a total of about 500 farmers, i.e. 13% of the total population (Table 6.2). The percentage of women was moderate, reaching about 30% at its maximum (Table 6.2).

Table 6.2 *Workshop outcomes*

Village	Inhabitants	Ethnic group	Workshops	Averabe nb people/ workshops	Total nb people (women)	Compost pits	Maintained after 7 months (by women)
Beroboka	1600	Sakalava	5	60	302 (72)	21	7 (5)
Kirindy	500	Tandroy	4	33	133 (26)	11	2 (0)
Marofandilia	1800	Tandroy/ Antesaka	1	57	57 (23)	3	0 (0)
TOTAL	**3900**	-	**10**	-	**492**	**35**	**9 (5)**

During the practical parts of the workshops, the time recorded to build a compost pit and prepared the material varied from 5 to 6 hours for two men: 1h to dig the compost pit, 1h to collect about 50 kg of wood and 3h to 4h to chop it. The quantity obtained was around 300 liters. As one liter is needed to amend one maize bunch, i.e. about 3 maize plants, 900 maize stems could be amended with that compost. As the planting density is about 1.3 plant m^{-2} (Gay-des-Combes et al., 2017), this would correspond to a field of 700 m^2.

A total of thirty-five compost pits were built by the farmers after the workshops, each pit being managed by about 5 persons (Fig. S6.2). Thus, around 30% of the attendees built their pit. However, after 7 months, only 9 compost pits (over the 35) were still well maintained, i.e. the compost was watered and mixed every week (Table 6.3). Concerning the unique workshop performed in Marofandilia, a comparable number of people than in Kirindy and Beroboka participated. A smaller number of pits were created (3 pits). None of them was maintained through time.

Structural equation modeling showed that compost pit abandonment was mostly driven by men (Fig. 6.3, path = 0.68) and in a lesser extent by women (Fig. 6.3, path = 0.31). The model showed that the lack of time (Fig. 6.3, path = -0.41) and of motivation (Fig. 6.3, path = 0.83) were the main drivers leading men to abandon compost fields. For women, the distance to the water well (Fig. 6.3, path = 0.91) was the main variable explaining why they tended to abandon compost pits.

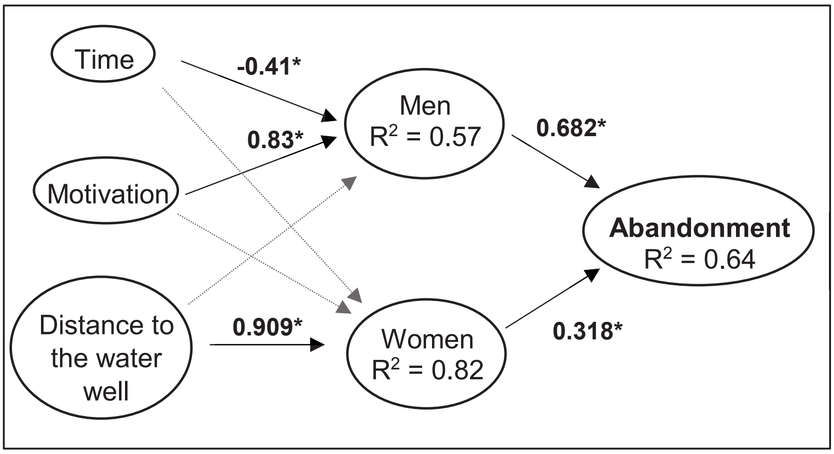


Figure 6.3 *Structural equation model for the social data. Asterisks show significant relationships (pathways) between variables and numbers next to arrows show standardized parameter estimates (i.e. standardized regression weights). Grey dotted arrows correspond to non-significant relationships which were removed from the model for stability reasons. Squared multiple correlations (R^2) for the predicted/dependent factor are given below the dependent variables. All model fit indices were good: chi-square = 3.38, P = 1, GFI= 0.91, RMSEA= 0, SRMR= 0.49 and AIC = 27.38.*

6.3.3 Compost maturation and quality assessment

When assessing the maturity stage of the different composts after four months, it appears that the maturity was advanced but not yet reached (Fig. 6.4, Fig. S6.3), F and M composts being closer to maturation than P and T composts. M compost seems to be the most balanced compost in terms of nutrient compositions (Table 6.3).

The four compost types showed several significant differences with respect to the measured maturity indicators (Fig. 6.4, Table 6.3). Concerning pH, only compost P (*Poupartia sylvatica*) seemed below the maturity threshold of 7, while compost M (Mixed of 3 species) was near 7 and composts T (*Tarenna sericea*) and F (*Fernandoa madagascariensis*) were slightly basic, reaching pH values of 8.2 and 7.8, respectively. With respect to C/N ratio, F and M composts were the closest to the maturity threshold of 17 by reaching a ratio of 22 and 24, respectively, while the two other composts had still very high values (>36) and were therefore at a less mature stage. CEC was lower for compost T (below 60), but similar for all other composts (> 72). The ratio of fine to coarse material showed that compost P had the most advanced degradation with the highest ratio (about 0.5).

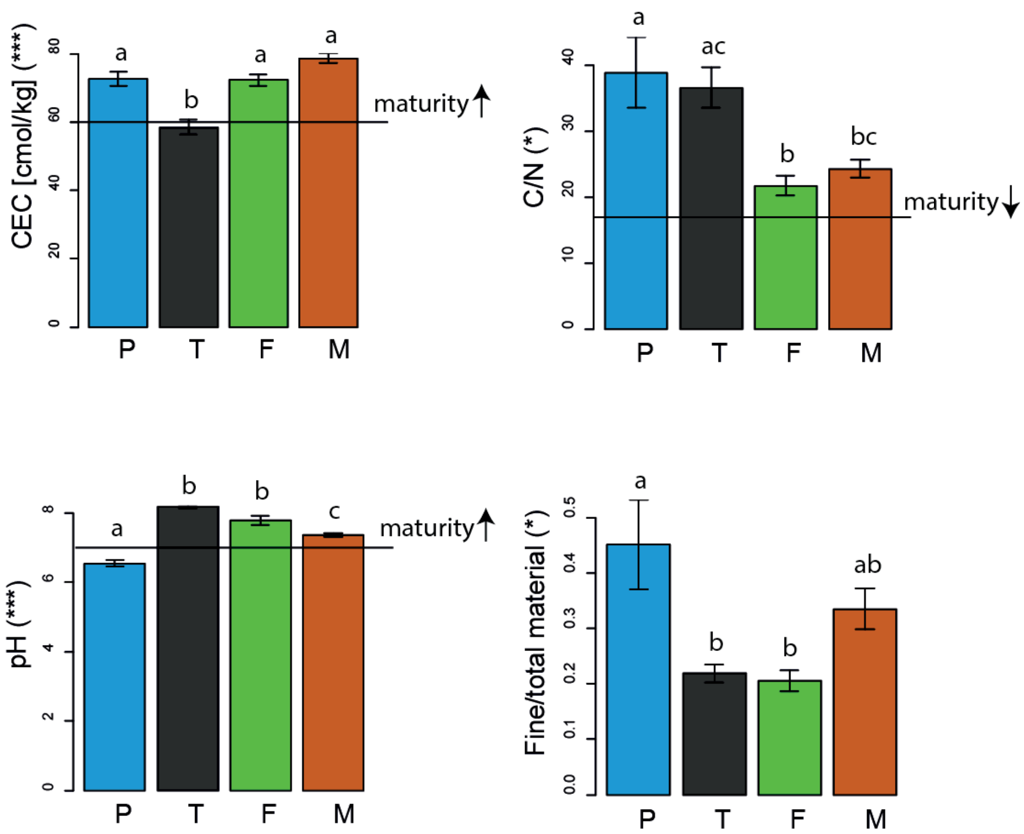


***Figure 6.4** Maturity of the different compost types at the end of the rain season (i.e. 4 months maturation). P: Poupartia sylvatica compost; T: Tarena sericea compost; F: Fernandoa madagascariensis compost, M: mixture of the three species. CEC: cation exchange capacity. P-values for significant differences between the four compost types are given in brackets (ANOVA). Significant difference between each compost type are indicated with different letters (Tukey's Post Hoc test). Maturity level for each indicator is indicated with the horizontal line and arrow. The maturity reference for CEC was 60 as in Jimenez and Garcia (1991), for C/N ratio it was 17.9 as in Hirai et al. (1986) and for pH is was 7 as in Francou (2003).*

Finally, concerning the nutrient content of the various composts, potassium was highest in compost F (Table 6.3, $P = 0.021$), calcium in composts T and M (Table 6.3, $P = 0.014$), nitrogen in compost F and M (Table 6.3, P = 0.034) and magnesium was present only in compost P (Table 6.3, P = 0.053). Phosphorus and carbon did not differ significantly between the different compost types (Table 6.3, P > 0.05). Overall, the mixture of the three species (M) seems to yield, after four months, the most balanced compost for agricultural purposes (Table 6.3, Figs 6.4 & S6.3).

Table 6.3 *Mean (±SE) of some variables of the different compost types after 4 months of maturation. P: Poupartia sylvatica compost; T: Tarena sericea compost; F: Fernandoa madagascariensis compost, M: mixture of the three species. CEC: cation exchange capacity. P-values for significant differences between the four compost types are given.*

		P	T	F	M	*P* value
CEC	cmol kg^{-1}	72.72 ± 2.10	58.51 ± 2.17	72.37 ± 1.65	78.82 ± 1.37	<0.001
P	mg kg^{-1}	33.00 ± 5.57	27.93 ± 3.44	35.00 ± 3.20	30.36 ± 1.37	n.s.
K	mg kg^{-1}	4080 ± 1900	7046 ± 650	12920 ± 1235	9280 ± 180	0.021
Mg	mg kg^{-1}	3180 ± 383	2313 ± 78	2333 ± 147	2913 ± 52	0.053
Ca	mg kg^{-1}	5100 ± 503	6013 ± 190	4193 ± 396	6013 ± 40	0.014
C	mg g^{-1}	437.07 ± 2.55	443.92 ± 1.84	391.54 ± 53.19	441 ± 4.03	n.s
N	mg g^{-1}	11.60 ± 1.37	12.25 ± 0.91	18.12 ± 2.78	18.21 ± 0.83	0.034
C/N	-	38.95 ± 5.38	36.68 ± 3.06	21.78 ± 1.51	24.33 ± 1.37	0.012
pH	-	6.55 ± 0.09	8.17 ± 0.03	7.78 ± 0.13	7.36 ± 0.06	<0.001
Mn	mg kg^{-1}	24.27 ± 2.94	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	<0.001
Fine/tot material	-	0.45 ± 0.14	0.21 ± 0.03	0.20 ± 0.03	0.33 ± 0.06	0.017

6.4 Discussion

Generally, local farmers had very little knowledge about composting, but they were interested in alternative agricultural practices. They pointed out the lack of restituting information from previous research and conservation projects in the region. There is apparently a communication gap between scientists and the people targeted in their studies. However, result restitution were often included in scientific research programs (Cabalzar, 2015). Most probably, follow-ups on the long term and sufficient partnerships with local farmers association were missing (Rives et al., 2013). Therefore, the information had not the time to circulate properly and to reach a significant amount of local farmers. The transmission of knowledge could have also failed because of the significant population movements within the forest. Thus, the people who have been taught of a project outcomes may not live any longer in the forest. Indeed, during our field missions, we could observe numerous moves of families from one village to another or from the forest to the exterior and vice versa. The unsecure land tenure, the climate instability and the traditional nomadism of some ethnicities lead naturally to a high number of migrations in and out of the forest (Jarosz, 1993; van Vliet et al., 2012).

The first worry of the farmers during the workshop was the amount of compost needed to amend a satisfying field area. The labor required to produce sufficient compost could be a potential barrier to implementation. We recorded that for one day of work, 700 m2 of crop field could be amended. Considering that most farmers possess 0.5 to 1 ha (Dirac Ramohavelo, 2009), they would need about 14 to 20 days to produce enough compost to cover their entire fields. Besides, if farmers prune all the trees in the secondary successions, they may harm the ecosystem anyway and could even incentivize deforestation. Therefore, we would rather recommend compost as a tool to sustain cultivation on the most degraded fields, rather than a solution for large scale fields.

When farmers were asked why they gave up on maintaining theirs pits, the reasons were mostly the watering constraints on a long duration. Women seemed better at maintaining the compost pits than men. Collecting the water at the water well is generally a woman task (Dirac Ramohavelo, 2009). Therefore, taking care of the pit probably fits better with the traditional tasks of women in the region. In addition, numerous zebu thefts were recorded in the region and men were busy, away from the house, to deal with those problems. This could be the reason why they did not find the time or the motivation to maintain the compost pits. On the other hand, women were abandoning their pits because carrying extra buckets of water for the compost was too fastidious for them. The distances between the pits and the water wells were too long. Furthermore, a severe drought happened in the region in 2016, leaving most households water limited. Using extra water to keep the moisture of the compost at an adequate level undoubtedly became irrelevant compared to their other needs. With global warming, droughts are expected to increase, worsening the conditions for households and preventing the adoption of composting. Yet we argue that this problem could be mitigated by organizing the pits around water wells. We would not recommend to perform compost maturation during the rainy season and to water the pits with the rains. The strong rains of the region could cause a strong leaching of the compost nutrients, reducing significantly the compost quality (Gay-des-Combes et al., 2017). Besides, the compost leachates could also pollute the neighboring water sources because of their high nitrate content (Sorrenti and Toselli, 2016).

