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Weed management using a no-till system with *Stylosanthes guianensis* cover crop in upland rice-based cropping systems in the Mid-West of Madagascar

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Declaration

I hereby declare that this PhD thesis comprises only my own research work except where indicated. Any external contribution regarding data collection or analysis as well as all the sources of information or any other material used have been fully acknowledge in accordance with the standard referencing rules. I certify that this thesis has not been previously submitted, neither partially not totally, to any University or Institution for the award of any other degree.

Rafenomanjato Antsa

SUMMARY

Food production in rich countries relies strongly on intensive use of external inputs at the expense of the environment and human health, whereas in poor countries, agriculture is characterized by low use of external inputs resulting in a meager production. To tackle these issues, agroecological practices based on crop diversification is considered as a promising approach to reduce inputs, and maintain or even improve crop production. In the Mid-West of Madagascar, the rain-fed and dry seeded upland rice system has become widely adopted by farmers because of limited irrigable lands. This cropping system is strongly infested by weeds, which are hardly under control because the only weeding intervention the poor farmers can afford is the time consuming hand pull method. An innovative upland rice cropping system using *Stylosanthes guianensis* cover crop, managed as a living mulch in a no-till system, was lately introduced in the region. This system was proven to supply nitrogen and suppress the parasitic weed *Striga asiatica* but its effect on weed community was not yet studied.

A three years research was conducted from 2016 to 2018 in the Mid-West of Madagascar in order to understand if this innovative system can be a useful tool of weed management. The methodology was based on weed floristic recording on farmers' fields, experimental fields on real farms, experimental fields on station, and surveys on farmers' perception.

Results indicated that the variables: weeding intervention timing, crop field age, the presence of maize intercropped with rice and soil management influenced the weed community. The no-till system with stylosanthes was observed to suppress dominant weed species of conventional tilled systems namely *Digitaria* spp., *Richardia scabra* and *Eleusine indica*, thus reducing the total weed biomass at harvest by 67%, and the total weed cover by 47% to 93% depending on the sampling dates. The innovative system also promoted other species namely *Mitracarpus hirtus, Cyperus* spp. and a few occasional species. The weed suppressive effect was attributed to the stylosanthes mulch which limited weed emergence and growth at early dates of the growing season. Mineral inputs combined with manure increased weed cover and weed biomass compared to manure alone. The dominant species *Digitaria* spp. increased in abundance with increasing mineral fertilization. The innovative system poses no threat to rice production, instead it was observed to increase the yield in a few cases. In weed-free conditions, higher yield in the no-till system with stylosanthes might be attributed to nitrogen supply by the legume cover crop and global soil fertility improvement such as soil texture or water regime reported in the literature. In weedy conditions, higher yield in the innovative system was interpreted as the reduction of yield loss due to competition with weeds. Results indicated that in a high weed infestations context, the yield loss was 81% - 99% in the conventional system, and reduced to 33% - 54% in the innovative system as a consequence of the weed suppression effect. In a moderate infestation context, yield losses were 39% and 26% in the conventional system and the innovative system respectively. The difference between the two systems is not significant if weed infestation is low. All this indicated that the benefits from the innovative system with respect to yield is more expressed in fields with severe weed problems. Mineral inputs increased rice yield in general, but decreased the yield when it promoted weed growth. The no-till system with stylosanthes affected also the critical period of weed interference by delaying the starting date of weed-crop competition by 11 days up to 18 days. This delay was also attributed to the stylosanthes mulch which limited weed emergence and growth at early dates of the growing season. In addition, results indicated that the presence of highly competitive weed species such as *Richardia scabra* may prompt the beginning of weed-crop competition at early dates. Farmers' general perception was in agreement with the results from field experiments. They also perceived that the innovative system decreased the weed infestation and posed no threat to rice yield. Instead, they sometimes found that yield increased. The main factors that slow down the adoption rate of the innovative system at farmers' level were the fact that a few years are required for its establishment and this time may be too long for them, insufficient fields to settle the new system, investment on necessary tools such as the roller-crimper and lack of technical skills for its management.

Information provided by this research should improve the knowledge about weeds in upland rice-based cropping systems, the relation between cover crops and fertilization, and the implication of cover crops on the critical period of weed interference. The potential benefits of stylosanthes highlighted in this study can be used to address weed issues in other countries where stylosanthes can be grown.

Keywords: weed community, weed management, cover crop, living mulch, *Stylosanthes guianensis*, upland rice, Madagascar

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1.1 Biodiversity for food and agriculture

Agriculture and food security are nowadays challenging issues in some part of the world, in the coming future they are predicted to be of high concern at worldwide scale. Progress has been achieved over the past century in increasing food production thanks to leaps in agriculture technology, yet some countries, mainly concentrated in sub-Saharan Africa and South Asia, are lagging behind and remain in a food insecure situation. Thus, the number of chronically undernourished people in the world stands at 815 million (FAO 2017b). By mid-century the world population is expected to reach more than 9 billion (World Bank, 2016). There is a need to increase food production, and a need to find a sustainable agriculture system to support this population growth.

Food production in developed and developing countries are facing a contrasted situation. Agriculture in Western countries mostly relies on large-scale intensification, using high levels of external inputs such as chemical fertilizers, pesticides, herbicides. This approach is not sustainable as it has exhausted non-renewable resources, caused severe environmental damages, and undermined the nutritional and health value of foods. For instance, phosphorus may begin to run out in the next centuries (Ashley et al. 2011), and the level of nitrogen pollution will become unacceptable (FAO 2017a). In developing countries, the agricultural sector uses very low external inputs resulting in a low productivity. In order to compensate the gap between demand and supply they use an important labour force and yet still unable to satisfy the countries' needs for food. World Development Report noted that three out of four people in developing countries are living in rural areas, accounting for nearly half of the world's population. An estimated 86 % of people living in rural areas consider agriculture the main source of income on which depends their livelihood (World Bank, 2008). Both situations, in developed and developing countries, are not acceptable and another agriculture model should be implemented to increase production and ensure its sustainability. The ideal approach is a trade-off between reducing inputs and increasing production. The use of biodiversity in agriculture presents itself as a realistic option to meet the challenges ahead.

It was stated in an expert workshop held by FAO (2010) that biodiversity can contribute to food security and agricultural sustainability. The *Convention on Biological Diversity* in 1992 defined biodiversity as diversity at genetic, species and ecosystem level (United Nation 1992). The rationales behind biodiversity conservation in natural areas are the intrinsic and aesthetic values attributed to them and the risk of destroying species or ecosystems. In agroecosystems, the first interest in biodiversity is the selection of more productive species or varieties. It can therefore be characterized as an interest in increasing *functionality* (Moonen and Bàrberi 2008). Agronomists focus mostly on the role that the cultivated and associated biodiversity may play in an agroecosystems in relation to beneficial or antagonistic effects on food production.

Functions that help to support production of harvestable goods can be considered services to agriculture, and ecological processes that detract from agricultural production can be considered as disservices (Zhang et al. 2007). Those services, provided by biodiversity, are mainly genetic resources, soil fertility enhancement, erosion protection, water flow regulation, water flow purification, pollination, pest control and weed control (Garbach et al. 2014). Biodiversity also provides disservices as many non-cultivated plants can hosts pest and pathogen, and compete for nutrients, water and pollination with cultivated crops (Zhang et al. 2007). Competition for the common pool of resources (water, light, space, and nutrients) that is often limited in field conditions and is a major determinant of crop yield, is mainly carried out by weeds (Asif et al. 2014). Weeds are in fact, the component of biodiversity that produce the most important source of disservices in agriculture. Crop yield reduction due to weeds was estimated to be higher compared to losses caused by animal pests or pathogens (Oerke and Dehne 2004).

Since the mid-twentieth century, herbicides have been the primary means of weed management in developed countries (Cerdeira and Duke 2006). Unfortunately, its use has quickly shown many downsides, and governments in different countries had establishing restrictions or limits on several chemical products (Brookes et al. 2017). In developing countries, herbicides were never been widely adopted. The initial capital expenditure was beyond small-scale farmers' financial resources unlike the use of hoes and sticks, furthermore herbicides use requires technical skill and appropriate equipment (Ampong-Nyarko and De Datta 1991). This situation impeded developing countries to produce while rich countries increased their food production, at the expenses of the environment. However, it offered an opportunity to by-pass the bad experience of developed countries with herbicides, and move directly to a better concept of agriculture through the design of food production systems that use biodiversity and place greater reliance on biological processes to achieve productivity and sustainability. Sometimes, it involves the introduction of a new component in the cropping system to counteract disservices from other components. This research was done in this framework. It focused on the impact assessment of the introduction of a cover crop in a rice-based cropping system, its effect on weeds and rice production, in a resource poor farmers' context.

The principle goal of using cover crops for weed control is replacing an unmanageable weed population with a manageable cover crop (Teasdale 1996). It cannot be achieved easily and requires knowledge on weed biology and ecology and weed management principles, as well as agricultural practices and the socio-economic context of the study area. Before going to the heart of this research work, an overview of the state of art on weeds was provided, followed by the description of the cropping system in the study area: the upland rice in the Mid-West of Madagascar.

1.2 Weeds in agroecosystems

1.2.1 Definition and concept

There are many definitions of weeds in the literature. Authors generally suggest that weeds are spontaneous plants, misplaced, useless, unwanted, troublesome, and often with high competitiveness against the plants favored by farmers: weeds are plants in a wrong place (Nelson 1946), weeds are plants which grow spontaneously in an environment modified by man (Godinho 1984), the very name weed suggests useless and harmful plants that persistently grow where it is not desired (Singh 2008), or weeds are defined as plants that impact adversely on economic, aesthetic or environmental aspects of any system (http://www.ewrs.org/weedresearch.asp). Nevertheless, it is also recognized that plants commonly considered as weeds may have some usefulness or valorization. Weeds are the first stage in the vegetative succession after land clearance or disturbance and, as such recycle nutrients and protect the soil from erosion (Rodenburg and Johnson 2009). Many species are used as human food or medicinal purposes (Stepp 2004). Weeds support a high diversity of beneficial insect species (Marshall et al. 2003). The term weed is actually a relative and anthropocentric concept rather than an absolute category (Singh 2008), and a plant species cannot be classified as a weed under all conditions (Ampong-Nyarko and De Datta 1991).

1.2.2 Weed management

Weeds form a serious limitation to agricultural and food production. Looking at the major crops in the world (wheat, rice, maize, barley, potatoes, soybeans, sugar beet and cotton) weeds have higher yield loss potential (32%) than animal pests (18%) and pathogens (15%). However, as weed control can be achieved through mechanical or chemical means, worldwide efficacy in weed control (68%) was considerably higher than the control of animal pests or diseases (39% and 32% respectively), which rely heavily on pesticides (Oerke and Dehne 2004). However, given the high damage potential of weeds, farmers have to allocate an important part of their resources to this activity in order to contain the pests in such a way that weeds do not only decrease yield but increase also the production cost.