When assessing the rapidity of compost maturation, it appeared that the mixture of 3 species compost (type M) was the fastest in attaining the maturity and the most balanced compost in terms of nutrient composition. This kind of compost would be ready for field disposal in about five to six months, reducing slightly the maintenance work compare to single amendment composts. According to the outcome of workshops, the compost maturation is the most challenging task and may prevent the implementation of that technique in the region. Consequently, a short maturation would potentially make an easier implementation. By preparing the compost of type M in November, it would be ready for April, before corn harvest and extensive field works, ensuring a better integration of that task in the cultivation calendar. Finally, the nutrient content of a compost, along with its potential effects on soil properties, is strongly dependent on the tree material (Lima et al., 2004).

Kitchen waste or grass residues would probably contribute to higher nitrogen contents. Indeed, nitrogen content has been reported to reach values of 40 g of N/ kg in kitchen waste/grass composts (Mokolobate and Haynes, 2002), while in our study we reached only about 12 g of N/kg. Nonetheless, a compost derived from trees has the advantage to be up-scalable because of the higher availability of material compare to kitchen waste (very limited in rural areas) and safer than grasses which could propagate seeds and led easier to field weed invasion (Randriamalala et al., 2015).

6.5 Conclusion

The particular proposed technique could probably not be extended at the forest scale due to labor constraints. However, it could be used as a tool to sustain cultivation on the most degraded lands and to alleviate the deforestation in the primary forest remnants. The most interesting outcome of this study is probably the high interest that people demonstrated. Even though, most of the compost pits could not be maintained through time, 13% of the population still participated in the 10 organized workshops. That number is significant given the very limited publicity done for the workshops and considering that we did not try to convince anyone for attending. Adopting a modest position throughout the study, following farmers' wills rather than trying to convince people, give more freedom to local people and allow their empowerment. However, our study showed that they should also remain accompanied punctually during the first years of the introduction of the new practices. This would allow to find technical or social solutions to cope with unforeseen events like drought. In conclusion, changing the agricultural practices is challenging task and a thorough co-design with the farmers is necessary at every stage of the process: from the workshop stage to the maintenance of the pit and the use of the compost. Finally, identifying slash-and-burn agriculture as a cultural heritage and attempting to make it sustainable opens the way towards a modern vision of traditional agriculture, which could fits within tropical forest conservation strategies.

Chapter 6 supplementary material

Table S6.1 Household survey in Beroboka and Kirindy village (March 2015). Number of positive and negative answers for some questions for a total of 40 households.

Questions	**YES**	**NO**
1. Are you using compost?	1	39
2. Are you aware of the benefits of compost for the soil?	0	40
3. Are you interested in trying this technique?	38	2
4. Could you invest more labor in making compost if benefits?	37	3
5. Do you agree to share a compost pit with others?	38	2
6. Is protecting the forest important for you?	36	4

Table S6.2 Components of hypothesis represented by structural equation model of Figure 6.3. A prior-knowledge to build the hypotheses consist in information gathered during interviews and composting workshops.

Path	**Hypothesized mechanisms based on *a-priori* knowledge**
Time -> Men	Men have time constraints.
Motivation -> Men	Men are not motivated in maintaining the pits.
Dist. water well -> Men	Men need to walk to the water wells & carry heavy water buckets.
Men -> Abandonment	Men are susceptible to abandon theirs compost pits.
Time -> Women	Women have time constraints.
Interest -> Women	Women are not motivated in maintaining the pits.
Dist. water well -> Women	Women needs to walk to the water wells & carry heavy water buckets.
Women -> Abandonment	Women are susceptible to abandon theirs compost pits.

Fig. S6.1 Poster for workshops

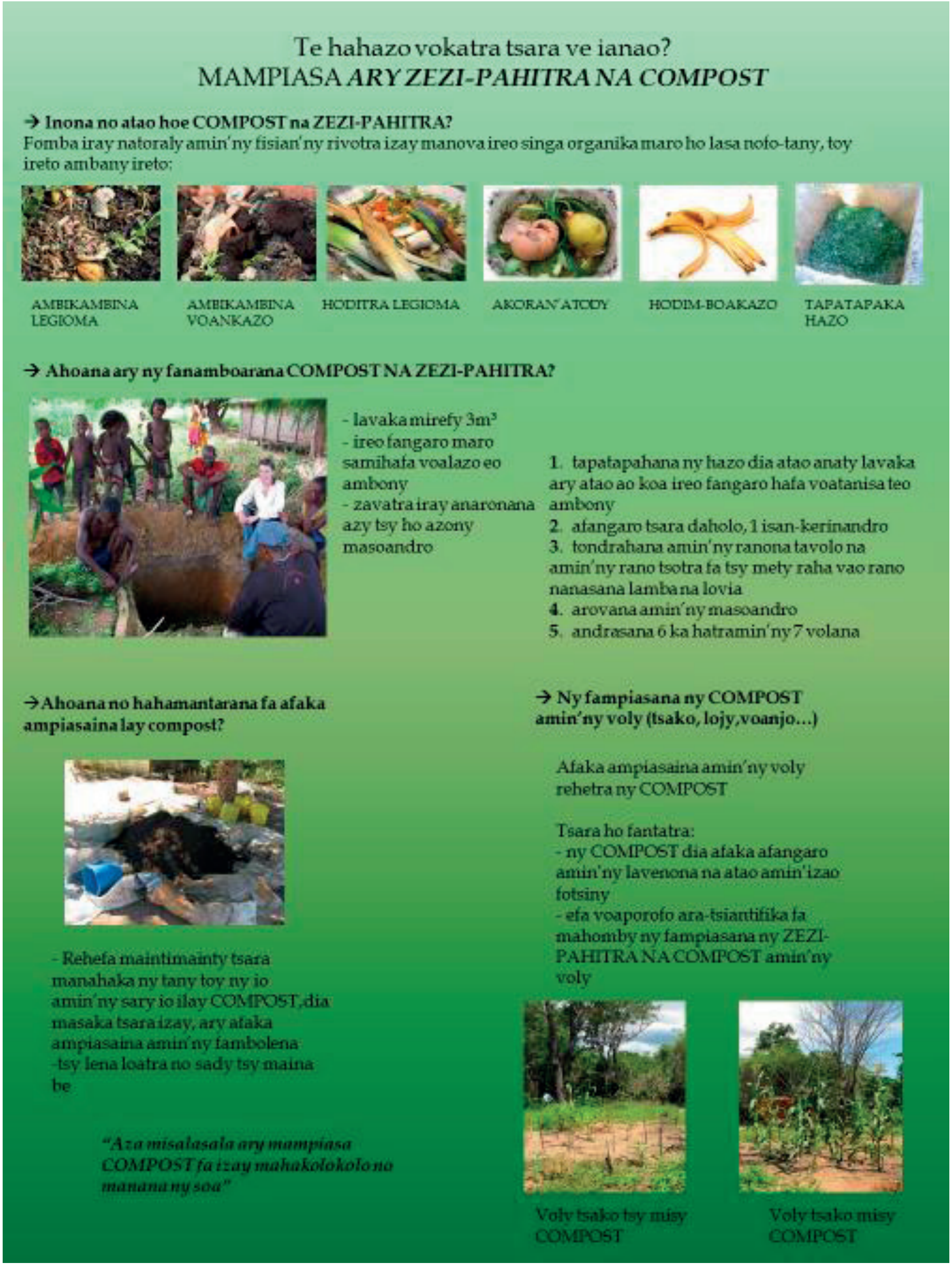
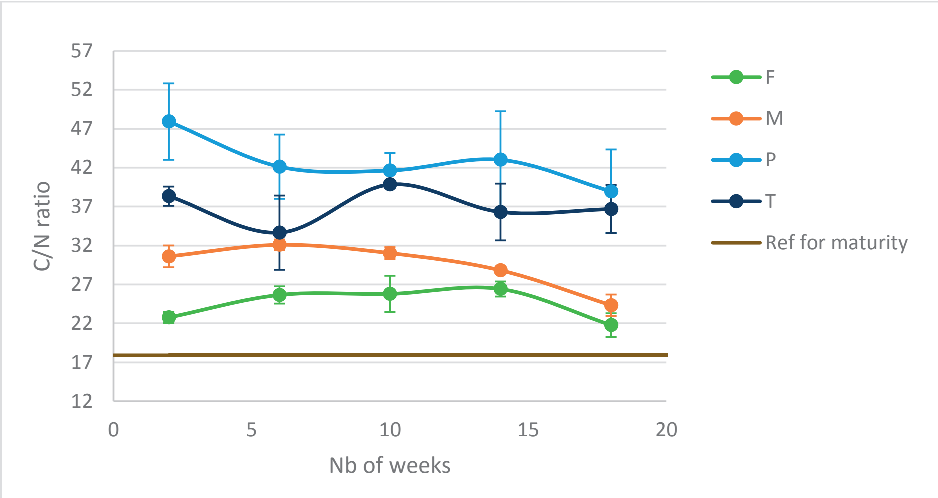
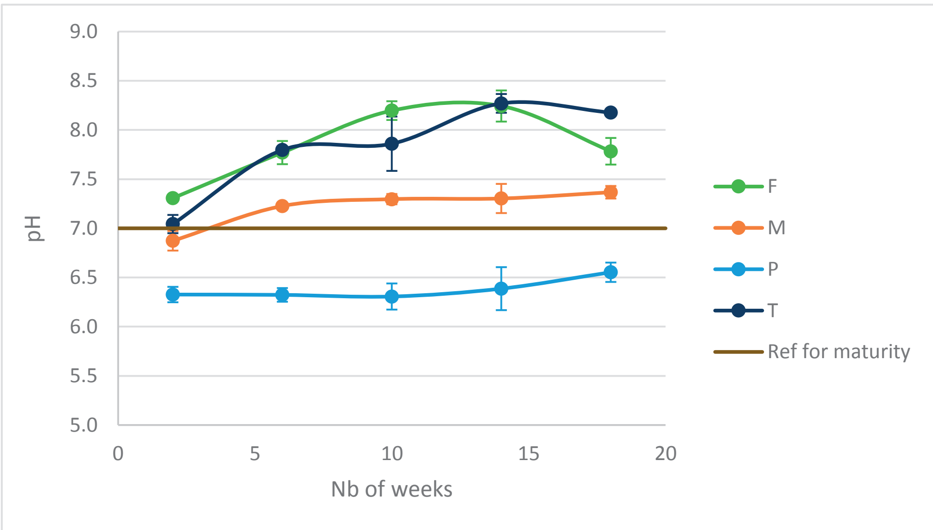


Fig. S6.2 Villagers of the Menabe constructing their compost pits. (Pictures from Lucas Freund, 2016)

Fig. S6.3 Evolution of the mean of various compost maturation parameters through time according to the different compost types





- CHAPTER 7 -

General discussion and perspectives

Picture: Big baobab trees on the outskirts of Kirindy village
Justine Gay-des-Combes, 2014

7.1 Introduction

The objective of my thesis was to study the potential of an alternative slash-and-burn practice which preserves and considers fire as an important agronomical mean to cultivate on tropical soils. Such approach on slash-and-burn agriculture has not been much studied so far, as fire use is considered as destructive for the natural environment. However, that appraoch might be viable as it keeps in place the socioeconomic values of traditional slash-and-burn practice in Madagascar. My research work focused on two aspects:

1) The characterization of the actual agricultural practices in the forest of Kirindy, a dry tropical ecosystem, highly valuable in terms of biodiversity and threatened of rapid disappearance.

2) To study alternatives to slash-and-burn agricultural practices, designed to safeguard the natural dry forest remaining in Western Madagascar.

During three-and-a-half years, I undertook field surveys and experiments in the forest of Kirindy and a series of mesocosm experiments under natural conditions, complemented with laboratory studies. Furthermore, I carried out a series of semi-structured interviews and participation workshops with groups of farmers. By this research, which spans from observational to experimental methodologies and draws from ecology and sociology, I intended to demonstrate the possibility of developing a sustainable slash-and-burn agricultural practice that preserves the socio-cultural values of local farmers. The aim of this chapter is to provide first a synthesis of the key results of the different chapters, along with a few new figures, and in a second step to discuss these results in a wider context. We aim at highlighting the impacts of the current slash-and-burn agricultural system and to provide valuable hints to develop a sustainable alternative.

7.2 The slash-and-burn system in Kirindy forest

Slash-and-burn cultivation cycles go as follow in Kirindy forest: first, a parcel in the forest is cleared by slashing-and-burning the trees, then corn is cultivated during 2 to 4 years before the field is either abandoned and left fallow, or groundnuts are planted during a few more years (Dirac Ramohavelo, 2009; Raharimalala, 2011). In previous scientific literature, the main reasons for field abandonment were singled out as weed invasion and soil fertility decline (Are et al., 2009; Béliveau et al., 2015; Giardina et al., 2000). Our work stays in line with those general considerations, but brings further insights on soil fertility evolution and management in slash-and-burn agriculture (**Chap. 2**, **Chap. 3**).

We used a space-for-time substitution approach in slash-and-burn corn (Zea mays L.) fields to describe the dynamics of soil fertility and crop performance. We demonstrated

(**Chap. 2**) that heavy tropical rains, especially cyclones, can have a much stronger impact on soil fertility and corn yields than plants with their nutrient uptake. Under normal climatic conditions, after three years of cultivation (cycles), a drop in yield of about 38% was recorded after 3 years of cultivation on the same parcel (from 4 to 2.5 t ha^{-1}). On the contrary, after a single cyclone event, the yield decline was recorded to be about 75% (from 4t ha^{-1} to 1t ha^{-1}). Indeed, rain can provoke a rapid leaching of nutrients in tropical soils (Thomaz, 2013), especially because the elements, mostly oxides, brought with the wood ashes are very soluble (Ohno and Erich, 1990; Ulery et al., 1993). In our study, we demonstrated that after three years the soil gets depleted in N, P and K after strong rains, while it became depleted only in N and P under normal climatic conditions. These nutrient deficiencies affected the crop performance and yield significantly. We also identified a legacy effect on soil N and P concentrations of a past cyclone 3 years after its occurrence. This legacy effect was not recorded for K concentrations. Potassium concentrations were replenished faster after the erosion and leaching caused by the rain. This is probably due to the high K content of ashes and because its yearly supply by ashes is superior to corn requirements. Consequently, cyclonic storms may have a long term effect on soil N and P fertility, but a short-term effect on K concentration.

Combining the soil data for total carbon and nitrogen that we measured under normal climatic conditions (unpublished data from the **Chap. 2**, measured during the year 2014 on the same described plots) and data measured previously in Kirindy forest, in the same area, by Raharimalala (2011), we were able to reconstitute the soil fertility over the entire life cycle of a field. Our data (left part of the graphs) represents a chronosequence for cultivated fields from one year of cultivation up to five years and the data of Raharimalala (2011) (right part of the graphs) span along 40 years of field abandonment, once the cultivations were stopped and the field left fallow. Both total carbon and nitrogen soil content show concentrations disposed in a U shape (Fig. 7.1). The cultivated soil drops at a very low fertility level within 5-6 years (-50%), then the soil fertility remains low up to 5 years of field abandonments and finally increases very slowly compare to the rate fertility declines when the fields are cultivated. For five years of corn cultivation, more than 40 years of field abandonment are necessary to build up a fertile soil. This shows that soil barely recover from slash-and-burn agriculture which may explain why the ecosystem sometimes never comes back to tropical forest and rather shifts into savannah.

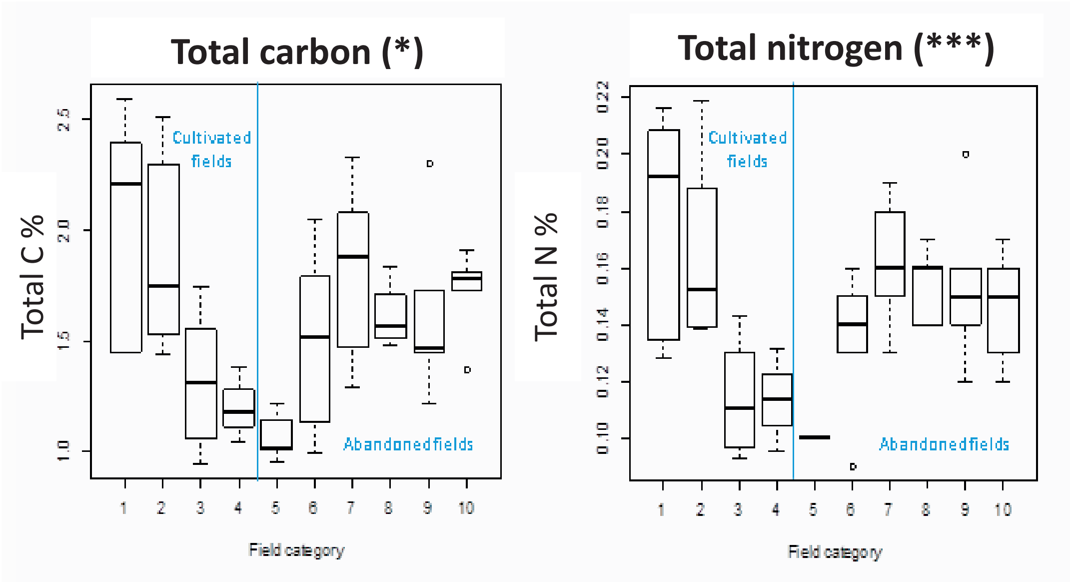


Figure 7.1 *Boxplots of total carbon and total nitrogen for a field life cycle. Field categories 1 to 4 referred to slash and burn cultivation cycles: (1) 1 year; (2) 2 years; (3) 3-4 years; (4) 5-6 years. Field categories 5 to 10 come from Raharimalala (2011) and correspond to ages along a gradient of abandonment: (5) 1-5 years; (6) 6-10 years; (7) 11-20 years; (8) 21-30 years; (9) 31-40 years; (10) more than 40 years.Asterisks indicate significant differences along the field life cycle ($p < 0.001$ = ***; $p < 0.01$ = **; $p < 0.05$ = *; $p < 0.1$= ·).*

In a second step, we elicited the local ecological knowledge (LEK) of farmers in the region through repetitive in-depth interviews with a small set of informants (**Chap. 3**). The results of the interviews were reported in a knowledge base constructed by means of the Agroecological Knowledge Toolkit (AKT) developed by Bangor University (http://akt.bangor.ac.uk/index.php.en). The AKT allowed to translate and codify the knowledge into unitary statements, either single phrases or conditional/causal relationships between objects, processes or actions (Dixon et al. 2001). The unitary statement were analyzed to assess how many farmers share the same detailed knowledge (Sinclair and Walker 1998a, 1998b, Dixon et al. 2001). Through that process, our findings demonstrated that farmers perceive field degradation mainly through weed invasion. Weed invasion seems to be an important concern for farmers. The following statements were extracted from farmers survey : weeds (i) are outcompeting the crops, (ii) can be difficult to remove, (iii) can make the soil harder; also, (iv) burning facilitates weeding; (v) the presence of weeds make tilling more difficult; (vi) there are only few or even no weeds on freshly cleared fields compared to older fields, (vii) cultivating more than three years on the same fields comes at the cost of having more 'bad weeds' and thus necessitates heavy weeding labor. In the ecological knowledge base, we recorded 146 statements related to weeds or weeding, versus 86 statements related to soil fertility. As a consequence, weeds have to be considered as a priority if we want to change the practices and find feasible alternatives for the long term cultivation. Thus, listening to farmers to understand their decision-making processes is crucial before any change is planned.

In the sidelines of the thesis project, a locust pest also damaged the corn fields in 2014, driving the corn yield down to zero on those fields (**Chap. 2**). Migratory locust outbreaks were common in Madagascar those last 6-7 years (FAO, 2016). Locust invasions depend strongly on locust control practices and related public policies, which are linked with the political stability of the island (Lecoq, 2001). Indeed, locust populations have grown significantly under the years of political instabilities in Madagascar because no effort and money were invested in an annual preventive control. They were declared as a national threat for the Island in November 2012 and a three-year emergency program has been launched to control this pest between 2013 and 2016 (FAO, 2016). Locust plagues were historically localized in south west, north and south of Toliara (Cooper et al., 1995). The apparition of a new locust zone in Kirindy is posterior to the political crisis of 2009 (FAO, 2016) and highlight well the insecurity of traditional agricultural techniques against natural hazards.

This first part of our research (**Chap. 2**, **Chap. 3**) demonstrates that slash-and-burn agriculture strongly degrades soil fertility although this was not the main reason leading farmers towards field abandonment. These chapters further raised the need for alternatives to slash-and-burn agriculture that would increase the stability and sustainability of the system to face environmental hazards and threats. To resolve the problem of soil fertility, fertilization means increasing soil security should be considered. Soil organic amendment or soil cover would favor a better retention of nutrients against rains, as well as soil protection against soil erosion and nutrient leaching. Possible solutions could be mulching or composting (Mbau et al., 2014; Rivero et al., 2004). Mulching would also help in dealing with weed invasion by preventing the establishment of their seeds during the cultivation period (Kader et al., 2017). In parallel, keeping trees within the field may offer shelter against locust invasion (Nair, 2013). Remnant trees also provide a higher seed bank for quicker forest re-establishment after cultivation (Mukul et al., 2016). In this thesis, we decided to combine those different alternatives to increase the resilience of the agro-forestry system and sustain cultivation on the fields.

7.3 A selective slash-and-burn agriculture with compost amendment

In previous research work conducted in Kirindy forest, it has been shown that farmers are willing to test organic fertilization and agroforestry to sustain cultivation on their fields (Dirac Ramohavelo, 2009). Thus, we aimed at building and testing an experimental alternative slash-and-burn practice following the willingness and the interest of local households. We have been testing, through a field experiment, a selective slash-and-burn agriculture (**Chap. 4**). Some trees were left intentionally within the fields (as in Carrière et al., 2002) to improve soil moisture and microbial activity. We coupled that practice with compost amendment to sustain soil fertility. Concerning the choice of the compost, we followed the results of Raharimalala et al. (2011, 2012), who showed that three local trees, *Poupartia sylvatica*, *Tarenna sericea* and *Fernandoa madagascariensis*, seem appropriate target species for forest management because of their high biomass and nutrient concentrations. Thus, those species were used as resources for composting.

A combination of wood ashes and compost appears to be a good solution for rehabilitating tropical depleted soils. The combined amendment of compost and ashes strongly increased corn yield, which was multiplied by 4 to 5 in comparison to ashes or compost alone, reaching 1.5 t ha^{-1} compared to 0.25 and 0.35 t ha^{-1} for ashes and compost, respectively. On control plots, yield was negligible as expected on these degraded soils. Compost and ashes were complementary fertilizing pathways having synergetic effects. Together they promoted soil fertility through positive effects on soil moisture, pH, organic matter and microbial activity. The increase of pH is favorable for the nutrient release by the added organic matter in these nutrient deficient soils, but also directly favorable for the plant growth and physiology. Concerning the tree cover treatment, yield was reduced on shaded plots (50% tree cover) compared to sunny plots (0% tree cover) for all soil amendments, except ashes. Indeed, trees acted as a light competitor for corn plants and consequently impacted negatively corn growth by preventing optimal conditions for photosynthesis. Therefore, tree cover should be kept at a minimum and corn plantation distance should be higer. Carrière et al. (2002a, 2002b) showed in South Cameroon that 3 to 7 trees for a field of 0.8 ha are enough to improve the slash-and-burn agricultural system. On one hand trees diminish the solar radiation, which reduces the photosynthesis of corn and consequently the yield, but on the other hand they provide organic matter with their litter fall and protect soils from erosion. Furthermore, their shading can be beneficial for the plant when the soil surface becomes too dark because of the ashes, in preventing the soil to warm-up excessively and dry out. Extra data that we have measured during farmers field survey (**Chap. 2**) shows further evidence on the importance of tree cover for preserving soil moisture (Fig. 7.2). In younger slashed-and-burnt fields, we witnessed already a selective slash-and-burn agriculture, as we have a remaining tree cover of about 12%. That tree cover preserves a soil moisture of 15 to 20%, compare to old bare fields where the soil moisture drops almost to 0%.

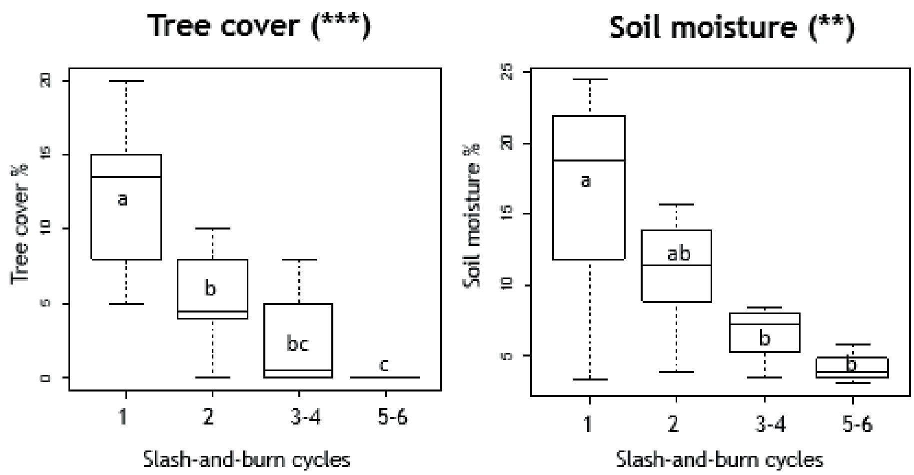


Figure 7.2 *Boxplots of tree cover and soil moisture for the different number of slash and burn cycles. Nb of cycles are: (1) 1 year; (2) 2 years; (3) 3-4 years; (4) 5-6 years. Means that are followed by the same letter are not significantly different (p > 0.05 according to contrast analysis; n = 4). Asterisks indicate significant differences along the gradient of age of clearing (p < 0.001 = ***; p < 0.01 = **; p < 0.05 = *; p < 0.1= ·)*

In a further step, the combination of wood ashes and compost was studied more in depth by means of two mesocosm experiments: a corn growth experiment in pots and a nutrient retention experiment in laboratory (**Chap. 5**). In the pot experiment, combining ashes with compost increased maize growth rate by 20% and advanced phenology stages for 25% of the plants, leading to 15 to 20% taller plants and 50% heavier corn cobs, compared to traditional slash-and-burn practices. Under amendments with only ashes or compost, a lower N and P concentrations in leaves was recorded than under a combination of ashes and compost. Thus, with only one of the two amendments, N and P may induce deficiencies in crop maturity. The combination of ashes and compost also helped dealing with nutrient soil deficiencies by mitigating their leaching during rain events. After the rain simulation experiments, stocks of nitrogen, phosphorus and potassium were 30 to 50% higher in the mixture of ashes and compost than in other substrates.