Many strategies have been developed in order to contain weeds. It includes cultural, genetic, mechanical, biological, and chemical means. That is, a single method is rarely adequate for effective and economical control (Ampong-Nyarko and De Datta 1991). The combination of many methods known as integrated weed management, and referred to as the “many little hammers ‘approach by Liebman and Gallandt (1997) is commonly considered as the correct way to deal with weed issues. An inventory of the most common method of weed management is presented in Table 1.

Table 1: Inventory of common weed management methods

METHODS	DESCRIPTION
Cultural	Land preparation to provide weed-free condition before sowing Increasing sowing rate to increase crop canopy Delay seeding to avoid weed characteristics emergence pattern Crop rotation to break cycle of favored weed species in the crop Intercropping to increase resource exploration by diverse crops Fertilizer precision application on each plant instead of broadcasting Fertilization application at good timing and at correct rate Transplanting to give the crops a size advantage Flooding to suppress non aquatic weeds Use of cover crop and mulch to suppress weed emergence and growth Fallow improvement by planting and managing plants during fallow
Genetic	Enhancing crop traits competition ability (early vigor, tillering, height…) Enhancing traits of weed-suppressive ability (allelopathy) Adoption of herbicide tolerant crops
Mechanical	Hand-pull and simple tools (sticks, hoe, spade) Motorized weeder with rotary hoes, discs, chains may be improved by computer control systems, GPS, cameras, sensors
Biological	Release of an exotic living agent (classic method) Massive release of living agent (inundative method)
Chemical	Application of synthetic herbicides

In mechanical or chemical weed management, the timing of intervention is particularly important. Each crop has a period of time during the growth cycle when it is very vulnerable to weed competition. Therefore, the notion of critical period of weed interference (CPWI) was developed in weed science in order to determine the good timing of intervention (Knezevic et al. 2002).

1.2.3 The use of cover crop managed as living mulch in weed management

The focus of this study was weed management using a cover crop managed as a living mulch in a no-till system, thus this section was dedicated especially on this topic. A cover crop is any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted (Hartwig and Ammon 2002). The use of cover crops has developed with time and, the new trend of management practice is nowadays in a no-tillage or reduced tillage system (Lu et al. 2000). Cover crops may provide many benefits such as erosion control, reduced runoff, improved infiltration, soil moisture retention, improved soil health, nutrient enhancement, and weed control.

Cover crops may affect weeds through several mechanisms which may also occur together. The cover intercepts a portion of the radiation reducing the quantity of light available to activate the germination of some weed species, and crop residue creates a physical barrier that may inhibit the emergence and growth of many weed species, and also affect soil humidity and temperature (Teasdale 1996). Cover crop species that emerge and grow rapidly are effective in smothering weeds (Lu et al. 2000). Some plant species release allelochemicals that may inhibit weed species germination and growth (Caamal-Maldonado et al. 2001). Cover crops actually affect chemical, physical and biological conditions of the habitat/cropped field which may have a direct or indirect impact on weeds. It affects weeds during the cover crop growing period, but also in the period following the cover crop because it changed or reduced the seedbank and therefore influence the future weed community.

Weed control by cover crops show some common features: i) Its effectiveness increases with increasing residue biomass. It was indeed reported that a low quantity of residue may stimulate weed emergence instead of reducing it (Ranaivoson et al. 2017). ii) Weed control is mostly species specific. A field study reported that cover crops decreased total weed density but promoted the weed species *Bidens pilosa* (Mhlanga et al. 2015, 2016). The authors explained that it was due to the nitrogen requirement by *B. pilosa* provided by the legume cover crop. iii) Weed control by a cover crop is incomplete; effectiveness of herbicides like glyphosate, was qualified as excellent because it suppressed weeds to almost 100% (Gianessi 2005). In general, cover crops effectiveness are lower and some weeds are still able to compete with the crop. However, it is well known that herbicides have severe impact on the environment and farmers' health (Sankoh et al. 2016). Furthermore, it was observed lately many herbicides are losing their effectiveness as many herbicide-resistant weeds begun to appear in several countries (Owen and Zelaya 2005). Thus different strategy of weed management must be explored and developed to avoid relying exclusively on herbicides.

One peculiar way of using a cover crop is managing the plant as a living mulch. In this context, it is planted either before or with a main crop and maintained alive partly or all of the growing season. Species used can be perennial or annual. Perennial living mulch offers the advantage of requiring no reseeding each year but have the potential disadvantage of competing with the main crop for resources (Teasdale 1996; Hartwig and Ammon 2002).

In a conventional cropping system there are basically two components: the crop and weeds which interact with each other. On the one hand, weeds have both positive and negative effects on the crop. The detrimental effects are in general more conspicuous, though weeds can also provide some beneficial effects on nutrient recycling, soil structure, erosion control or providing support to beneficial insects (Marshall et al. 2003; Blaix et al., 2018). On the other hand, the crop normally suffers from the presence of weeds some crop species or cultivars have a strong weed suppressive ability (Dass et al. 2017). The introduction of a third component, which is the living mulch, will change the pre-existing balance, as it disrupts the existing relation between weeds and the crop, providing new positive and sometimes negative effects on the crop and weeds. The objective is to manage the cover crop in a way to maximize the positive effect on the crop while suppressing the weeds (Figure 1). This evaluation focuses mainly on rice yield but may encompass other aspects such as system sustainability over time, labor and financial investment required by the new cropping system. In addition, the whole system might be affected by environmental factors such as temperature, climate, and soil but also influenced by human factors such as external inputs or crop management. They have to be taken into account when analyzing the system ever they affect significantly the balance between crop, weeds and the cover crop (Figure 1).

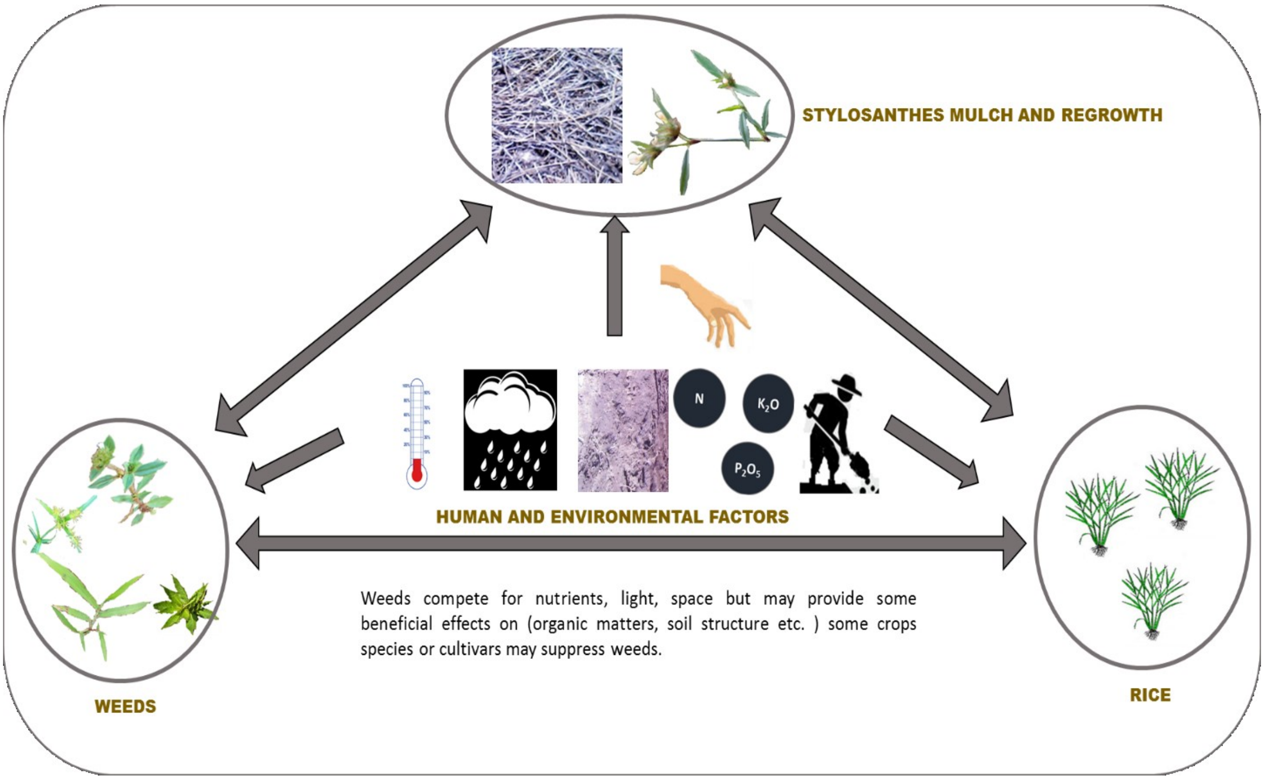


Figure 1: Interaction between weeds, rice, and stylosanthes, human and environmental factors

1.3 The context of smallholder farms in the Mid-West of Madagascar

Madagascar is an island in the Indian Ocean, near the South East Coast of Africa. The country is 587 000 km² big and it has 24.9 million inhabitants, with an average of 42 inhabitants per km² which can be considered as a relatively low population density. Malagasy people are extremely poor with only 400 US$ income per capita per year, for example the United States has 56 850 $ Gross National Income (GNI) per capita (World Bank 2016). Agriculture plays an important role in the national economy, this sector provide around 30% of the gross national income (MAAF 2014). Agricultural production relies almost entirely on family farming, made essentially of smallholder farms as 70% of Malagasy households practice agriculture as their first activity and main source of income. That means approximately 17.3 million people depend on the land, the crops and livestock in the country. These farmers depend in general on small pieces of land; 1.4 ha of crop fields per household is the national average, only 4.8 % of farmers own more than 4 ha (INSTAT 2010).

Madagascar has a diversified climatic conditions due to the elevation and dominant winds. The East part has a subequatorial climate and gets the heaviest rainfall, averaging as much as 3.5 m annually. The Central Highlands, 1000 m above sea level, receives around 1.4 m of rainfall every year, and has a cooler weather. The West coast is drier than either the East coast or the Central Highlands. The Southwest and the extreme South are semi-desert receiving as little as 33 mm of rainfall every year. Red lateritic soil predominates in a large part of the country. This soil type has a low fertility and so impose some limits to agriculture. However, there are richer soils in a few part of the island due to former volcanic activities. This diversity offers different agricultural characteristics for each region.

The Mid-West of Madagascar in-between the Center Highlands and the West Coast is at a middle altitude 800 - 1300 m above sea level (Figure 2). It receives an annual rainfall averaging at 1300 mm and temperature averaging at 23°C. There are basically two seasons, winter is the dry season beginning from June to September, and summer is the rainy season beginning from October to May. Many annual crops can be grown in the region during the rainy period of the year.