Together, the results of the field and mesocosm experiments provide insights on the potential of combining mineral and organic matter to improve the soil security in tropical regions. In optimizing slash-and-burn agriculture, better yields could be targeted, which in turn allows sustaining longer the cultivation of the fields. By increasing maize growth rate and advancing phenology stages, plant maturation time can be shortened and this reduces the risk of exposure to climate hazards. This could potentially help to cope with shortened rainy seasons in the context of climate change. However, considering that the study was done over only one year and on one particular type of soil, the proposed reclamation strategy needs to be checked over longer periods and in different sites before the results can be generalized. The duration of the effects of compost amendments and ashes should be assessed to determine the best frequency of fertilization. We have also seen that weed invasion is a crucial concern for farmers (**Chap.3**). Because of their time limitation, the effect of the aforementioned experimented techniques on weeds could not be assessed. Tree shade generally helps in fighting against weeds, but they reduce corn growth too (Reynolds et al., 2007). Compost could be also a useful mean in weed prevention if plants with particular properties are added during the composting process. For instance, plants like watermelon have allelopathic properties which prevent the development of weed seeds (Belz, 2007; Hao et al., 2007; Kong et al., 2008). Those interactions would be worth to investigate in further studies.

7.4. Implementation perspectives

Implementing new agricultural techniques can be sometimes difficult in rural traditional areas, because of a wide range of physical and psychological barriers like time constraints, general community interest, conflicts with other tasks in the field, fear of change, peer pressure, etc. In order to make our research valuable, we aim at testing the implementation possibilities of compost production in Kirindy forest (**Chap. 6**). We performed a Rapid Rural Appraisal (RRA) in various villages to understand farmer's knowledge on composting, and we also conducted ten workshops with a total of 500 farmers (13% of the villages population) to determine how new agricultural practices could be designed and implemented. In a second step, we also assessed the maturation rapidity and the quality of composts composed of three common tree species (*Poupartia sylvatica, Fernandoa madagascariensis, Tarenna sericea*), each species separately, as well as a mixed together.

We have calculated that farmers would take approximately 14 to 20 days of extra work compare to traditional slash-and-burn agriculture to make enough compost to amend their fields (**Chap. 6**). Thus, the particular proposed technique could probably not be extended at the forest scale due to labor constraints. However, it could be used as a tool to sustain cultivation on the most degraded lands and to alleviate the deforestation in the primary forest remnants. As compost has been shown to be rather effective to sustain cultivation (**Chap. 3, Chap. 4**), we could imagine using different type of organic residues to try to reduce labor work, such manure, kitchen was, grasses, corn residues. However, those solutions seem to have all also down-sides. For instance, manure is strongly limited in quantity as only richer farmers possess enough animals (zebus or chicken) to produce sufficient manure to amend their fields (Dirac Ramohavelo, 2009). Traditional composts made of kitchen waste are also difficult to use in large crop fields because, again, their quantity is limited. We would suggest to investigate other innovative possibilities for producing large quantities of compost. For instance, Morondava possesses now a place for composting the organic waste of the city. Thus, a collaboration between the city of Morondava and the farmers of Kirindy forest could be imagined.

Another highlighted constraint to the implementation of composting was the watering for compost maintenance. Both women and men had difficulties to water regularly the compost pits, however for different reasons. Men were busy with tasks outside of the village, thus when coming back, they were not much inclined to water, in addition, the compost pits. On the other hand, women had to carry the water buckets from the water well until their houses. The water wells were generally quite distant from the houses and to reduce the work, women started to place buckets in the yard to collect rain water. However, a severe drought occurred half of the rainy season in 2014, stopping rain water collection. Further, women found too fastidious to fill extra buckets from the water wells just for watering the compost pits. Yet we argue that this problem could be mitigated by either organizing the pits around water wells or by re-using lost water from those wells. We attempted in doing so by improving the access to the water wells (**Appendix**).

Despite the various highlighted constraints, the most interesting result of this part of the thesis was the interest and the motivation that people demonstrated. Although, most of the compost pits could not be maintained, 13% of the population still attended the 10 organized workshops. That outcome is important given the few advertisement done for the workshops. We adopted a passive behavior, i.e. our actions were driven by farmer's curiosity, rather by our will to convince people. Thus, only interested farmers participated. We believe that this attitude may have empowered the farmers significantly. However, people taking part in this action should also remain accompanied during the first years of the introduction of new practices. This would permit finding practical solutions to limit the negative impacts of unforeseen events (like water shortage in our case). Finally, changing the agricultural practices is challenging task and a systematic co-design with the local people is essential at every phase of the project development: from the workshop stage to the maintenance of the pit and the use of the compost.

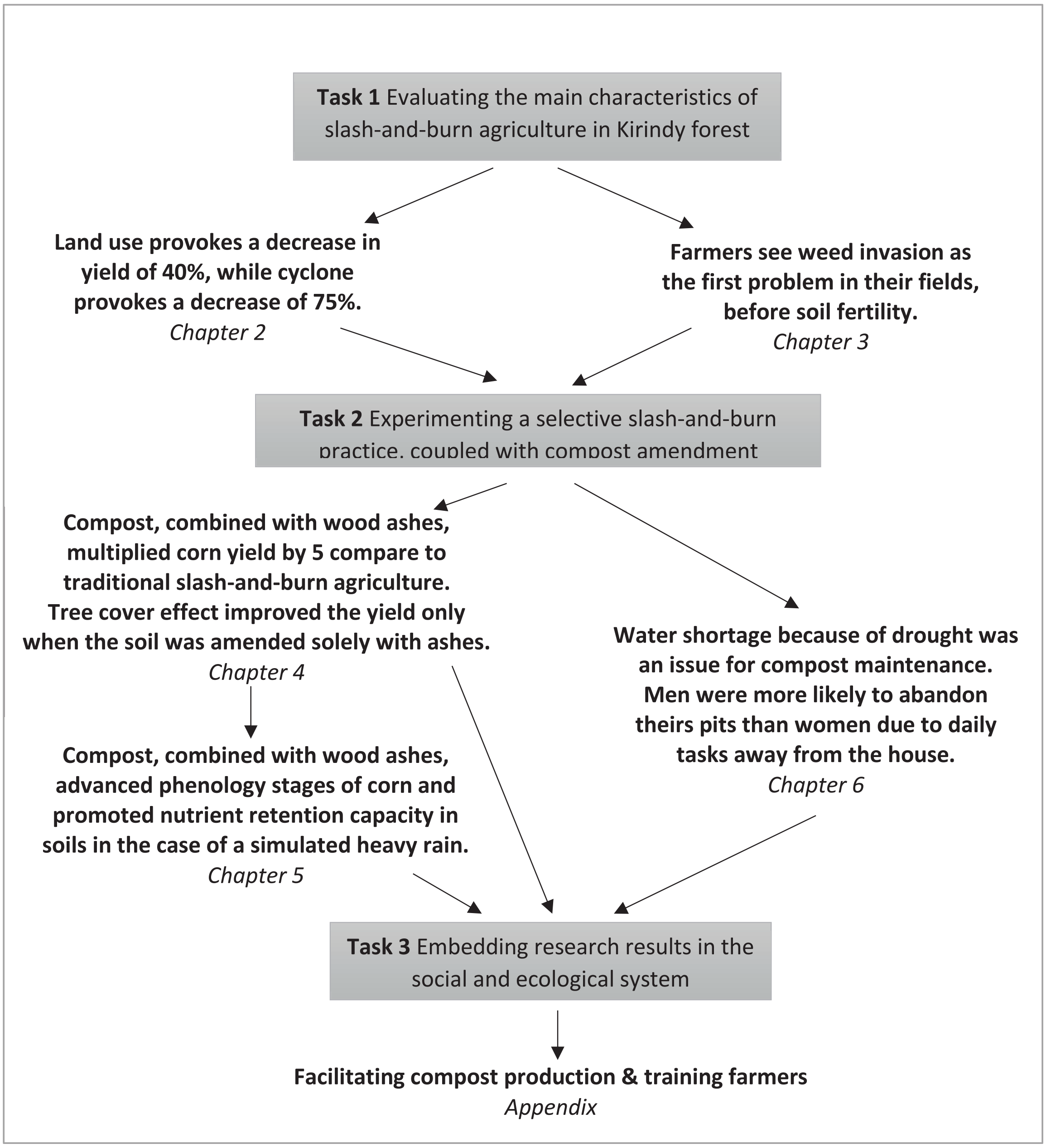


Figure 7.3 *Thesis key results by chapters. Chapter 1 & 7 are not mentioned in that figure but referred to the general introduction and discussion.*

7.5 General discussion

Socio-cultural background

Between the start and the end of that research work, a significant area of Kirindy forest has been deforested (Fig.7.4). Our findings highlighted that soil depletion due to plant uptake, erosion, leaching by heavy rains (**Chap. 2**, Fig. 7.3), and/or weed invasion **(Chap. 3**, Fig. 7.3) are important problems of slash-and-burn agriculture in Menabe. These different problems lead to field abandonments and incentivize deforestation. Despite the emergency of the situation, experts still disagree on how considering and managing slash-and-burn agriculture. Among the scientists, the political leaders and the different nature conservation actors, there is a dual vision of handling that type of agriculture. The first vision, and the most common one, consist in modifying the agricultural system by suppressing the use of fire and replacing it by perennial cultural practices sustained by agro-ecological means (Pauli et al., 2011). The second vision, which is also the vision followed by the current thesis, implies the maintenance of fire use and the improvement of slash-and-burn practices to increase yields and sustain re-cultivation (Hands, 2014). The latter has not been much studied, because the perpetuation of fire use is considered risky (Kull, 2000, 2002).

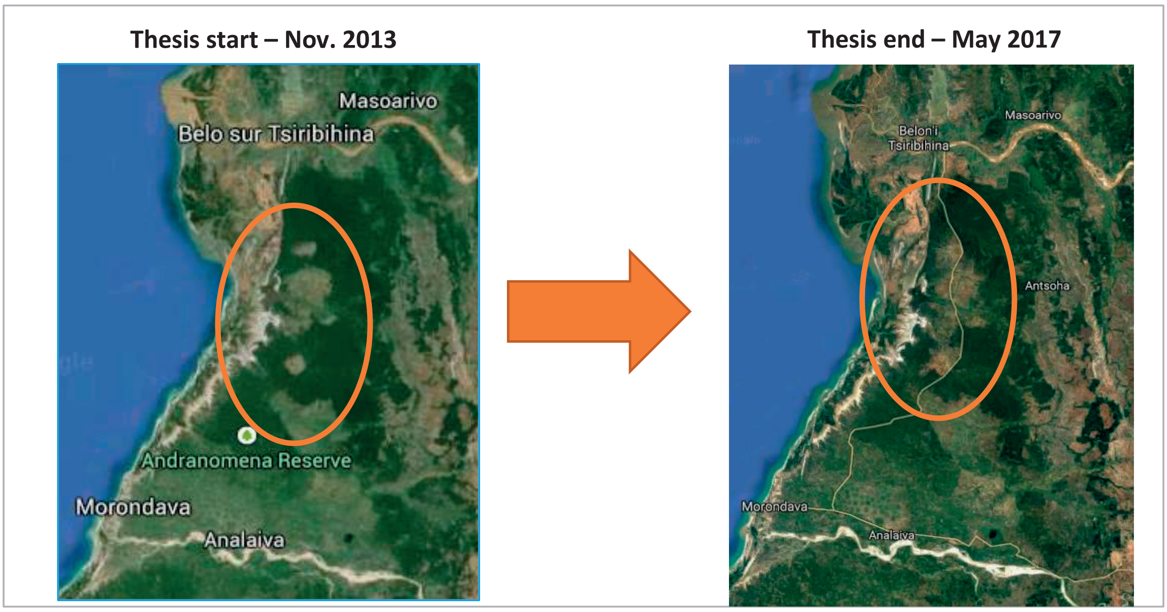


Figure 7.4 *Evolution of the Kirindy forest cover in 3 years and a half (Pictures taken from Google Earth, accessed November 2013 and May 2017)*

In Madagascar, as the situation stands now, fire is undeniably destructive. People fear that maintaining the actual practices and improving them may accentuate slash-and-burn practices, and therefore, strengthen the deforestation rate. People gets wealthier with increased yields which encourage them to cultivate more and leads to burning more forest areas. Those ideas typically place the blame on rural households, poverty and population growth. They overlook farmer's economic interests, historical and cultural contexts and the potential of Malagasy population to manage their resources positively (Kull, 2000). In addition, we argue that fire is not always destructive. It can even have a beneficial impact on the forest ecosystems by promoting the regeneration of plant species which where diminished because of the dense shaded forest. In comparison to fire-excluded forests, forests undergoing fires over small surfaces, have been shown to hold greater plant species richness (Mukul et al. 2016). Therefore, fire can also be also seeing as a tool for the ecosystem management if it is controlled and not over used.