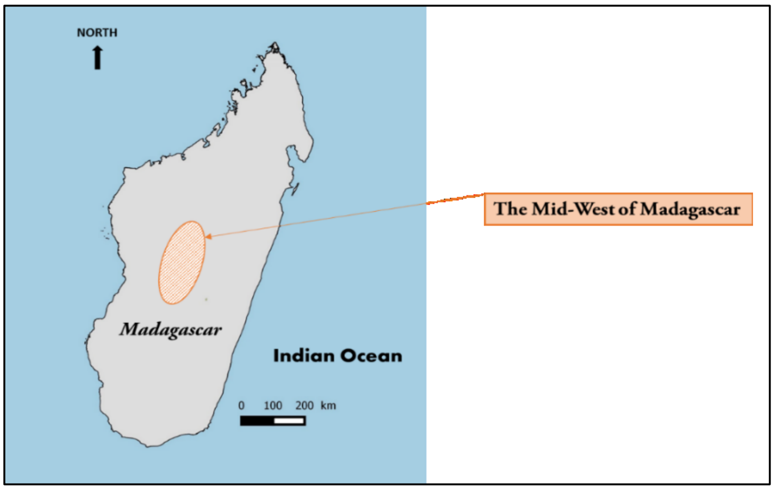


Figure 2: The Mid-West of Madagascar

A recent survey about agricultural practices in the Mid-West of Madagascar (Razafimahatratra et al. 2017) illustrated that the most popular crops are rice, maize, cassava, peanuts, Bambara groundnuts, but farmers grow also some vegetables. Rice is the most important, it occupies 42% of total crop fields. Fields are generally scattered around villages, one farmer cultivates on average seven crop fields having a relative small size (0.25 ha). In this context, agricultural operation are essentially done manually, with the help of a spade-like tool called *angady* (Photo 2). This tool is used for plowing, sowing and weeding. Some farmers can also afford animal traction for land preparation. Mineral fertilizer application is not very common, it is practiced by one farmer out of four at a very low rate, around 18 $kg.ha^{-1}$. The most widely used fertilizer is cattle manure applied at a very variable rate 2 - 5 $t.ha^{-1}$ depending on the cropping system, around 4.1 $t.ha^{-1}$ on upland rice. Farmers' use of chemical pesticide is only on seeds to provide protection against seed-eating insects after they are sown.

1.3.1 Expanding cropping systems based on upland rice

Rice has arrived in Madagascar probably a thousand years ago, brought by the first settlers from Indonesia and Malaysia, since then it has become the staple food. Consumption rate is estimated to be around 98 kg milled rice per person per year (FAO/WFP 2018) ranked among the highest in the world. It highlights the enormous relevance of this cereal in Malagasy people diet. Rice field occupies around one-third of the total cultivated land, even though the country does not produce enough to satisfy the population‘s need. Madagascar imports 240 000 tons/year to fill the gap (FAO/WFP 2018).

In the Mid-West, like in many regions of Madagascar, rice is mainly cultivated in two different agroecosystems depending on water supply (Photo 1). The most common system is the irrigated system where rice is grown in lowlands and receives water supply both from irrigation and rainfall. The other system is the upland rice grown on higher topography and relies exclusively on the rainfall for water supply. In the irrigated system, rice is usually transplanted and then flooded. This method gives the crop an important size advantage over weeds and limits infestation by suppressing non aquatic weeds. On upland, rice is direct seeded then losing the benefits of transplanting, and without the standing water protection, aerobic weed species are able to grow freely. For these reasons, farmers primarily chose the lowlands for rice cultivation. However, during the last few decades, lowlands in the Mid-West were rapidly saturated due to a fast growing demographic. Population increased by 2.7% per year according to World Bank (2016). This accentuated the need to increase rice production already in deficit. As an alternative, farmers begun to extend rice cultivation on the uplands. Currently upland rice has become vital for the population in many parts of Madagascar, especially in the Mid-West where lowlands are quite limited and uplands are rather large due to the typical topography of the region. Around 65% of total crop lands in the Mid-West are uplands (Razafimahatratra et al. 2017).

lowland rice (Autfray P., 2017)

upland rice (Rafenomanjato A., 2017)

Photo 1: Rice fields in the Mid-West of Madagascar

In uplands, rice is commonly rotated with other crops such as bambara groundnuts, peanuts, and cassava and very often associated with maize. In this association and succession pattern, rice is always the central crop. It is the more convenient to consider the whole system as an upland rice-based cropping system. The conventional rice cultivation method is by plowing the soil 20 cm deep in October for land preparation, then rice is sown in November in shallow hole in 20 x 30 cm grid and harvested in March-April. All activities are done manually and with simple tools: *angady* for plowing and seeding, and sickle for harvesting. This system is facing many constraints threatening its sustainability. They are mainly soil depletion due to erosion, insect attacks, and weed infestation. The Mid-West is endangered by erosion due to the frail characteristic of the soil, water run-off drags fertile particles from the top of hills to the bottom and severe ravines can be observed almost everywhere in the Mid-West landscape. Regarding insect pests, the white grubs (*Heteronychus* spp.) is a plague for upland rice in the Mid-West. To tackle the problem, farmers apply the insecticide imidacloprid on rice seeds, this method helps to control to a certain extent the insect. It is actually the only pesticide used in upland rice cropping systems. Finally, weeds form the biggest constraint because they are very difficult to control and cause important yield losses in rice and other upland crops.

1.3.2 Weed management in upland rice systems

In the context of poor resource farmers in the Mid-West of Madagascar, the use of herbicides did not gain popularity because of the price of the product and its non-availability in the market. Motorized weeding machineries are even less adequate as farmers worked on small pieces of lands. Therefore, the main method of weed removal in upland rice is hand-pull combined with the spade-like tool called *angady*.

Photo 2: Weeding by hand and by the *angady* (Rafenomanjato A., 2017)
(When weeds are still small the angady is a helpful tool, but when they grow up the weeding is exclusively achieved by hand because of the risk to cut rice roots with the blade of the metal tool)

The hand-pull method can reduce direct competition from weeds and prevents weed seed production when achieved in good timing and properly. However, it is not always the case as hand weeding is a painful work and time-consuming. Some farmers hire contract workers but it is expensive. In the Mid-West, the salary for weeding is 0.8 € per days for six hours of work, but considering the time necessary it may become a substantial sum. The hand weeding also shows some disadvantages. It is not effective in dry soil where weed seedlings break and resprout easily. Repetitive hand weeding is then necessary because very small weed seedlings that are not removed grow quickly to reinfest the rice field (Ampong-Nyarko and De Datta 1991). Therefore, the hand-pull method can be implemented only when weeds have reached a sufficient size to be pulled. Thus the weeding intervention is often practiced later than it should be, by which time competition for resources, extraction of metabolites, or phytotoxic effects, in case of parasitic weeds, has already taken place (Rodenburg and Johnson 2009). The last bottleneck that hinders weeding activities in upland rice is a work overload. Farmers usually begin to sow rice in November shortly after the first rainfall, thus a serious weeding has to be achieved in December when rice seedlings are still small and weak against weed competition. At the same period, many other agricultural tasks should be accomplished, mainly transplanting of lowland rice. This situation narrows farmers' availability for weeding on upland rice.

There was an urgent need to design a new rice-based cropping system able to reduce weed problems and maintain rice production. The extensive use of herbicide is not a viable alternative because of the high damage and risks for the environment and human health due to these chemical products (Yadav et al. 2015; Sankoh et al. 2016; Kim et al. 2017). An agroecological solution based on the use of cover crops can be a potential solution. Several cover crops have been tested by researchers and promoted by rural development projects in the Mid-West and one of them showed to have the potential to be adopted by farmers. It is the legume cover crop *Stylosanthes guianensis* (Razafimahatratra et al. 2017).

1.3.3 An innovative cropping system based on the use of *Stylosanthes guianensis* CIAT 184

Stylosanthes guianensis (Aubl.) Sw is a legume with a wide distribution in tropical, subtropical and temperate regions of America, Africa and South East Asia (Williams and gardener, 1984). In India, it is extensively utilized in pastoral, agropastoral and silvipastoral systems for animal production, due to its ability to restore soil fertility, improve soil physical properties and provide permanent vegetation cover (Chandra et al. 2006). The cultivar CIAT 184 has gained popularity because of its broad adaptation, potential for multiple uses and high productivity in acid, infertile soils (Guodao and al., 1997). This cultivar was introduced by a local rural development NGO TAFA and the French research institution CIRAD in 2002 for experimental purposes, and then distributed in real farms since 2004.

The adoption rate of stylosanthes in upland rice cropping system is still low, about 2%, Nevertheless, it appeared to be the only cover crop that is actually adopted by farmers (Razafimahatratra et al. 2017). Most trials to introduce other species on real farms (e.g. *Mucuna pruriens*, *Arachis pintoi*, *Cynodon dactylon*) have failed and only studies on experimental stations are available. There are a few reasons behind the relative success of stylosanthes. Firstly, it can be managed as perennial crop and therefore requires no extra-investment for seeds every year. Secondly, it can produce the very high amount of biomass needed to cover the soil completely and this trait is very appreciated for a cover crop. Finally, its management can be achieved without herbicides (Séguy et al. 2012). Originally, the objective of stylosanthes introduction in Madagascar was to restore soil fertility, limit erosion as a permanent cover of soil surface, and provide additional forage for the cattle. It is well known that cover crops influence many aspects of cropping systems including nutrient availability, soil texture, soil temperature, soil moisture, erosion, leaching, crop establishment and weed control (Teasdale 1996). Therefore, an integrated approach is needed in order to assess the full potential of stylosanthes. Recent experiments on this cover crop in the Mid-West of Madagascar showed that stylosanthes has a positive effect on nitrogen supply for the crops (Zemek et al. 2018), and reduced the parasitic weed *Striga asiatica* (L.) Kuntze infestation, compared to the conventional tilled system (Randrianjafizanaka et al. 2018). In the lastly cited study, it was noticed that total weed biomass was lower in the system with stylosanthes compared to the conventional system. This is supported by others results from Laos (Saito et al. 2006) and Southern Benin (Saito et al. 2010) which have also proven some suppressive effect of stylosanthes grown during fallow on weeds.

The possibility of undersowing rice and stylosanthes in an intercropping system was already investigated in Laos 43 years ago, it was back then managed as an annual cover crop, then seeded every year simultaneously with rice (Shelton and Humphreys 1975). In Saito et al. (2006, 2010) stylosanthes was seeded a few days after rice and also managed as an annual cover crop. In the Mid-West of Madagascar, stylosanthes is managed as a perennial living mulch, an innovation management of the system in itself. Seeded once during the year of its establishment, stylosanthes regrows spontaneously by sprouts and its own seeds the subsequent years.

Details of the cropping system management is as following. In preparation of the coming cropping season, stylosanthes is rolled during the dry season to control its development (Photo 3). To fully control stylosanthes, two rollings are done in June, just with a one-week interval and another in September. The rollings are done by a heavy cylinder pulled by cows called *rolo-faca*. It is a tool developed in Latin-America for living mulch control, and is similar to the tractor-mounted roller-crimper used in developed countries. It consists of a cylinder or drum with blunt blades set across its lengthwise, the cylinder rolls around an axle, which is pulled along behind the power source. The blades on the drum crimp and crush the plant shoot as it rolls over them (Wildner et al. 2004). The rollings do not kill the cover crop but turn it into a sleeping flat mulch. From sowing, then the cultural calendar to that of the conventional system. Rice is sown by hand through the mulch in November. It begins to germinate and grows up first. About two or three weeks later the stylosanthes wake up and begins to revive by producing new green leaves via sprouts or germinates by its own seeds. In March-April, rice is harvested and the stylosanthes left to grow on the field until June when it is rolled again for the next cropping season. In general, the following crop that will grow with stylosanthes is maize, and sometimes cassava.

Photo 3: Stylosanthes rolling and rice emerging through the stylosanthes mulch (**Rafenomanjato A., 2017**)

1.4 Thesis framework and general methodology

The present study has been achieved within the framework of the research project STRADIV (System approach for the TRAnsition to bio-DIVersified agroecosystems). The project works in the Mid-West of Madagascar and other countries addressing agroecosystems and biodiversity issues.

In the Mid-West of Madagascar, upland rice has gained popularity because of the saturation of lowlands for irrigated rice. Yet upland rice - based cropping system produces a low yield because of the poor soil fertility, weed infestation, and limited time availability for farmers to implement hand weeding. The agroecological solution based on the use of stylosanthes, managed as a living mulch in a no-till system, has been introduced originally in the region to enhance soil fertility and protect against erosion. It has been proven recently to improve nitrogen availability (Zemek et al. 2018) and suppress the parasitic weed *Striga asiatica* (Randrianjafizanaka et al. 2018), but its effect on weeds abundance and community composition was not yet studied in the region. Based on the assumption that some plants that produce an important biomass are capable of dominating naturally occurring weeds, this study was conducted with the aim to evaluate the capacity of stylosanthes, managed as a living mulch, to suppress weeds and provide sustainable rice yield. Farm observations, field experiment on farms and on station were carried out. In addition, a survey among farmers was conducted to acquire knowledge on farmers' practices and their perception regarding the main rice weeds and stylosanthes.

The definition of weeds within the framework of this study was that any species which was not planted deliberately by the farmer in the current cropping season was to be considered as a weed. This is based on the definition of weeds stating that weeds are plants in a wrong place (Nelson 1946), or plants that grow spontaneously in an environment modified by man (Godinho 1984). This definition was taken as it is easy to apply on the field and subject to less ambiguity.

The research specific objectives in this study were:

- Describe the weed community composition in upland rice in the Mid-West of Madagascar and define field and management characteristics that affected the weed community composition. The hypothesis was that a few weed species dominate the weed community, and weeds respond to some field and management characteristics, especially the past crop and the current rice growing method (rice alone, rice intercropped with maize or rice in a no-till system with stylosanthes mulch)
- Compare the conventional rice system based on tillage with the no-till system with a stylosanthes cover crop in terms of weed community composition, weed infestation and rice yield. The hypothesis was that the alternative system would change the weed community composition, reduce total weed cover and biomass and pose no threat to rice production.
- Determine the effect of mineral fertilizer application in terms of weed infestation levels in the conventional system and in the no-till system with stylosanthes. The hypothesis was that mineral fertilizer application would increase weed infestation and interact with soil management.
- Determine the difference in critical period of weed interference with the crop among the conventional system and the no-till system with a stylosanthes cover crop. The hypothesis was that the crop-weed competition timing is influenced by soil management.
- Determine the farmers' perceptions on the most important weeds of upland rice, on the difficulties regarding weed management, and on the no-till system with stylosanthes as an agroecological option for weed management. This was done by means of survey to collect farmer's opinions, in sight of opening the way for a future participatory research process on weed management.

The study was carried out in 2016, 2017 and 2018 growing seasons. Rice cropping season in the upland systems in Madagascar is between November and April. The growing season is referred to as the year in which harvest took place. Climate data during the study and the previous decade are presented in Figure 3 and Figure 4. Data were obtained from a meteorological station setup by a collaboration between the French research institution CIRAD and national research institution FOFIFA. The station is located at a village called Ivory (19°33.29'S, 46° 24.91 'E). The climate data showed that the temperature is stable over time since the curves of the years of the study and the average of the last 10 years were almost identical. Rainfall data instead showed an important variability. In January, February and March of the year 2015, the amount of rainfall was abnormally high. This year was particularly rainy as the total rainfall during the cropping season was 1715 mm while the average of the previous decade was 1099 ± 145 mm. In 2016, 2017 and 2018 the average rainfall during the cropping season were 1220 mm, 1231 mm and 1241 mm respectively. The rainfall during the three years of field experiments was slightly higher than the standard year but still in the range of normal rainfall amount. The year 2015 is prior to the experiments but it was intentionally mentioned as it may affect the subsequent year in term of weeds or crop development.

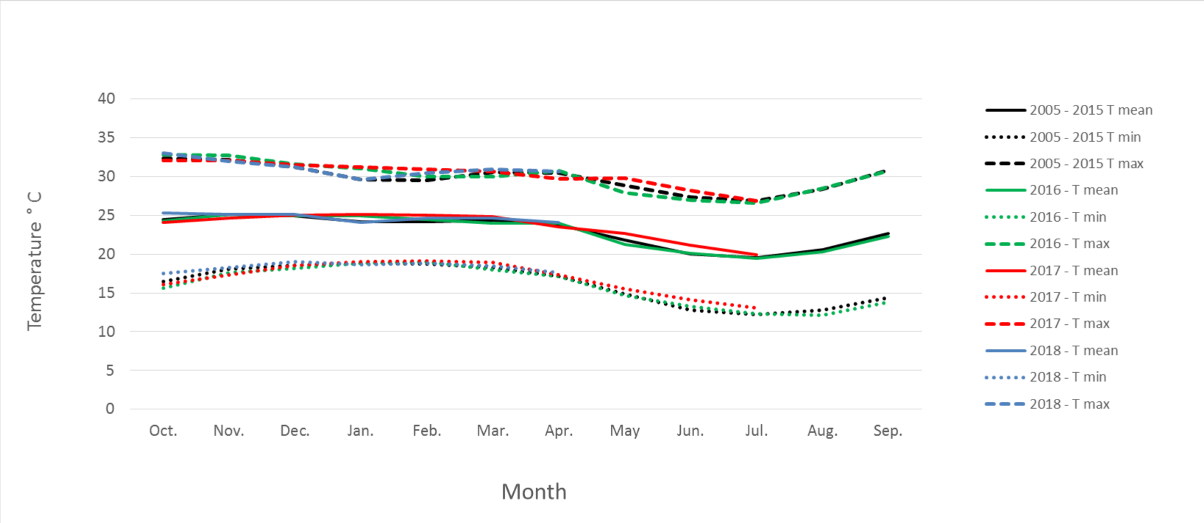


Figure 4: Average monthly temperature during the experiment and the previous decade
Climate data of August and September 2017 and from April 2018 on were not available

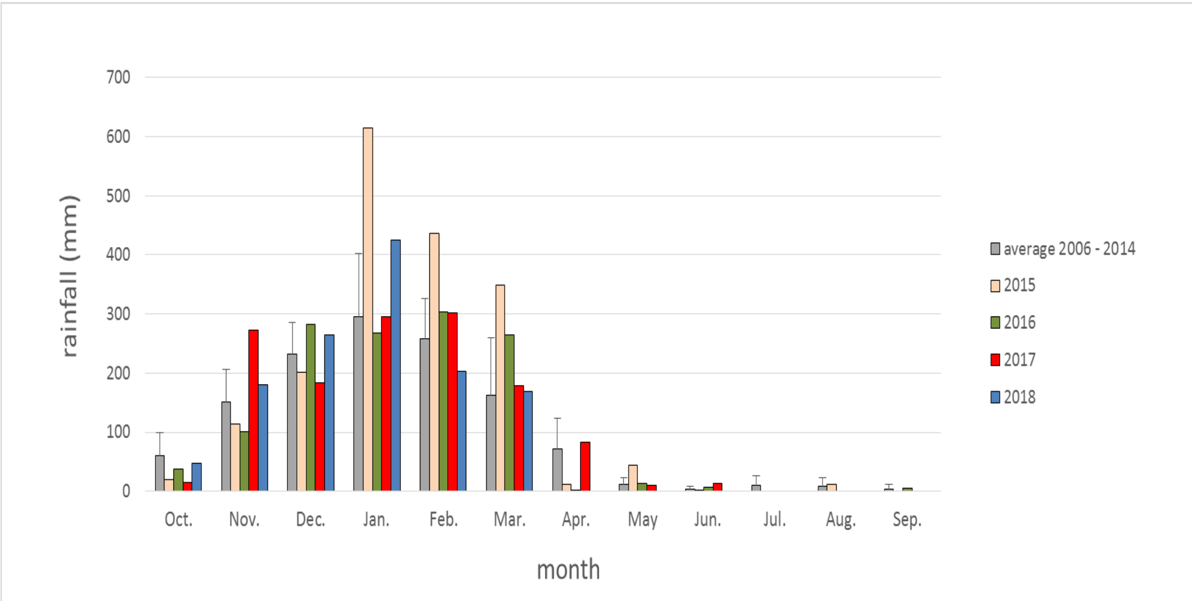


Figure 3: Monthly rainfall
Climate data of August and September 2017 and from April 2018 on were not available
Error bar on top of the average rainfall between 2006 -2014 is the standard deviation

The thesis is articulated in seven chapters:

- **Chapter 1:** General introduction
- **Chapter 2:** Weed community composition of upland rice in the Mid-West of Madagascar (To be submitted for publication)
- **Chapter 3:** Effect of soil management on weeds and rice yield (experiments on farms) (To be submitted for publication together with the previous chapter)
- **Chapter 4:** Effect of soil management and fertilization on weeds and rice yield (experiments on station). (Poster presentation at the 18^{th} EWRS Symposium in Ljubljana, Slovenia in June 2018; to be submitted for publication)
- **Chapter 5:** Critical period of weed interference (Oral presentation at the 18^{th} EWRS Symposium in Ljubljana, Slovenia in June 2018; to be submitted for publication)
- **Chapter 6:** Farmers' perception on weeds and stylosanthes (Oral presentation at the First agroecology Europe Forum in Lyon, France, October 2017)
- **Chapter 7:** General discussion and conclusion

Chapter 2 : Weed community composition of upland rice in the Mid-West of Madagascar

2.1 Introduction

The description of the weed community is the first step in elaborating a weed management strategy. Information on weeds in Africa and other tropical countries including Madagascar is already available in *Adventrop* (Le Bourgeois and Merlier 1995) and the web site WIKWIO (http://portal.wikwio.org/). A weed community characterization was done in the South-West of Madagascar (Randriamampianina 2001), and another recent work was achieved to provide an inventory of the main weeds in the whole country (Husson et al. 2010). Prior to the present research, a preliminary study was carried out in order to have a global description of weed community in upland cropping systems in the Mid-West of Madagascar (Rakotoniriana 2015). However, these studies were mostly descriptive.