Furthermore, recent studies enlighten the cultural importance of fire techniques for farmers in several regions of Madagascar (Desbureaux and Brimont, 2015; Hume, 2006; Kull, 2000, 2002; Scales, 2012). We have witnessed the importance of fire for local ethnics of Kirindy during field work as we watched people lighting fires to chase spirits on several occasions. *Tavy* (in malagasy) or *hatsake* (in sakalava dialect, Menabe region) was inherited from ancestors and its perpetuation represents not only a way of respecting the previous generations but also creates cultural identity and social order in local communities. However, most of the conservation initiatives in Madagascar provide solutions based on economical or ecological arguments only (Styger et al., 2009; van Vliet et al., 2012). The socio-cultural background of slash-and-burn agriculture is often ignored in conservation projects (Brimont and Karsenty, 2015; Hume, 2006). Besides, farmers are often reluctant to speak openly about traditions related to fire, as fire is demonized in most discourse of the government and NGOs (Scales, 2012). This retention of information does not help in giving a more important consideration to local traditions in research and conservation projects.

Lamb et al. (2005) demonstrated the difficulty to propose restoration strategies for the tropical forest which balance well biodiversity conservation and the economic interests of the livelihoods (Fig. 7.5). When the forests are replaced by commercial plantations (monocultures most of the time), they generate an income increase for the farmers, but practically no benefit for the biodiversity (arrow 1, Fitzherbert et al., 2008; Hamilton et al., 2016). At the opposite, solutions which are tailored to sustain biodiversity generally do not let a lot of space for agriculture expension (arrow 2, Garcia et al., 2010). Solutions which enhance forest regrowth (arrow 3) engenders improvements in both biodiversity and farmers' incomes, though the ecnomic benefits depends strongly on the commercial values of the tree species (Razafintsalama, 2011). That patch could be improved by the promotion of plants with a commercially high value (arrow 4). However, in poor rural areas, like in Kirindy forest, it may be essential to give the priority first to reclamation strategies which enhance the economic benefits of local people (arrow 5), and move smoothely then to actions preserving the biodiversity such as cultivating with remnants trees, with association of species, on small patches etc (Carrière et al., 2002; Kader et al., 2017; Mukul et al., 2016; Nair, 2013). Furthermore, the proposed strategies should be easily accessible to the farmers and meet a high social acceptance in order to be fast applied. In this context, preserving the socio-cultural context of *tavy/hatsake* could allow a faster shift in the agricultural practices by the local communities.

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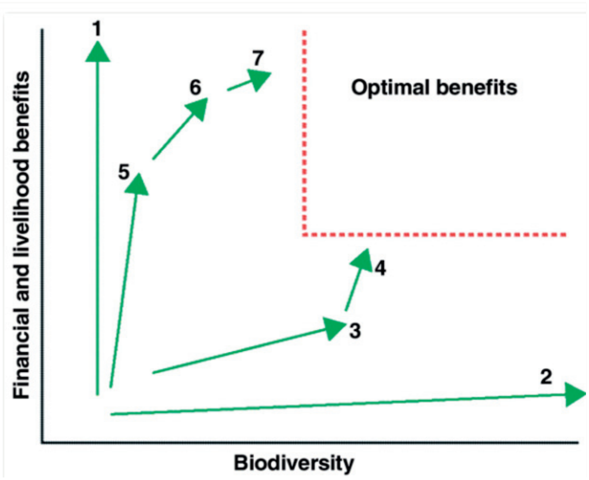

Figure 7.5 *Figure taken from Lamb et al. (2005), showing the different strategies for restoring the tropical forest and their potential contribution to livelihood benefits and biodiversity. Arrows 1 to 7 are explained in detail in the text. Arrow 5 corresponds to the strategy followed during the present research work.*

Compost as a sustainable alternative

We demonstrated that maintaining slash-and-burn agriculture, and combining the subsequent wood ashes with compost seems a promising solution to sustain cultivation on the fields and to fight against soil depletion (**Chap. 4** & **Chap. 5**, Fig.7.3). We were even able to reclaim highly degraded soils for agricultural purposes (**Chap. 4**). Our solution follows the arrow 5 of the figure proposed by Lamb. (2005). With the present research work, we also provide good evidences that amendments combining organic matter and ashes are undeniably superior to amendments with solely wood ashes or compost. Therefore, the proposed solution is more efficient than switching to a system where we would promote only organic amendments (Fonte et al., 2010; Pauli et al., 2011). The proposed alternative may eventually also be superior to the use of biochar amendments. Indeed, that alternative uses easily accessible materials, and free of cost. Biochar has been proved to be difficult to implement in rural poor communities, because its production often generates some cost that people are not able to pay (Cernansky, 2015; Pratt and Moran, 2010).

However, adjustments have still to be made for implementing composting in the forest dwelling communities. Indeed, we showed that several remaining barriers to its implementation. The most important were the watering constraints over a long duration (several months) related to compost maturation process (**Chap. 6**, Fig.7.3). To counter those barriers, we would like to refine the reclamation strategy compare to what we have proposed at the beginning of this work. As organic amendments seem hard to upscale, we would like to encourage farmers to use urban organic waste compost from Morondava to avoid time and labor constraints (Fig. 7.7). Indeed, the city possesses now an organic waste composting place. Such a system could be implemented by the means of micro-credits. Micro-credits are extensively used nowadays to alleviate poverety in developing countries and have proven to be an effective solution in most of the cases (Rooyen et al., 2012; Samer et al., 2015). Finally, following the conclusions of the **Chap. 4** and **5**, fewer trees (than what we experimented in **Chap. 4**), as well as mulching, could be added to improve the system.

The need now is towards a fast and efficient development of solutions which alleviate the pressure on the primary forests. Promoting the use of secondary forest and facilitating compost production (or access to these substrates) are keys towards the adoption of the innovative developed practices (Fig. 7.6). To be truly effective, the local stakeholders should be involved in every decision step (Rives et al., 2013). In fact, they should be the main actors and take the decisions step by step, supervised by a team of experts in conservation ecology, agro-ecology, sociology and economics. The expert team should have a modest and reserved attitude to foster farmer's empowerment and not to bias the decision process (Wilmé et al., 2016). Finally, the dimension of time must be taken into account: as traditional *tavy/hatsake* will certainly persist in the immediate future, it can only be gradually modified. The most innovative and motivated households should be encouraged to initiate the change first. This would allow skeptical people to observe first and to be progressively convinced by the project.

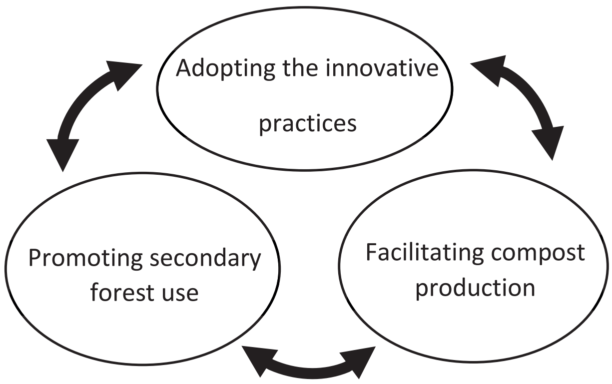

***Figure7.6** Key elements towards an agricultural change*

The present study launches the basis of a new conceptual framework to perceive and deal with slash-and-burn agriculture. If the proposed alternative could be implemented in Kirindy forest and proved to be sustainable for the primary forest on the long term, we would make a U-turn on how slash-and-burn agriculture is actually considered and studied. The actual failure of most conservation projects is related to a lack of communication or consideration towards the rural farmers. Hence, only a direct, clear and true integration of the main stakeholders would make a change in the actual forest management on the island. The proposed alternative would precisely establish a new type of dialogue with the farmers, because their traditional agricultural practices would be authorized and, thus, transparent. Identifying slash-and-burn agriculture as a component of the Malagasy identity and trying to preserve that identity paves the way towards a more socially acceptable agricultural transition, perhaps also towards a more effective transition.

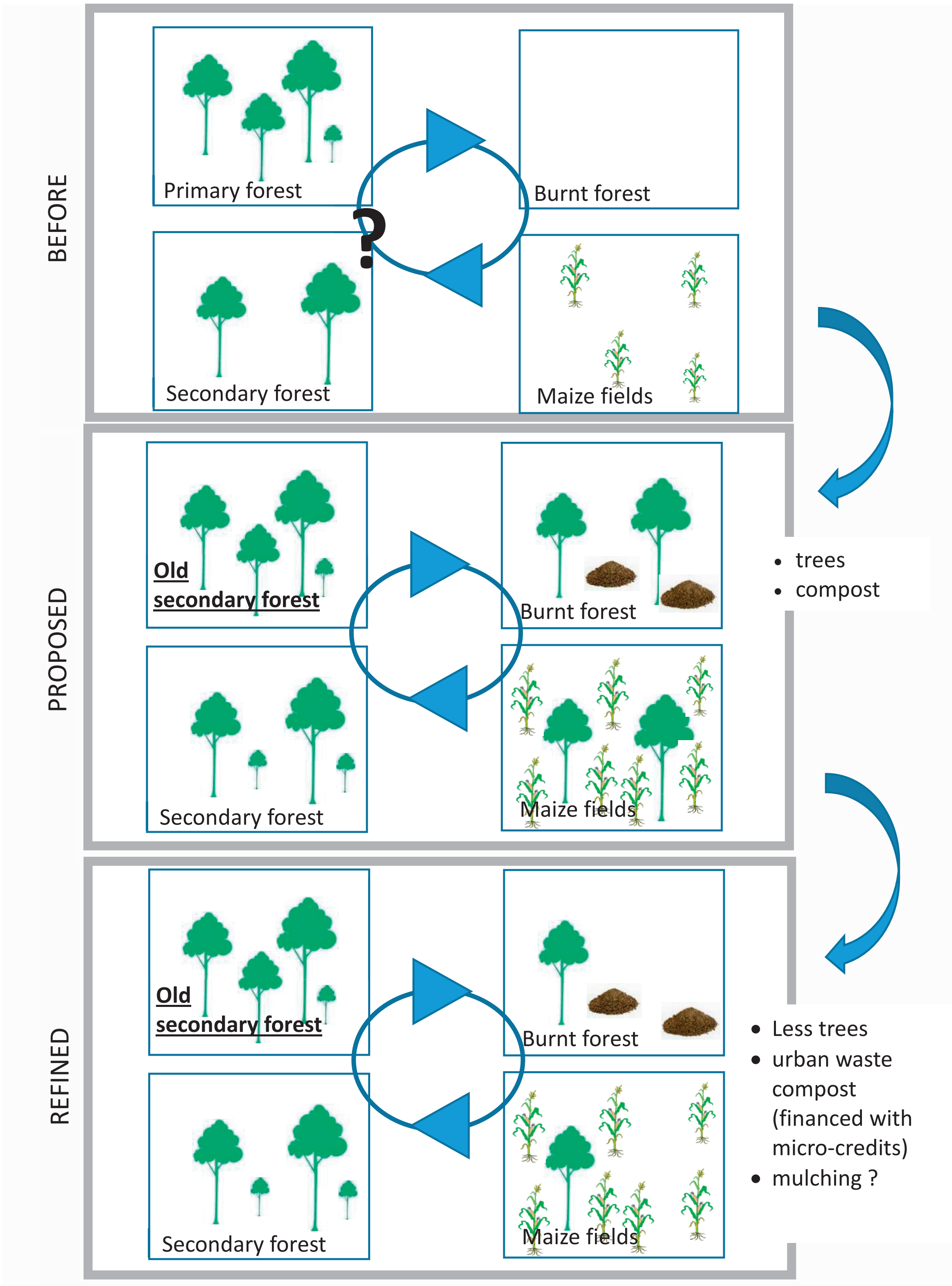

Figure 7.7 *Refined proposed alternative slash-and-burn practice*

7.6 Research recommendations

To complete this work and make possible a transition towards alternative practices, we would recommend the following specific research pathways:

- **Sociology:** We would recommend an in-depth investigation of the traditions around slash-and-burn agriculture, both in Kirindy forest and in other forest dwelling communities in Madagascar. Hints point towards the strong importance of those practices for farmers, but very little research has been done in general (Hume, 2006; Kull, 2002). Due to the diversity of ethnics in Madagascar, those aspects should be clarified at the country level in order to tailor efficient solutions to tackle the negative impacts of slash-and-burn agriculture.