Literature reports several possible ways in which cropping practices and environmental conditions may affect the weed community composition. According to a study at national scale in France, the most important factors that determine weed community composition are human management factors, current crop type, soil pH and to a lesser extent soil texture(Fried et al. 2008). The crop sequence in a rotation pattern may influence weeds due to the dissimilar management practices (Rao et al. 2007), allelopathic interference (Nichols et al. 2015), unstable and frequently inhospitable environment that prevents the proliferation of a particular weed species (Liebman and Dyck 1993). Where crop rotation is practiced, a diverse weed flora will result (Ampong-Nyarko and De Datta 1991). The crop spatial arrangement may impact as well the weed population, some species sometimes reduce in abundance and other increase when additional crop were added with the main crop in the field (Baumann et al. 2000; Banik et al. 2006). In general, the practice of monoculture is thought to intensify the simplification of weed communities, resulting in weed flora dominated by one or a few weed species highly adapted to the growing conditions (Liebman and Dyck 1993). Tillage management is also assumed to influence considerably weeds composition based on different mechanisms. The plowing moves upside-down the weed seedbank on the top layer of the soil (Ampong-Nyarko and De Datta 1991). No-till systems accumulate seeds near the soil surface where they are more likely to germinate but are also exposed to greater mortality risks through weather variability and predation (Nichols et al. 2015). The use of cover crops which is frequently associated with no-till systems changed profoundly the system and consequently the weed infestation which may result (Teasdale 1996; Ranaivoson et al. 2017).

Given the diversified crop rotation sequence, crop combination and the recent introduction of a no-till system with a cover crop in the Mid-West, one may expect variability in weed flora. However, as many weeds species show a strong adaptation to the change in their environment, it may also happen that no significant difference in weed community composition exist different rice-based cropping systems. The objective of this chapter was to determine if the weed communities are affected by factors such as previous crop, current rice growing method, fields' age, tillage management and cover crops.

The specific objectives were (i) to make an inventory of weeds growing in rice-based cropping systems in farmers' fields in the Mid-West (ii) to determine the dominant species (iii) to identify fields' characteristics that may act as a driver of the weed community composition.

2.2 Materials and methods

2.2.1 Study area and monitored fields

The study was conducted during two cropping seasons: 2016 and 2017. The study area was the administrative units: Ankazomiriotra (19.6597° S, 46.5324° E), Vinany (19.6308°S, 46.4927°E) and Inanantonana (19.72054°S, 46, 6140°E), stretching across 30 km along the national road 34. A total of 91 farmers' fields were monitored: 48 and 43 fields in 2016 and 2017 respectively (Figure 1).

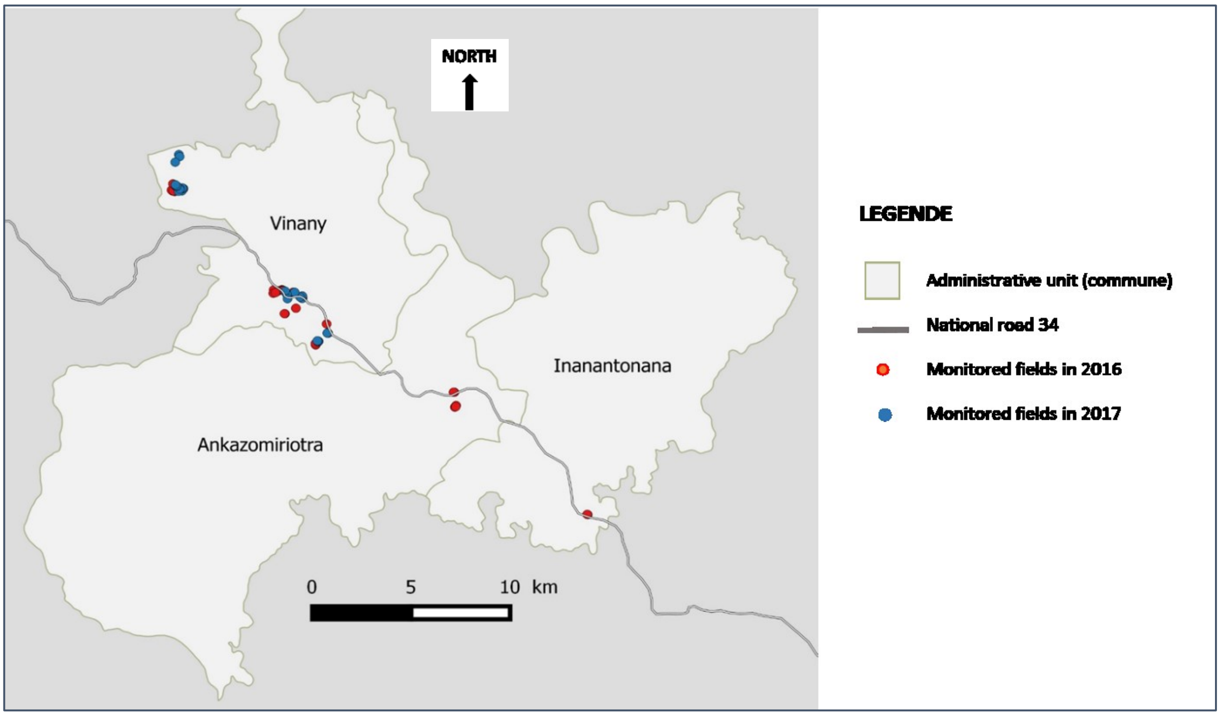


Figure 1: Dispersion of monitored farmers' fields in the study
(Shape.file data base FTM 200 (Foiben'ny Taontsarintanin' i Madagasikara), performed with QGIS 2.10)

2.2.2 Crop management

All monitored fields were sown with rice or rice intercropped with maize. The maize – rice intercropping is very frequent crop association in the Mid-West where maize is always sown at a very low density (1 m x 1.5 m grid). The fields were managed by farmers according to local practices in this region: in October the soil was plowed 20 cm depth with spade (except for a no-till system), then rice seeds sown in November-December and harvested in March-April. The sowing was done by hand in 20 x 30 cm grid and manure applied at the same time at a rate of 5 $t.ha^{-1}$ dry matter approximately. No mineral fertilizer was used or applied at a very low rate (only one field received 37 $kg.ha^{-1}$ of mineral input). Weed management was a systematic combination of spade weeding and hand-pulling between 20 DAS and 40 DAS, afterwards interventions were generally sporadic and localized weed removal depended on the weed infestation level and the farmers' availability. No herbicide was used. Rice cultivars planted by farmers were very diverse including a few cultivars developed by different research centers (Chhomrong dhan, scrid 98, scrid 91, sebota, nerica 4, nerica 9) and several local cultivars on which little information is available. The following field's characteristics were recorded based on interviews and fields observation: current crops, previous crop, tillage management, cover crops, fertilization, field age, and first weeding date.

2.2.3 Data collection

Weed sampling was performed at 60 DAS and 90 DAS in order to characterize weed community composition. Circles of 5 m radius (about 78 m^2) in the middle of each field were used as sampling quadrats (two quadrats for fields > 2000 m^2 which were subsequently averaged, and one quadrat for fields < 2000 m^2). Weed sampling consisted in recording all weed species growing in the quadrat, and making an estimation of total weed cover and of each species cover inside the quadrat. It would have been better to have two or even three quadrats for each fields, in order to reduce the effect of weed flora variability inside the field, but many fields were too small to allow sampling spatial repetition without going too close to field borders.

2.2.4 Data analysis

Weed species were classified according to their frequency of occurrence and their local cover in sampling quadrats. Frequency is the proportion of sampling unit (quadrats) that contains the species. Cover is estimated by the projection of the weed species biomass on the ground surface expressed as percent covered by each species, or by the overall weed community to obtain the total weed cover. Local cover is the average cover of a given species in quadrats where the species was present. This classification was adapted from the method presented in Le Bourgeois and Merlier (1995). In the present chapter, species having high frequency (> 30%) and high local cover (>5%) were considered as dominant, whereas species with a low frequency (< 10%) and a low cover (< 2.5 %) were classified as occasional species. It referred to the famous 1-5 Braun-Blanquet cover-abundance scale (Braun-Blanquet 1932), where the threshold of 5% cover corresponds to the scale-value '1' describing very scant species. That would separate species more relevant or less relevant in the weed-crop competition outcome. The other thresholds in the classification were chosen arbitrarily. In general, when there was an important gap of frequency or cover value between two or many species, a threshold was chosen in-between to gather species with approximately the same value of cover or frequency in the same class. Preliminary data analyses demonstrated that the species classification from sampling data at 60 DAS and 90 DAS presented a similar pattern, therefore only species classifications at 60 DAS was presented in the results.

To detect weed community variability across years and sampling dates, analysis of variance was performed on total weed cover using the ***lme*** function in the package ***nlme*** **(Pinheiro and al. 2016)** in R program version **3.3.2** **(R Core Team 2016)**. To explore weed community composition pattern and identify field characteristics which may explain the weed community composition, ordination analyses were performed using the CANOCO program version 5.2 (Ter Braak 2017). A linear model was used to assess field characteristics affecting the abundances of dominant weed species, whereas a unimodal model was used to detect the effect of field characteristics on species turn-over between fields. In a first step, a RDA (Redundancy Analysis) and a CCA (Canonical Correspondence Analysis) with forward selection of the treatments, year as co-variable, and a Monte-Carlo Permutation test with 499 replications, were performed to assess which characteristics significantly contributed to the difference in species composition. In a second step a PCA (Principal Component Analysis) and CA (Correspondence Analysis) were performed and the significant field characteristics were superimposed in the ordination space, in order to express the maximum variability in species composition and the correlation with the treatments. Species data were transformed to meet homogeneity of variances according to: 2*arcsine (square-root (proportion weed cover)).

Preliminary analyses showed no great differences between the species composition of 60 and 90 DAS, and since at 90 DAS some species were already at senescence, results for 60 DAS was shown because it represented the full expression of the weed community, and in the period between 20 and 60 DAS the weed community has the biggest impact on rice yield (ref. Chapter 5).

2.3 Results

2.3.1 Weed community composition

A total of seventy-nine species were recorded during all samplings. The classification showed that the most dominant species were *Digitaria* spp. and *Richardia scabra* having high frequency and high cover. *Digitaria* spp. is actually a combination of three species, *D. horizontalis*, D. *bicornis* and *D. ciliaris,* which occur all together in this area but cannot be distinguished at a young stage. The other dominant species were *Eleusine indica, Cleome hirta* which had also a high frequency but with an average local cover. Highly frequent species with low cover was *Mollugo nudicaulis* and species with low frequency but high cover was *Rottboellia cochinchinensis* (Table 1).

Regarding weed groups, broadleaved weeds showed the highest species number represented by 61 species, grass accounted 14 species, and sedges only 4 species. However, grasses and broadleaved weeds had the same total cover, in 2016 grasses had even a higher cover. This is due to the highly dominant grass weed *Digitaria* spp. (Table 2).

Table 1: Species classification by frequency and local cover

Sampling data at 60 DAS from 2016 and 2017

		Frequency of occurrence		
		100% - 30%	30% -10%	10% - 0%
Local cover	100%- 5%	*Digitaria* spp. *Richardia scabra*	NONE	*Rottboellia cochinchinensis*
	5% - 2.5%	*Cleome hirta* *Eleusine indica*	NONE	*Jacquemontia tamnifolia,* *Echinocloa colona,* *Spilanthes costata,* *Brachiaria umbellata,* *Melinis repens*
	2.5%- 0%	*Mollugo nudicaulis*	*Mitracarpus hirtus,Urena lobata,* *Melochia pyramidata,* *Sida acuta, Cyperus* spp. *Acanthospermum hispidum,*	OCCASSIONAL SPECIES

- NONE *means that no species has fallen in the class*
- *A complete species list is provided in supplementary material* 1

Table 2: species richness and abundance for each weed group

Sampling data at 60 DAS from 2016 and 2017

weed group	number of species	Average cover (%)
Grass	14	10.47
Broadleaved	61	10.68
sedge	4	0.11

Average cover is the sum of the cover of all species in the group inside the quadrats divided by the total number of samplings

2.3.2 Change in the weed abundance across years and sampling dates

The total weed cover was significantly higher in 2017 compared to 2016 (p = 0.0024, df = 1), and significantly higher at 90 DAS compared to 60 DAS (p= 0.0017, df = 1) (Figure 2). This result indicated a variability of weed infestation level across years, and also showed that weed cover keeps on growing after 60 DAS despite some interventions which could have been implemented by the farmers.

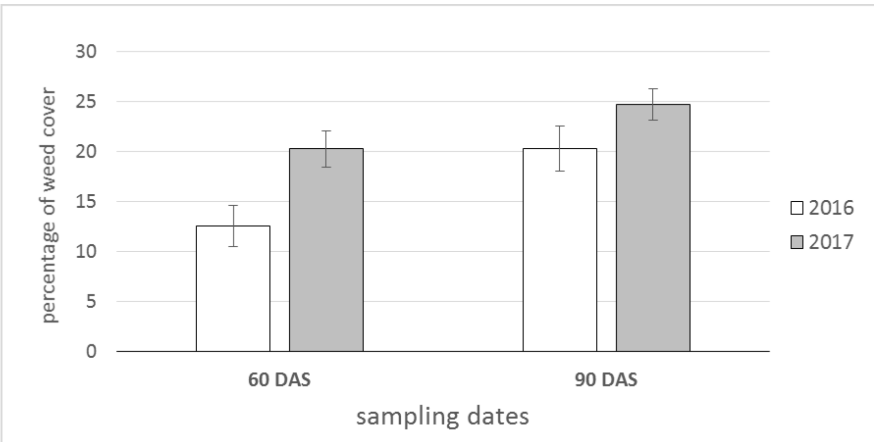


Figure 2: Total weed cover

- Year effect was analyzed using year as fixed factor and sampling date as random factor
- Date effect was analyzed using sampling date as fixed factor and year as random factor

2.3.3 Effect of field characteristics on weed community composition

A summary of field characteristics recorded is presented in (Table 3). The majority of rice fields were managed in a conventional till system and a few were managed in no-till system with stylosanthes cover crop. The majority of fields were more than 10 years old and a few were younger than 10 years. The current crops were rice monocropping or rice-maize intercropping with roughly balanced number between the two possibilities. Previous crops were classified to legume (groundnuts, peanuts), grass (rice or maize) and tuber (cassava) in case of intercropping the dominant crop in terms of presence was chosen. The first weeding mostly occurred around 30 DAS but with some variability: earliest at 20 DAS and latest at 40 DAS. Fields were fertilized only with manure, except one field which received 37 kg.ha^{-1} of mineral input.

Table 3: summary of fields' characteristics recorded

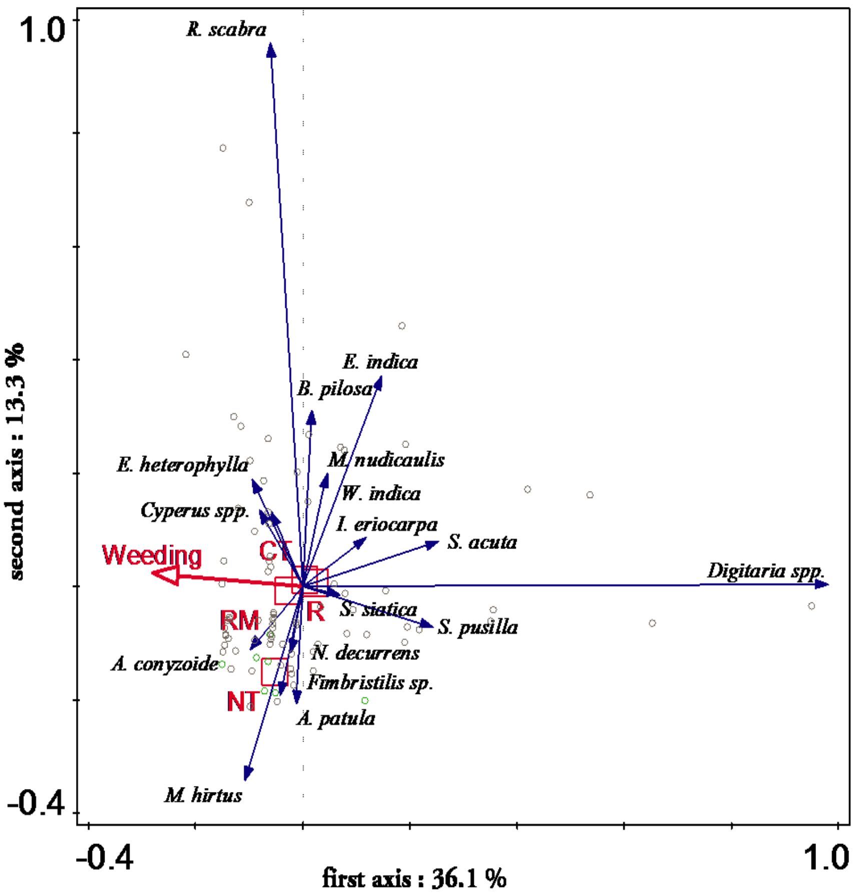
Factors	Description and number of fields
Soil management	CT = 84, NT = 7
Crop field age	> 10 years = 85, < 10 years = 6
Current crop	rice = 50 , rice + maize = 41
Previous crop	grass = 49 , tuber = 25, legume = 17
First weeding date	average = 30 ± 5 DAS, min 20 DAS and max 40 DAS

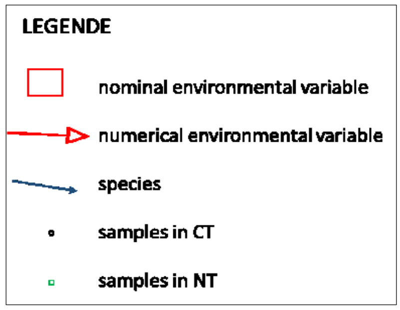
The PCA showed that farmers' fields can be characterized in three categories (Figure 3): fields highly infested by *R. scabra,* fields highly infested by *Digitaria* spp*.,* and fields which were not particularly infested by neither of the two species. The NT system appeared to be in opposition with strong infestation of *R. scabra* and in association with *Mitracarpus hirtus* and *Neojeffreya decurrens*. With increasing weeding date the infestation with *Digitaria* spp*.* decreased. The rice - maize intercropping was associated with *Mollugo nudicaulis* and in opposition with *Digitaria* spp. The effect of these three factors were significant but they explain only a small part (8.5%) of the total variability in the community composition (Table 4).

The CCA showed that soil management, crop field age, current crop, and the first weeding date impacted significantly the weed species turn-over. The impact of these factors were generally low (8.8% of total variability explained), but still significant (Table 5). The NT system was associated with the probability of the presence of *Mitracarpus hirtus* and *Neojeffreya decurrens*, a late weeding date increased the probability of the presence on *Sida acuta* (Figure 4). It was not clear which species among those who contributed to the diversity of the community was particularly associated with the current crop and the crop field age. Young fields were strongly associated with *Hyparrhenia* sp*.* but this species was not presented in the graph due to its low participation to the community composition diversity.

Table 4: Factors that significantly affected weed species composition with regard to abundance
P-value determined by the Monte Carlo permutation test through interactive forward selection of Redundancy Analysis (RDA)

Factor	Explain (%)	P –value
first weeding date	4.0	0.008
soil management CT	2.4	0.044
present crop	2.1	0.048





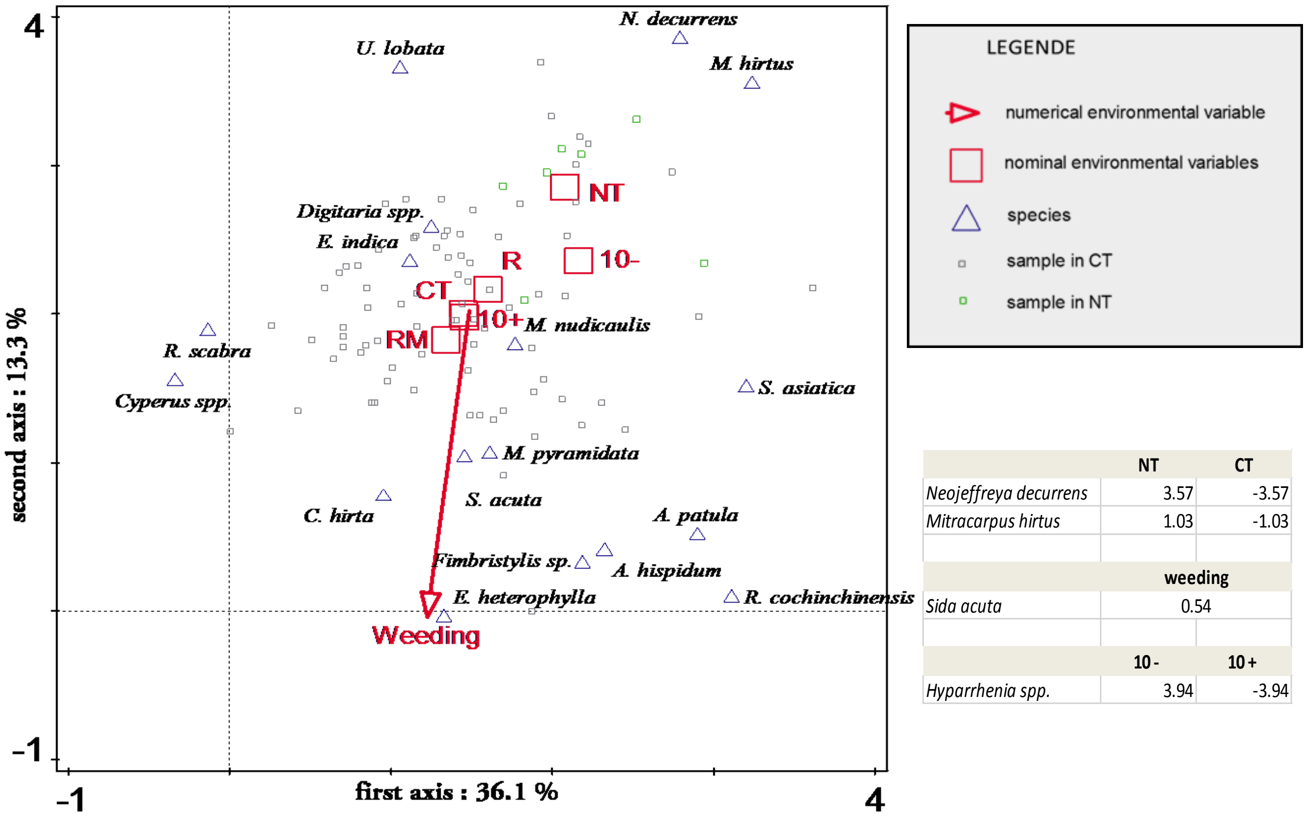
	NT	CT
Mitracarpus hirtus	0.60	-0.60
Neojeffreya decurrens	0.33	-0.33
Richardia scabra	-0.43	0.43
	R	**RM**
Digitaria spp.	0.63	-0.63
Mollugo nudicaulis	-0.37	0.37
	weeding	
Digitaria spp.	-1.19	

Figure 3: Principle Components Analysis on weed community composition with supplementary explanatory variables in case they resulted to affect the weed community composition significantly based on the Monte-Carlo Permutation test. Only the 17 species with the strongest contribution to the sample ordination were represented. Table on the right presents the strongest association observed between species and explanatory variables: the higher is the absolute value of the score the stronger is the association, a positive score means a positive association and a negative score means a negative association.