- **Ecology:** Further tests of agroforestry technics should be carried out. Even though agroforestry does not seem appropriate for corn cultivations, it could be appropriate for other crop which need less light. Moreover, remnant trees are a necessary landscape element which permits the fast regeneration of secondary forests (Bechara et al., 2016; Mukul et al., 2016; Toriola et al., 1998). Mulching is also an option that we did not have the time to explore. It is recognized as one of the staple practice in conservation agronomy and would help to mitigate the effects of rain on the soil (Kader et al., 2017). Finally, due to our promising agronomical results concerning compost, we would recommend to investigate further the possibilities for combining organic amendments with wood ashes, particularly with plants with allopathic properties to fight against weeds (Belz, 2007; Hao et al., 2007; Kong et al., 2008). We would also recommend to perform field experiments to compare the differences between biochar amendement and compost, combined with ashes, amendement.

- **Economy:** Compost making is labor and time consuming. However, this does not necessarily mean that this option should be rejected for large scale forest management. On the contrary, we would suggest to investigate the potentialities for producing large quantities of compost. For instance, Morondava possesses now a large place for composting the organic waste of the city. Thus, a collaboration between the city of Morondava and the farmers of Kirindy forest could be organized. That compost could be collected and used to improve soil fertility in Kirindy forest. A study on the potentialities of developing a micro-credit system would be helpful to allow farmers to buy compost from the city.

- **Legislation:** A better organization of the lands should be studied and proposed within the forest area. An official zone where agriculture is permitted should be recognized at the same level than the reserve area to preserve the primary forest. The administrative procedures should be fast and simplified. Farmers should be encouraged to cultivate within that zone. This may allow more transparency in the land use, which in turn would help in monitoring better the agricultural practices.

7.7 Beyond the PhD thesis: from research to application

During surveys, farmers pointed out the lack of restituting information from previous research and conservation projects in the region. Undeniably, there is a communication gap between scientists and the people targeted in their studies. Because of those observations, we were willing to improve the information restitution on the current research project. We decided to carry out a side applied project, which would go beyond the scope of the present thesis. This project promoted farmers' training on composting methods and the improvement of water access in several villages as a first step towards the changes of the agricultural practices. The project relies on an initiative of Justine Gay-des-Combes, Philip Herlalaina, Auréla Malalaniaina and Leia Falquet. It had help from the association of EPFL, Ingénieurs du Monde and financial support from FEDEVACO (Fédération Vaudoise de Coopération), various generous donors and from ECOS laboratory (EPFL). More details on that side-project can be found in Appendix.

Figure 7.8 *Water wells in Kirindy (left) and Beroboka (right) villages which need urgent rehabilitation (Picture from Leia Falquet, 2015)*

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- Appendix -

From research to application

Picture: Water well with a pumping system in Beroboka village,
Leia Falquet, 2014

The Blue for Green project

This particular appendix of my thesis goes beyond the scope of my research grant. It explains my personal efforts outside of my working time in disseminating the knowledge that I have gained during my thesis and collaborating with local people to make a small change in the Kirindy Forest.

All started, during my second field mission, in March 2014. One day, some irritated farmers stopped me at the entrance of one village and forbid me to take measurements of their corn fields. By talking with them, I could only agree and understand. They were profoundly upset to see students coming to interview them and measure the forest or the fields over several years without never having a return of information. I realized by this time the huge time lapse between doing research and applying it, especially in developing countries. Six months later, I met Philippe and Auréla, two students in social sciences in the University of Antananarivo. I hired them to help me in the field mission of November 2014. They were very motivated and smart young sociologists. We became friends and we decided together that we would attempt to disseminate more quickly and efficiently the outcomes of my thesis to the local farmers.

In September 2014, I was also president of an association called "Ingénieurs du Monde" and based at EPFL. Ingénieurs du Monde is an association of students from both the Ecole Polytechnique Fédérale de Lausanne (EPFL) and the University of Lausanne (UNIL), who feels concerned by developing countries. Its aims to promote North-South scientific cooperation and to raise awareness of the Global South problems within academia. Through Ingénieurs du Monde, I was able to postulate for a grant which would allow Philippe, Auréla and me to run regular workshops in Kirindy and provide services like repairing water wells, buying new seeds for farmers, building common gardens for vegetable growth in the villages etc. A colleague and friend of mine, Leïa Falquet, lab technician for the EML group of Prof. Rizlan Bernier-Latmani (EPFL), joined by this time the project. She would coordinate the project in Madagascar and manage also the project budget.

I postulated in December 2015 for a grant from FEDEVACO (Fédération Vaudoise de Coopération), an organism which redistributes Swiss money for projects in developing countries in the region of Vaud. We obtained it, after a written and an oral examination, in March 2016. Our project, called "Blue for Green" (blue for water and green for both agriculture and forest) runs now since April 2016. Below, we present the official public documents which served for the grant application. They explain a bit our organization & goals of our applied project.

CONTEXTE, ETAT DES LIEUX

Géopolitique (acteurs en présence, qui fait quoi, etc.)

Les crises politiques se sont succédé à Madagascar (1972, 1991-92, 2001-2002 ou 2009). La dernière crise date de mars 2009, où, le président en exercice Marc Ravalomanana fut chassé par Andry Rajoelina, homme fort du pays. Le bilan de cette période de gouvernement de transition (entre 2009 et 2013) est affligeant. Les richesses du territoire ont été surexploitées: trafic de bois précieux, surpêche, exploitation massive de gisements de pierres précieuses, trafic d'animaux protégés etc. A présent, les institutions étatiques sont encore très faibles et la plupart des projets de développements et d'éducation existants sont financés par des organes internationaux. L'avenir du peuple malgache dépend donc fortement, pour le moment, de l'aide extérieure.

Socio-économique

La crise politique a eu un impact très sévère sur le développement socio-économique du pays. La situation budgétaire de l'Etat est actuellement ex sangsue, laissant peu de marge de manœuvre au développement du commerce et du pays en général. Dans les classements internationaux, la Grande Ile se place loin dans les rangs. Le PIB a dégringolé et la population vit avec moins de 2$ par jour.

L'agriculture représente l'activité principale et 73.5% de la population vit en-dessous du seuil de pauvreté. Madagascar est également un des pays d'Afrique dont l'accès à l'eau est très réduit. Moins de 50% de la population seulement a accès à des sources d'eau potable : 79% de ces gens sont situés dans les villes, contre seulement 36% dans les régions rurales. (Selon l'étude menée par l'OMS)

Justification du projet par rapport au contexte

La situation socio-économique impose une pression anthropique trop forte sur les forêts malgaches qui sont actuellement en nette régression. La conversion des sols forestiers en terres agricoles en est la cause majeure. Cette déforestation résulte de l'agriculture sur brûlis, qui consiste à abattre des arbres, les brûler, et en récupérer les cendres pour fertiliser le sol. Or, après 4 ans de culture, le sol s'appauvrit et les paysans sont condamnés à abandonner leurs terres et à brûler une nouvelle partie de la forêt. Au Menabe Central, côte ouest de Madagascar, la perte annuelle de couverture forestière (forêt dense sèche) avoisine 1%.

Notre projet est primordial dans ce contexte-là puisque, par la création de puits, il vise à permettre le développement sanitaire de plusieurs villages de la région du Menabe, ainsi qu'une alternative à l'agriculture sur brûlis en permettant de fabriquer du compost. Cette technique peut permettre l'amélioration du rendement des cultures : des essais en champs sur du sol abîmé par le brûlis ont déjà montré une meilleure croissance des plantes lors d'ajout de compost. Il est possible de passer d'un rendement de 1 t/ha à 2.5 t/ha. Ce compost est créé avec des déchets ménagers et des branches broyées provenant d'arbres de forêt secondaire et sera arrosé grâce à la récupération des eaux perdues de nos puits. En effet, lors du remplissage des seaux d'eau, il y a constamment de l'eau qui est renversée et qui s'accumule au pied des puits. Cette eau sera canalisée et récupérée pour le compost. Les pertes d'eau pouvant être récupérées seront quantifiées précisément lors de l'étude de faisabilité du projet.

Résultats déjà obtenus

Entre février et mars 2015, une phase de pré-projet a été entreprise afin de récolter les données de base nécessaires à l'élaboration technique des puits. Ainsi, 44 ménages (composés en moyenne de 3 à 10 personnes), dans les villages de Kirindy, Beroboka et Andranolava, situés dans la forêt de Kirindy au Menabe, ont été questionnés sur leurs besoins en eau et leurs pratiques agricoles. Les villageois pratiquent tous l'agriculture et certains également l'élevage de zébus. L'accès à l'eau potable est très réduit. La consommation actuelle se situe entre 10-20l/jour/habitant selon notre enquête, ce qui est trop faible comparé aux normes préconisées de l'OMS qui suggère que pour vivre décemment il faudrait 50l/j/habitant. De nombreux cas de diarrhées, malaria et autres maladies hydriques nous ont été rapportés lors de nos visites sur le terrain. Il est difficile de quantifier le nombre exact de malades car l'information circule par le bouche à oreille et il n'y a pas d'infirmerie officielle dans ces villages. Par contre, à chacune de nos visites, nous rencontrions malheureusement toujours une à trois personnes souffrant de diarrhée ou d'une infection de la peau, qui aurait pu être souvent évitée par une bonne hygiène.

Des ONG locales ont été interrogées et plusieurs seraient d'accord de collaborer avec nous pour la réalisation technique des puits, dont FIKRIFAMA (cf. lettre en annexe). Une étude hydrogéologique générale de la région existe déjà et 3 puits sont fonctionnels dans le village de Beroboka. Il est donc possible d'entreprendre la construction de nouveaux puits de manière assez aisée et sans grande difficulté technique.

Comme déjà cité plus haut, des essais en champ sur des plants de maïs ont déjà été effectués et les résultats sont positifs quant à l'utilisation du compost (cf. annexe sur les résultats des essais en champs). Les puits sont donc la clef manquante à la création durable de ce compost.

PROBLEMES, FINALITE, OBJECTIF ET RESULTATS ATTENDUS

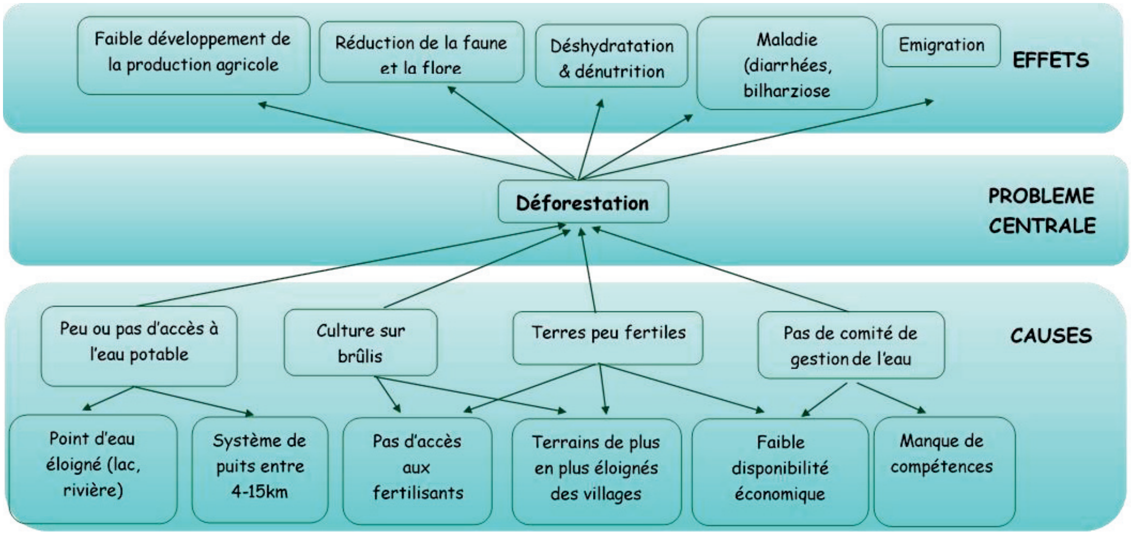
Les problèmes

Principal problème que le projet cherche à résoudre

La déforestation dans un premier temps, les conditions sanitaires médiocres dans un second temps.

Autres problèmes auxquels le projet devra s'atteler pour résoudre le problème principal

Le peu d'accès à l'eau potable, les mauvaises pratiques agricoles, des terres peu fertiles et le manque de comité de gestion sont tous des causes à la déforestation et des sous-problèmes auxquels notre projet touche également.



Finalité

Permettre un changement des pratiques agricoles des populations vivant dans la forêt de Kirindy, tout en procurant à ces gens un accès durable à l'eau potable. Sur le long terme, nous espérons aider à la protection de la biodiversité de la forêt de Kirindy.

Objectif

Fin 2017, la population des deux villages (soit 1000 personnes) a accès à l'eau potable ainsi qu'à un système de récupération des eaux perdues qui seront utilisées pour des fins agricoles.

Résultats attendus

Nous espérons les résultats suivants :

1) Les conditions sanitaires se sont améliorées à Kirindy et Andranolava.
2) Le rendement des champs des villageois a augmenté de 1t/ha à 2.5t/ha grâce à l'amendement en compost (créé grâce au système de récupération des eaux perdues des puits).
3) Une meilleure protection de la biodiversité de la forêt de Kirindy est atteinte.

Actions prévues

Quatre puits seront creusés, 2 en 2016 à Kirindy et 2 en 2017 à Andranolava. Chaque puit possèdera une surface étanche à sa base pour récolter les eaux usées et un système de rigoles qui conduira ces eaux dans une fosse à compost, creusée à proximité.

Les puits seront maintenus en bon état par la collecte d'une taxe villageoise de 100 ariary (mensuel et par ménage) et des formations de quelques jours données aux villageois (3x/année) quant :

1) aux principes de base de l'hygiène

2) à la réparation des puits

La taxe suit le même système établi dans d'autres villages avoisinants (Beroboka, par exemple). Ce système fonctionne bien d'après les villageois.

Le développement agricole se fera grâce à trois formations pour les agriculteurs, constituées de 1 journée intensive et d'un suivi hebdomadaire sur 3 mois, quant au compostage et à la mise en culture avec utilisation du compost. Suite à ces formations, une association d'agriculteurs sera créée pour l'entretien, la distribution et l'utilisation du compost.

LES ACTEURS

Le partenaire local chargé de la réalisation du projet

Nous collaborons directement avec les villageois de Kirindy et Andranolava. Justine Gay-des-Combes travaille, depuis 2013 déjà, avec ces personnes-là et avant Justine, deux autres projets avaient été effectués dans la région par des doctorantes (Clémence Dirac et Olga Raharimalala) du même laboratoire (le laboratoire ECOS) de l'EPFL. Il existe donc une collaboration depuis environ 10 ans entre les habitants de ces deux villages et le laboratoire ECOS.

De leur propre chef, les villageois ont décidé de créer une petite association pour la maintenance et la pérennité des futurs puits. Il s'agit du Comité de la Gestion des ressources en Eau de Kirindy (CGEK). Ce comité est composé des présidents des villages, Komity Sylvain (président d'Andranolava) et Komity Maharajivelo (président de Kirindy), ainsi que de Marcel Sinaotsy, guide régional et agriculteur et Gilbert Ramahatombo, agriculteur. S'ajoutent à ce comité, Philippe Herlalaina et Auréla Malalaniaina, agents de développement, qui travaillent dans ces villages depuis un peu plus d'un an maintenant. Ingénieurs du Monde travaillera donc directement avec les membres du CGKE.

Pour appuyer ponctuellement cette petite association de villageois, nous avons décidé de collaborer avec le Centre National de Formation, d'Etudes et de Recherche en Environnement et Forestier (CNFEREF). Le CNFEREF est une organisation basée à Morondava qui s'occupe de la protection de la forêt de Kirindy et de la sensibilisation à la biodiversité de cette forêt. Ils possèdent un centre éco-touristique au cœur de la forêt et leur équipe est composée de guides, de chauffeurs et de professionnels de l'éducation. La plupart des membres de l'équipe sont des habitants de Morondava et des villages de la forêt de Kirindy. Le CNFEREF est donc un partenaire idéal pour nous appuyer, en cas de besoin, pour la réalisation du projet.

CNFEREF
BP 117 Tsimahavaobe
619 Morondava
Madagascar
+261 32 40 165 89
cfpfmva20051@yahoo.fr
www.kirindyforest.com

Stratégie d'intervention de l'organisation partenaire (résumé) :

Le Comité de Gestion des ressources en Eau de Kirindy travaillera directement avec les bénéficiaires du projet, d'ailleurs les membres du comité sont tous également des bénéficiaires du projet.

Des réunions seront organisées avant la construction des puits, pendant et après afin de maintenir la population informée de l'état des travaux. Les présidents d'Andranolava et de Kirindy assurent la direction du CGEK.

Au sein du comité, Auréla, Philippe et Gilbert sont en charge des formations aux villageois quant aux principes de base d'hygiène, à la maintenance des puits et au compostage (cf. organigramme et chronogramme). Ces formations auront lieu périodiquement à un rythme de trois fois par année.

Un rapport sera transmis mensuellement du CGEK à Ingénieurs du Monde afin de maintenir le contact entre les deux partenaires et d'avoir un suivi régulier. Philippe assurera la rédaction des rapports du CGEK et les transmettra à Leïa Falquet ou Justine Gay-des-Combes, membres d'Ingénieurs du Monde et cheffes de projet.

Les bénéficiaires

Le nombre total des bénéficiaires sera de 100 ménages, soit environ :

~550 villageois à Kirindy

~450 villageois à Andranolava

Les bénéficiaires indirects, *nombre et caractérisation :*

Kirindy est situé sur un grand axe de passage qui relie la ville de Morondava à celle de Belo-sur-Tsiribihina. Les haltes sont rares sur cette route. De nombreux agriculteurs y transitent à pied, en charrette à zébus ou encore en taxi-brousse. Les puits de Kirindy pourraient donc bénéficier, selon un accord avec le président du village, aux voyageurs itinérants. Nous pouvons imaginer également que si plus de gens s'arrêtent, il serait possible de développer des commerces supplémentaires à Kirindy, voir un petit hôtel.

Les plus grands bénéficiaires indirects seront également la faune et la flore locale, qui avec le changement des pratiques agricoles, retrouveront un meilleur habitat.

Impact sur les groupes bénéficiaires

Les villageois bénéficieront d'un accès à l'eau potable, de meilleures conditions d'hygiène, d'une source de compost et donc de nouveaux fertilisants agricoles. Nous espérons que les conditions de santé s'amélioreront avec la réduction des maladies hydriques et des carences en eau. Avec les nouvelles techniques agricoles, les paysans devraient également produire plus et ainsi améliorer leur économie. Les rendements actuels sont d'environ 1t/ha pour les champs de maïs de la forêt de Kirindy. Nous espérons passer à 2.5t/ha, soit plus du double de la production actuelle. Les essais préliminaires en champs montrent que c'est possible (cf. annexe sur les résultats des essais en champs).

Autres intervenants sur le terrain, partenaire du programme et/ou en relation avec les domaines d'intervention du projet

Partenaire(s) financier(s):

Ingénieurs du Monde bénéficie du soutien de l'EPFL et de la FEDEVACO. Les fonds ne provenant pas de la FEDEVACO sur ce projet pourront donc être puisés dans les fonds d'Ingénieurs du Monde attribués par l'EPFL.

Partenaire(s) technique(s) :

Nous pensons engager l'ONG FIKRIFAMA pour la réalisation technique des puits (cf. lettre de FIKRIFAMA en annexe).

- **FIKRIFAMA ONG**, Tananarive
  Analyse hydrogéologiques, forages, construction de puits, aménagements
  Responsable : M. Fanja, directeur +261 32 07 577 63

Néanmoins, nous avons une liste de diverses ONG qui nous avaient également donné un retour positif sur notre projet et avec qui nous pourrions également collaborer :

- **SEHATRA**, Tananarive
  Analyse hydrogéologiques, forages, construction de puits, aménagements.
  Responsable : Mme Mbola, ingénieure +261 33 11 382 31
- **Ecole supérieur d'Antsirana,** Tananarive
  Analyse hydrogéologiques, forages, construction de puits, aménagements
  Responsable : Rakotozanakajy Toniniaina, ingénieur électromécanicien et hydraulicien +261 33 12 68518

Structures étatiques / institutions :

- Ministère de l'eau, Tananarive contact M. Jaques +216 33 09 630 70
- Direction régionales de l'eau, Morondava, contact M. René +261 34 05 997 10

Groupes de population / réseaux :

Les communes, villages et hameaux, à Madagascar, sont organisés en fokontany. Ce sont les subdivisions administratives. Les fokontany de Kirindy et d'Andranolava, et leurs présidents respectifs, vont donc collaborer avec nous pour ce projet de puits.

- A Andranolava, il s'agit de Mr. le président Sylvain.
- A Kirindy, il s'agit de Mr. le président Maharajivelo.

APPROCHE ET STRATEGIE DE MISE EN OEUVRE

Approche

Le projet sera mis en œuvre sur une période de deux ans et touchera 1000 personnes, 550 (village de Kirindy) la première année, 450 (village d'Andranolava) la deuxième année. Notre approche s'appuie sur les principes en vogue d'aide au développement qui favorisent une participation active des bénéficiaires du projet, plutôt qu'une observation passive. Nous favorisons également un apprentissage non intrusif et discret des techniques que nous désirons amener dans cette région.

Notre idée est de montrer, dans un premier temps, que notre technique agricole peut améliorer les rendements, sans critique, ni jugement quant à l'agriculture sur brûlis pour ne pas brusquer les gens. Nous avons donc fait des essais en champs entre novembre et mai 2015. Nous avons fait pousser du maïs sur 4 traitements de sol différents : compost, cendres, compost et cendres et aucune fertilisation. Les rendements des champs ayant reçu du compost dépassaient celui de tous les autres. Ces essais en champ ont été faits à proximité du village d'Andranolava. Aucune formation n'a été donnée avant cela aux villageois et nous les avons simplement laissé observer ce qu'il se passait pendant la période de croissance. Avant de récolter le maïs, nous avons réuni tous les villageois et leur avons demandé ce qu'ils pensaient, et leur avons expliqué plus en détail ce qu'était le compost. Ils étaient tellement enthousiasmés des résultats qu'à présent 4 fosses à compost ont déjà été creusées à Andranolava.

Un lien de confiance s'est donc créé et de nombreuses personnes nous ont demandé plus de formations quant au compost. Le projet de puits a également suscité beaucoup d'intérêt et de réjouissance. Dans les futures étapes du projet, nous espérons maintenir ce lien de confiance en restant proche des villageois, de leurs coutumes et à leur écoute. La participation locale est importante pour assurer le succès et la viabilité du projet

Renforcement institutionnel des groupes bénéficiaires :

Une association des agriculteurs sera créée avec l'aide des présidents des villages et du CGEK. Cette association sera composée d'un président, d'un vice-président et de toute personne volontaire et intéressée à la création du compost et à sa mise en culture. Cette association permettra une gestion des ressources en compost : le maintien de sa qualité durant le processus de dégradation, sa distribution aux différents agriculteurs et sa mise en culture correcte sur les champs qui en ont le plus besoin (càd les champs aux rendements les plus faibles, soit les champs âgés d'environ 4 ans et ayant un rendement de 1t/ha). Cette association permettra aussi une meilleure circulation des informations transmises durant les formations du CGEK concernant le compostage et la mise en culture. Ainsi nous espérons que 100% des agriculteurs auront suivi les formations et 60 % feront partis de l'association.

Intégration des dimensions genre et équité:

Les femmes seront prises en compte dans notre projet puisque les formations s'adressent autant aux hommes qu'à ces dernières. Lors de nos enquêtes entre février et mars 2015, le soin a été pris d'interviewer autant d'hommes que de femmes, afin de récolter les avis et les besoins des deux genres.

Les femmes seront les grandes gagnantes de ce projet puisque c'est souvent à elles qu'incombent la tâche de la collecte d'eau, pendant que les hommes sont au champ. Elles auront, ainsi, des trajets plus courts à effectuer, se fatigueront moins et pourront consacrer plus de temps à d'autres tâches.

Outils de réalisation, genre d'actions mise en œuvre dans le projet.

Signaler par un « **x** » le ou les outils utilisés pour réaliser le projet.

Formation initiale	x	Appui-conseil	x
Mise en relation		Subvention	
Plaidoyer, lobbying		Information	x
Perfectionnement		Renforcement de capacités	x
Suivi-accompagnement	x	Crédit	
Structuration-organisation	x	Autre -> lequel ? …..	
Formation professionnelle			

Dispositif de suivi

Système de suivi des activités et analyse d'impact :

Un rapport sera transmis mensuellement du CGEK à IdM afin de maintenir le contact entre les deux partenaires et d'avoir un suivi régulier. Philippe Herlalaina assurera la rédaction des rapports du CGEK et les transmettra à Justine Gay-des-Combes et à Leïa Falquet d'Ingénieurs du Monde.

Le rapport mensuel comprendra les trois aspects suivants du projet : état des lieux technique du projet, gestion du temps et des équipes, satisfaction de la population. Ce rapport sera discuté entre les différents membres du projet (CGEK et IdM) et présenté aux séances de comité d'IdM. Il sera donc possible en tout temps de corriger le projet en fonction des attentes et inputs des divers acteurs : IdM, les partenaires locaux, la population.