Variables codes: **weeding** is the first weeding date after sowing; soil management: **NT =** no-till with stylosanthes cover crop, **CT =** conventional tilled. Current crop: **R** = rice monocropping, **RM** = rice-maize intercropping

Table 5: Factors that significantly affected weed species composition with regard to species turn-over
P-value determined by interactive forward selection of Canonical Correspondence Analysis (CCA)

Factor	Explain (%)	P -value
soil management	2.9	0.002
crop field age	2.5	0.012
current crops	1.7	0.004
first weeding date	1.7	0.032



	NT	CT
Neojeffreya decurrens	3.57	-3.57
Mitracarpus hirtus	1.03	-1.03
	weeding	
Sida acuta	0.54	
	10 -	10 +
Hyparrhenia spp.	3.94	-3.94

Figure 4: Correspondence Analysis on weed community composition with supplementary explanatory variables in case they resulted to affect the weed community composition significantly based on the Monte-Carlo Permutation test. Only the 17 species with the strongest contribution to the sample ordination were represented. Table on the right presents the strongest association observed between species and explanatory variables: the higher is the absolute value the stronger is the association, a positive score means a positive association and a negative score means a negative association.

Variables codes: **weeding** is the <u>first weeding date</u> after sowing; <u>soil management</u>: **NT =** no-till with stylosanthes cover crop, **CT =** conventional tilled; <u>current crop</u>: **R** = rice monocropping, **RM** = rice-maize intercropping; <u>crop field age</u>: **10+** crop field cultivated more than 10 years and **10 -** less than 10 years.

2.3.4 Discussion

The total of 79 species recorded in farmers' fields was very close to the number obtained from the preliminary study of Rakotoniriana (2015) which yielded 77 weed species. Considering the fact that some species presented are actually a group of species (*Digitaria* spp*., and Cyperus* spp.). It can be assumed that the actual number of species in upland cropping systems in the Mid-west is slightly above this figure. A review of the literature on weeds in rice-based cropping systems across Africa by Rodenburg and Johnson (2009) yielded 61 common weed species of uplands. Only a few weed species dominate the population in each rice ecosystem (Johnson and Kent 2002), weed management should mainly focus on those species because occasional species pose no threat to the cultivated crops and since their occurrence cannot be predicted, no preventive measures can be taken to control them.

The lower weed cover in 2016 compared to 2017 is maybe linked to the climate of the previous year. The rainfall amount in 2015 was extremely high. The result of Rakotoniriana (2015) showed a particularly high weed infestation in 2015 which may have reduced the weed seeds ready to germinate the next year. Another possible explanation is a lower quantity of rainfall at the beginning of 2016 cropping season causing a weed emergence delay (Chapter 1: Figure 4). It was indeed reported that rainfall may impact the weeds (Fried et al. 2008). All this may indicate a complex impact of climate across years on the weed infestation.

In this study *Digitaria* spp*.* and *Richardia scabra* were the most dominant species. *Eleusine indica* and *Cleome hirta* can be also considered as dominant at some extent*. Digitaria horizontalis* is among the most cited weeds of upland rice in Africa (Rodenburg and Johnson 2009). During the sampling it appeared that *Digitaria horizontalis* had the highest proportion in the *Digitaria* spp. actually made of three species, the two other species *D. bicornis* and *D. ciliaris,* were less present and appeared mostly towards the end of rice growing cycle. It was difficult to evaluate the precise proportion of the three species during the sampling given their morphological similarities at young stage. However, when *D. bicornus* and *D. ciliaris* begun to flower around 90 DAS, (*D. horizontalis* began to flower earlier), a rough estimation showed that *D. horizontalis* occupied around 70% of the total cover of the group *Digitaria* spp*.* The other dominant species *Eleusine indica* is a fast growing and prolific-seed-producing weeds (Rodenburg and Johnson 2013), each plant can produce up to 40 000 seeds (Le Bourgeois and Merlier 1995). According to farmers, *E. indica* and *Digitaria* spp*.* are suspected to be spread by cattle manure which is the common fertilizer in uplands (see chapter 5). This may explain the high frequency of those species in upland rice fields. The dominant broadleaved weed *Richardia scabra* was also reported as dominant species in some studies in sub-Saharan Africa (eg. Mhlanga et al. 2015), although it was not mentioned in the literature review of upland weeds in Africa by Rodenburg and Johnson (2009). It is possible that *R. scabra* emerged after the publication of the above review. That would make this broadleaved weed a relatively new emerging species. This seems to be in line with the farmers' statement relating the recent arrival and rapid dispersion of this pest in the Mid-West of Madagascar (see Chapter 5).

With respect to weed groups, broadleaved weeds presented the highest number of species, and sedges the lowest. This is not a particularity of the Mid-West of Madagascar as such relative proportion was frequently observed in studies on upland rice in other countries (e.g. Amadou et al. 2013). In general, sedges did not appear to be important weeds of upland cropping systems, weeds in the *Cyperaceae* family are mostly weeds of lowland rice (Rodenburg and Johnson 2009).

The factors recorded showed a low contribution in explaining weed community composition. This is probably linked to the high variability in real farms condition. However, some variables showed significant effect and allowed to engage interpretation. The no-till system with stylosanthes affected the weed community by reducing the abundance of *R. scabra* which was one of the two most dominant species in tilled systems. It already gives an indication that this system might be a useful tool to control this species. On the other hand, no-till the system appeared to promote *Mitracarpus hirtus* and *Neojeffreya decurrens*. It is a confirmation of literatures stating that cover crops suppressive effect on weeds is species specific (Teasdale 1996). An early weeding appeared to increase the abundance of *Digitaria* spp*.* This species can appear sooner or later in the rice growing season, it can easily reinfest the field after an early weeding, and can therefore be abundant at 60 DAS. The association of *Hyparrhenia* sp. with young fields should indicate that it is a weed of fallow fields, this species can be observed in many non-cultivated land in the Mid-West. It was difficult to speculate about the reason behind the association between the presence of maize intercropped with rice and the apparition of *Digitaria* spp*.* or the reduction of *Mollugo nudicaulis,* experiments may highlight these points.

The effect of the no-till system with stylosanthes cover crop (NT) appeared to be an interesting path for further investigation. The soil management factor was actually unbalanced, 84 fields in conventional till (CT) and only 7 fields in NT, thus limited the interpretation of the results. The choice to focus on CT fields was to give more importance to this system which is still by far the dominant upland cropping system in the region. A more accurate assessment of the effect of the NT system on the weed flora needed a more balanced observation between CT and NT. However, it is remarkable that the variability in weed composition among the seven NT fields was low as they were grouped in the same area of the ordination space, indicating that this system resulted in a clearly distinguished weed composition (Figure 3 and Figure 4).

Regarding the sampling methodology, *density* and *frequency* are the two most popular methods of measuring abundance in weed science. *Density* is the number of individuals per unit area, whereas *frequency* is the proportion of sampling units that contains the species. In this study however, it was decided to use *cover* and *frequency*. *Density* estimation is time consuming, necessitates an ability to identify weed species at very young stage which is always difficult, and does not take into account the difference in size between individuals. *Cover* on the other hand is a visual estimate, and as such, can be subjective and relatively inaccurate, but *cover* estimation is a fast and easy method and might provide a better indication of the importance of the competition carried out by weeds because as it gives more weight to individuals reaching important size (Nkoa et al. 2015). The actual limit of the methodology is maybe that the importance of damage due to the parasitic weed *Striga asiatica* cannot be correctly assessed by the parameters *cover* and *frequency*. This species spends long part of its life cycle underground, during which it makes the most important damage on rice. This species cannot be neglected as the parasitic weed is well known to be a major biotic constraint in african upland rice cropping system, including Madagascar's (Teka 2014; Rodenburg et al. 2016). Thanks to a recent study in the Mid-West of Madagascar, it was proved that the NT system with stylosanthes can reduce *S. asiatica* infestation level by 79 % (Randrianjafizanaka et al. 2018).

2.4 Conclusion

The upland rice-based cropping system in the Mid-West of Madagascar consists of a weed flora of at least 79 species. The most dominant species were *Digitaria* spp. and *Richardia scabra.* Broadleaved weeds and grasses had the same importance in terms of cover even though broadleaved weeds were more diverse in term of species. Sedges had a lower prevalence and represented mainly by the genus *Cyperus*. Weed infestation level may vary considerably across year, this variation was attributed to rainfall. Timing of the first weeding intervention, soil management, current crop, and age of crop field affects significantly the weed community although they explain only a small part of the total variation in species data. The effect of the weeding timing and the soil management are interesting to be investigated furthermore because they are the components on which the farmers can actually intervene. The suppressive effect of NT system on the dominant species *R. scabra* and the positive effect of late weeding on *Digitaria* spp. abundance may be a good start to launch new hypotheses. In this perspective, experiments were conducted with a more balanced number of treatments to compare fields and plots with different soil management and weeding regime. These are developed and discussed in the following chapters.

Chapter 3 : On-farm experiments to determine the effect of the no-till system with stylosanthes on weed abundance, weed composition and rice yield

3.1 Introduction

Agroecology is a concept which gained popularity during the last decades. The term initially referred to crop production and protection aspect. Today, it has evolved to encompass a scientific discipline, agricultural practice, and apolitical or social movement (Wezel et al. 2009). Among agroecological practices, the introduction of cover crops in an agroecosystem has arisen a lot of interest because of the many potential benefits that it may provide. The most conspicuous management practice for using cover crops is in no-tillage or reduced tillage cropping systems (Lu et al. 2000). All over the world, research is being carried out on the possible integration of diverse cover crops species in cropping systems and many interesting results were reported and reviewed in literature (Teasdale 1996; Lu et al. 2000; Hartwig and Ammon 2002).

There are several possible ways to use cover crops, however they are not all suitable in the specific context of the Mid-West of Madagascar. Instead of copying successful practices in the North and trying to fit it in the South part of the world, a better approach is probably to develop innovative cropping systems using knowledge from all over the world and collaborate with local farmers. The possibility to grow stylosanthes in rice cropping systems was already proven in Laos, Benin, Thailand (Shelton and Humphreys 1975; Saito et al. 2006, 2010). In these contexts, the cover crop was managed as an annual crop and fallow crop instead of living mulch like it is done in Madagascar. The rolling technique used on stylosanthes was imported from Latin America where it was already a popular method to control cover crops (Wildner et al. 2004). It can be said that the no-till system with stylosanthes in the Mid-West of Madagascar is born from a combination of knowledge and experiences learned from abroad and applied in the local context.