Méthode de capitalisation, ou comment rendre l'expérience partageable:

Les rapports mensuels sont un premier pas quant à la capitalisation du projet. Dans un second temps, un rapport annuel sera également rédigé afin de rassembler au mieux l'information. Ce rapport annuel pourra être mis à disposition de la FEDEVACO et de ses associations membres. L'évolution du projet pourra aussi être suivie sur le site internet d'Ingénieurs du Monde (http://idm.epfl.ch).

PERTINENCE ET VIABILITE DU PROJET Appréciation par l'AM

Articulation du projet avec la stratégie programme de l'AM

Ingénieurs du Monde désire promouvoir la coopération scientifique Nord-Sud et sensibiliser le milieu académique aux problèmes de développement. Ce projet s'intègre pleinement dans cette optique et permettra également à IdM d'améliorer sa visibilité en présentant un projet concret au sud afin de valider son expérience dans les pays en voie de développement. L'association obtiendra ainsi une meilleure crédibilité auprès des autres associations du réseau FEDEVACO. Blue for Green pourra également bénéficier aux étudiants de l'EPFL puisqu'il donnera lieu à la création d'au minimum 2, voir 3 stages étudiants, publiés sur la plateforme d'IdM. Ces stages permettront d'aider bénévolement à l'étude hydrogéologique et au design technique des puits.

Adéquation par rapport aux domaines de compétences de l'AM (référence à la stratégie programme) :

L'AM est tout à fait compétente à gérer ce projet puisque celui-ci touche directement ses thématiques de prédilection.

Viabilité, pérennité de l'action

Le Comité pour la Gestion des ressources en Eau de Kirindy assure la gestion et la maintenance des puits. Les règles de suivi ainsi que la réalisation des travaux seront établis selon les normes malgaches (code de l'eau du Ministère de l'eau et assainissement), une taxe sera rassemblée par foyer pour assurer les petites réparations des puits et le remplacement de pièces usagées (cf. 2.5 actions prévues). Le CGEK sera en charge de la collecte de cette taxe. La maintenance et les contrôles de qualité de l'eau seront effectués précisément selon un calendrier des tâches établi. Les habitants seront formés à l'hygiène et à la bonne gestion de l'eau.

Mesure en faveur de l'autonomisation du projet

L'autonomisation du projet passera par les formations données aux villageois par le Comité de Gestion des ressources en Eau de Kirindy. Nous espérons que les villageois prendront soin, petit à petit, par eux-mêmes des puits et du système de récupération pour le compost. Ils seront responsabilisés par la collecte de la taxe qu'ils devront payés pour la contribution aux réparations des puits.

Perspectives d'après projet et ressources pour assurer la continuité

De nouveaux financements seront cherchés auprès de fondations ou par crowd founding, durant l'année 2016, afin d'avoir un fond de réserve en cas de réparation conséquente d'un ou de plusieurs puits.

Depuis deux ans déjà, Justine a implémenté la technique du compost dans ces villages ce qui permet de bonnes perspectives pour le projet. Le but est d'étendre ces techniques au plus de personnes possibles et de sensibiliser les autres organisations présentes dans la région à ce développement. Ce premier projet sera un essai pilote, afin de reproduire l'expérience dans d'autres villages et de développer la région. De nouveaux puits pourraient être financés après 2017 par Ingénieurs du Monde pour intensifier l'impact positif sur la région si le système établi fonctionne.

Estimation des chances de réussite du projet (points forts / points faibles)

Grâce à de longues années de collaborations et plusieurs travaux de recherche sur le terrain, ECOS, le laboratoire où Justine Gay-des-Combes effectue sa thèse, a lié beaucoup de contacts sur place et les villageois se sont intéressés à nos essais. Les résultats obtenus ont été convaincants ce qui nous a valu la confiance de la population et une motivation forte de leur part pour le projet.

Risques et faiblesses du projet (points faibles) :

Madagascar étant dans une crise de banditisme, le vol de pièces ou le ralentissement dû au conflit peuvent ralentir la phase de réalisation du projet. Certains risques sont aussi liés à l'emplacement des puits qui peuvent devenir une source de querelles entre villageois. Toutefois, ceci peut être évité en prenant soin d'écouter la population avant de définir l'emplacement définitif des puits.

Principales suppositions qui conditionnent la réussite du projet :

La réussite est conditionnée par la stabilité de la région. Si la région reste stable durant ces prochaines années, il est alors fort probable que nos puits puissent être utilisés pleinement et bénéficier à la population.

LES MOYENS

Infrastructures et moyens propres engagés dans le projet par l'AM

L'AM contribue au succès du projet par l'envoi d'étudiants en stage pour participer à l'élaboration technique des puits. Elle mobilise donc des bénévoles et met à disposition l'expertise technique des étudiants de l'EPFL. L'AM possède également un réseau de contacts développés sur place grâce à la connaissance de la région de Justine Gay-des-Combes et Leia Falquet.

Des fonds supplémentaires à ceux attribués par la FEDEVACO seront débloqués. En effet, Ingénieurs du Monde possède également des fonds provenant de l'EPFL et ceux-ci peuvent être utilisés pour le développement de projets SUD.

Infrastructures et moyens propres engagés dans le projet par le partenaire local

Le Comité de Gestion des ressources en Eau de Kirindy, ne possède pas de fond propre, mais possède, par contre, les ressources humaines dont le projet a besoin. Le partenaire possède également une excellente expertise de la région et des outils de formation adaptés aux populations locales.

Le CNFEREF possède des voitures qui peuvent être louées pour les déplacements professionnels, du matériel de broyage pour aider à la réalisation du compost si besoin, des outils divers, des panneaux solaires et également des infrastructures pour loger et restaurer d'éventuels bénévoles.

Le partenaire local technique (FIKRIFAMA) est en charge de l'étude hydrogéologique et du forage des puits. Il fournira également les machines et les matériaux (y compris le transport de ceux-ci) nécessaires à la réalisation du projet. Il devra délivrer à la fin du projet, des puits fournissant un débit suffisant et une eau potable de qualité pour les villages de Kirindy et Andranolava.

Engagement des bénéficiaires

Les villageois, via leurs présidents Komity Sylvain et Komity Maharajivelo et le Comité de Gestion des ressources en Eau de Kirindy, s'engageront lors de la construction comme main-d'œuvre et s'assureront du fonctionnement des puits ainsi que de leur pérennité sur un minimum de dix ans.

Justine Gay-des-Combes

Environmental Engineer, specialized in soils, ecosystems & hydrology

18.09.1987 – single – Switzerland
Rue de la Gare 34, 1003 Lausanne, Switzerland
+41794753017 - justine.gaydescombes@gmail.com

Experience

EPFL - Ecole Polytechnique Fédérale de Lausanne, Switzerland 11.2013 – 30.07.2017
Ecological Systems Laboratory (ECOS) http://ecos.epfl.ch
Doctoral Candidate in Ecology
Applied research on sustainable alternatives to slash and burn agriculture in Madagascar.

- Study of the soil fertility and land cultivation techniques of degraded areas.
- Extensive work in rural areas in collaboration with local farmer associations
- Supervision: Prof. Alexandre Buttler, Co-supervision: Dr. Bjorn Robroek & Dr. Robert Mills

Good Festival, Lausanne, Switzerland 10.2016
Jury Member for the Good Festival, annual conference on sustainable and social innovation. The jury was also composed of the World Bank, UNDP, Ashoka and others.
http://www.goodfestival.ch

Project "Blue for Green", Morondava, Madagascar 02.2016 - 30.07.2017
Project Manager
Application of scientific research for the development of agroecology in Madagascar.
***Particular achievements*:**

- Raised 50'000 CHF (Swiss Francs) to construct an innovative well system to produce compost.
- Managed 10 people to complete the tasks.
- http://www.blueforgreenproject.org

Ingénieurs du Monde, Lausanne, Switzerland 09.2014 - 12.2015
President
IdM (idm.epfl.ch) is a student association at EPFL and UNIL (annual budget CHF 70'000), with an objective of raising awareness in development aid
***Particular achievements*:**

- Increased the membership from 35 to 70 and the number of projects handled by 30%
- With partner associations organized **semaine COP 21**, a program certified by the **French Ministry of Environment**, to raise campus awareness about the **COP 21**

Pontificia Universidad Católica de Chile, Santiago, Chili 04.2013 – 09.2013
Department of Hydrology
Research Engineer
Study of the environmental benefits of green roofs in Santiago.

EPFL - Ecole Polytechnique Fédérale de Lausanne, Switzerland 05.2012 - 10.2012
Environmental Microbiology Lab
Research Engineer
Optimization of the bioremediation of chromium contaminated groundwater. Field and laboratory work.

Impact Concept SA, Lausanne, Suisse 09.2011 - 04.2012
Environmental Engineer
Private firm. Environmental impact assessment for constructing works in Lausanne Region. Consulting to regional stakeholders (city hall, farmers, small businesses)

Education

Ecole Polytechnique Fédérale de Lausanne (EPFL) 2006 - 2011

- Master Thesis "A functional comparison between native and invasive plant species from novel assemblages in York Gum woodlands, Western Australia"
  Effectué à ***University of Queensland*****, Brisbane, Australie**
- Master of Science in water protection, soils and ecosystems Grade: 17.2/20
- Bachelor of Science in environmental engineering Grade : 16.4/20
  Exchange Program: ***Indian Institute of Technology*** **Madras, India**

Student assistantship

- Teaching assistant for the soil sciences course (3rd year of bachelor) in 2014, 2015, 2016
- Nicolas Savioz, master thesis, 2016
- Lucas Freund, engineer internship for the bachelor degree, 2016
- Clara Sanz Carillo, master thesis, 2015 - collaboration EPFL- Madrid University
- Paul Auvray, master semester project, 2015
- Nuria Turrero, master semester project, 2014 - collaboration EPFL- Madrid University
- Clara Sanz Carillo, master semester project, 2014 - collaboration EPFL- Madrid University

Scientific communication

- **Oral communications**

  Public Award 2015 "My thesis in 180 secondss", https://www.youtube.com/watch?v=Eb90yzzwQOE

  Gay-des-Combes J.M., Mills R.T.E., Robroek B.J.M., Hervé D., Ramamonjisoa B., Randriamboavonjy J.C., Razanaka S., Buttler A., 2016. Selective slashing coupled with compost amendment can lead to a sustainable slash and burn agricultural system in Madagascar. Proceedings of ATBC conference, Montpellier, France.

  Dillmann C., Swen B., **Gay-de-Combes J.M.**, Buttler A., Garcia C., 2016. If soil fertility is not the problem, compost is not the solution. Proceedings of ATBC conference, Montpellier, France.

  Gay-des-Combes J.M., Dillmann C., Sanz Carrillo C., Mills R.T.E., Garcia C., Hervé D., Robroek B.J.M., Buttler A., 2016. Can compost solve the problem of field abandonment and deforestation in a slash and burn agricultural system? : a socio-ecological study in Madagascar. Proceedings of EcoSummit conference, Montpellier, France.

- **Publications in peer-reviewed journals**

  Lai, H.R., Mayfield, M.M., **Gay-des-combes, J.M.**, Spiegelberger, T. and Dwyer, J.M. Distinct invasion strategies operating within a natural annual plant system, 2015. ***Ecology Letters***, 184: 336-346

  Gay-des-Combes J.M., Robroek B.J.M., Hervé D., Guillaume T., Pistocchi C., Mills R.T.E., Buttler A., 2017. Slash-and-burn agriculture and tropical cyclone activity in Madagascar: Implication for soil fertility dynamics and corn performance, ***Agriculture, Ecosystems & Environment***, 239: 207-218.

Gay-des-Combes J.M., Sanz Carrillo C., Robroek B.J.M, Jassey V.E.J., Mills R.T.E., Arif M.S., Falquet L., Frossard E., Buttler A, 2017. Tropical soils degraded by slash-and-burn cultivation can be recultivated when amended with ashes and compost. ***Ecology and Evolution***, in press.

- **Submitted publication**

  Gay-des-Combes J.M., Robroek B.J.M., Savioz N., Freund L., Hervé D., Ramamonjisoa B., Randiramboavonjy J.C., Razanaka S., Pistocchi C., Frossard E., Buttler A. Combined use of compost and wood ashes enhances maize growth and nutrient availability in poor tropical soils. Basic and Applied Ecology, under review (18th May 2017).

- **Publications in preparation**

  Gay-des-Combes J.M., Waeber P.O., Herlalaina P., Malalaniaina A., Freund L., Buttler A. Implementation perspectives of a new soil fertility management in traditional slash-and-burn cultivation in Madgascar.

  Ragaglini G., Branca T. A., **Gay-des-Combes J.M.**, Colla V. Use of BOF steel slag in agriculture: column test evaluation of effects on alkaline soils and drainage water.

Language Skills

French – Mother Tongue
English – Professional working proficiency (110/120 TOEFL)
Spanish – Professional working proficiency
German – Basic skills

Other experience

- Diving Certificate PADI « advanced » (max. 30m-deep diving) 11.2014
- Participated at the Patrouille des Glaciers, Verbier, Switzerland 2010 & 2014
  Ski touring high level competition in team