Studies in northern Laos and Benin showed that stylosanthes used as a fallow crop can increase subsequent rice yield and reduced weed biomass (Saito et al. 2006, 2010). In addition to its potential effect on weed suppression, stylosanthes was reported to have the ability to restore soil fertility and improve soil physical properties (Chandra et al. 2006). For these reasons it was considered as an interesting candidate for the degraded soil of the Mid-West of Madagascar. Two studies were carried out on stylosanthes in this region, and were recently published. They demonstrated that stylosanthes managed as living mulch in a no-till system improves crop nitrogen supply (Zemek et al. 2018), and suppresses the parasitic weed *Striga asiatica*, if compared to the conventionally tilled systems (Randrianjafizanaka et al. 2018). However, the effect of this innovative system on the weed community was not yet evaluated in the Mid-West of Madagascar until the present study.

The objective of this chapter was therefore to evaluate the effect of the NT system with stylosanthes on weed community composition, total weed cover and rice yield. The hypothesis was that this agroecological practices would change the weed species composition, reduce the total weed cover and pose no threat to rice yield compare to the conventional system, in the context of real farm conditions.

3.2 Materials and methods

3.2.1 Study area and monitored fields

The study was conducted during two cropping seasons: 2016 and 2017 in the administrative units of Ankazomiriotra (19.6597° S, 46.5324° E) and Vinany (19.6308°S, 46.4927° E), both in the Mid-West of Madagascar. The soil of the region can be characterized as a clay-loam Oxisol (USDA). The elevation is between 9 00 m and 1100 m above sea level. During the cropping season (November - April) the average temperature is around 24.5 ° C and stays stable across years while the total rainfall is 1100 ± 145 mm subject to some variation across year. During the experiments the rainfall during the cropping season were 1220 mm, 1231 mm in 2016 and in 2017 respectively.

Two upland rice cropping systems were compared: the conventional tilled cropping system (CT) with the no-till system with stylosanthes cover crop, managed as a living mulch (NT). The experiment was conducted on a total of 41 farmers' fields (Table 1). In 2016, the soil management treatment was unbalanced due to technical problems, but it was correctly balanced in 2017.

Table 1: Number of field managed in CT and NT during the two years of experiment

	cropping season 2016	cropping season 2017
CT	12	12
NT	5	12

3.2.2 Crop management and experimental design

In CT the fields were plowed 20 cm deep before sowing. In NT, stylosanthes was grown alone during the previous rainy season (November - May), and during the dry season (June-October) it was rolled three times using a roller crimper (the *rolo-faca)*, there was no plowing but rice was sown directly in the stylosanthes mulch. NT fields were managed without tillage with stylosanthes cover crop for several years (> 5 years) by the farmer in charge. Therefore, they can be considered as stable cropping systems. Similarly, fields in CT were plowed in the conventional way for many years and therefore can be assumed to be stable as well. Weed management in all monitored fields was consistently based on hand-pull method for several years backwards, herbicides application on upland crops is negligible in the study area.

Crop management for both systems was as following: rice was sown by hand in a 20 x 30 cm grid in November-December and harvested in March-April, manure was applied at sowing at 5 $t.ha^{-1}$ rate of dry matter. These management practices were carried out by farmers according to local practices in this region, they were not imposed for experimental purpose.

At rice emergence, for experimental purpose this time, plots of 3m x 3m were defined inside each field, and different weeding regime (treatments) were imposed on each plots. Treatment locations were randomized. Each treatment was replicated 3 times in the field: **3 weedy plots**, **3 weed-free plots**, and **3** plots where weeds are managed by farmers in the standard local practices (**FM)**. In the NT fields 3 more plots were added that were **weed-stylo-free**. The weed management in each treatment is described in (Table 2) and the disposition of plots in (Figure 1).

The local weeding practice is through hand-pulling with the help of a spade-like tool called *angady*. One full intervention around 30 days after sowing followed by a sporadic and localized intervention depending on weed infestation and farmers' availability. No herbicide was used.

In 2016, farmers were allowed to use the rice cultivar of their choice, as a result the cultivars were not the same in all monitored fields: some cultivars were from different research centers (scrid 98, sebota, nerica 4) and others were local cultivars on which little information is available. In 2017, it was decided to homogenize all cultivars into Nerica 4 provided by STRADIV project to reduce source of variability related to rice cultivars and seeds origins.

Table 2: Weed management details for each treatment

Treatment	Description
weedy plots	unweeded from sowing until harvest, in NT stylosanthes regrowth was not removed
weed-free	weekly weeded, in NT stylosanthes regrowth was not removed
weed-stylo-free	weekly weeded and stylosanthes regrowth were removed (exist only in NT)
FM	weeds and stylosanthes management by farmers in standard local practices

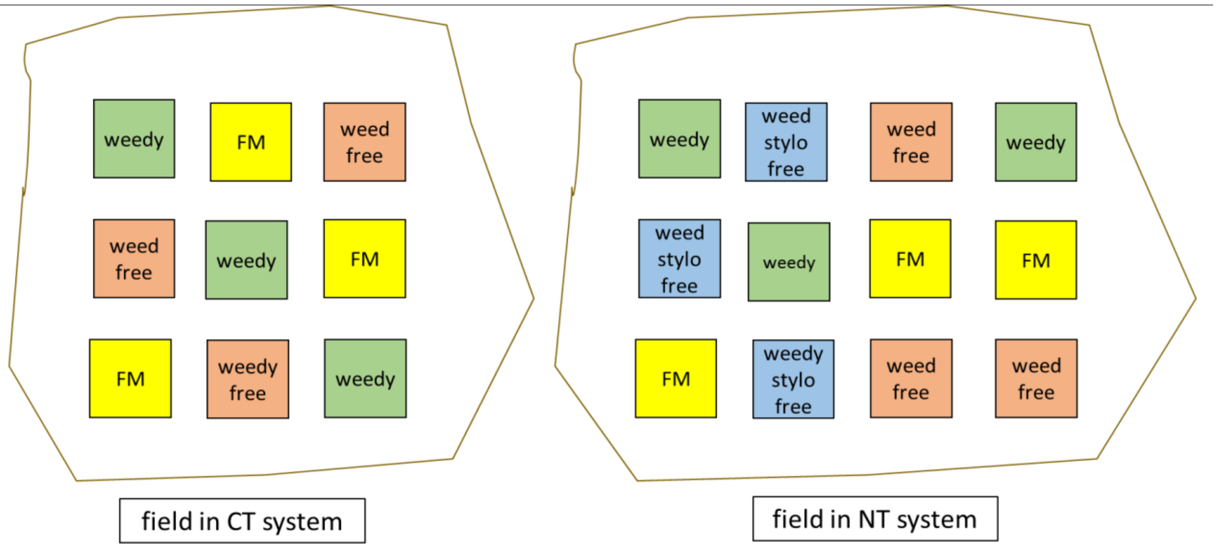


Figure 1: Plots disposition inside the field

3.2.3 Data collection

Weed sampling was performed at 60 DAS, 90 DAS and 120 DAS using the whole plots as quadrats, the last date corresponds approximately to harvest date. At harvest, rice grain yield, weed biomass and stylosanthes regrowth biomass were weighted inside the same quadrats of the weed sampling. Grasses, broadleaved weeds and sedges were weighted separately. Samples of rice grains, weeds and stylosanthes were collected at harvest, dried 72 hours in oven at 60 °C to estimate moisture content. Grain yield was then adjusted to 14%.

3.2.4 Data analysis

Weed species were classified according to their frequency of occurrence and their local cover, thus the species having the highest frequency and local cover were considered as dominant species. Frequency is the proportion of sampling unit (quadrats) that contains the species. Cover is estimated by the projection of the weed species biomass on the ground surface expressed as percent covered by each species, or by the overall weed community to obtain the total weed cover. *Local cover* is the average cover of a given species only from the quadrats where the species was present. This classification was adapted from method presented in Le Bourgeois and Merlier (1995). In this chapter, species having a high frequency (> 30%) and a high local cover (10%) were considered as dominant, whereas species with a low frequency (≤ 10%) and low cover (≤ 5 %) were classified as occasional species. It referred to the famous 1-5 Braun-Blanquet cover-abundance scale (Braun-Blanquet 1932), where the threshold of 5% cover corresponds to the value '1' describing very scant species. That would separate species more relevant or less relevant in the weed-crop competition outcome. The other thresholds used in the classification were chosen arbitrarily. In general, when there is an important gap of frequency or cover value between two or many species, a threshold was chosen in-between to gather species with approximately the same value of cover or frequency in the same class. Preliminary data analyses demonstrated that the species classification from sampling data at 60 DAS and 90 DAS presented similar pattern, therefore only species classification at 60 DAS was presented in the results.

Analysis of variance was used to evaluate the soil management effects on weed cover, weed biomass and rice yield. The analyses were performed with ***lme*** function in the package ***nlme*** **(Pinheiro and al. 2016)** in R program version **3.3.2** **(R Core Team 2016)**.

Ordination analyses were used to identify weed species associated to CT or NT, performed with CANOCO program version **5.2** **(Ter Braak 2017).** In a first step, a RDA (Redundancy Analysis) with forward selection of the treatments based on the Monte-Carlo Permutation test, year as co-variable, was performed to assess which factor significantly contributed to the difference in species composition. In a second step a PCA (Principal Component Analysis) was performed and the significant treatment variables were superimposed in the ordination space, in order to express the maximum variability in species composition and the correlation with the treatments. Mean species abundance sampled at 60 DAS was calculated based on the three sub-samples taken per fields. Data were transformed to meet homogeneity of variances according to 2*arcsine (square-root (proportion weed cover)).

All results presented with respect to weed community composition refer to the sampling data at 60 DAS, because that is the period in which weeds most heavily impact rice yield as has been shown from the critical period of weed interference experiment (see Chapter 5). Furthermore, results from the analyses of the species composition at 90 and 120 DAS were quite similar (data not shown).

3.3 Results

3.3.1 Species classification

The total number of weed species during the samplings were eighty. Based on the assumption that weed composition varies between soil management the species classification was performed separately for CT on one hand and NT one the other hand (Table 3 and Table 4). The result of weed species classification from weedy plots showed that the dominant species in CT were *Digitaria* spp., *Richardia scabra* and *Eleusine indica* (Table 3). Most dominant species in NT were *Digitaria* spp. and *Cyperus* spp.

Table 3: Species classification by frequency and local cover (CT system, 60 DAS, weedy plots)

		Frequency of occurrence		
		100% -30%	**30% -10%**	**10% -0%**
Local cover	**100%-10%**	*Digitaria* spp., *Richardia scabra*, *Eleusine indica*	NONE	NONE
	10% -5%	NONE	*Cleome hirta*	*Sesbania sesban, Cyperus* spp., *Tridax procumbens, Cucurbita* sp
	5%-0%	*Mollugo nudicaulis*	*Urena lobata*, *Hibiscus asper*	OCCASIONNAL SPECIES

- NONE *means that no species has fallen in the class*
- *A complete species list is provided in supplementary material* 1

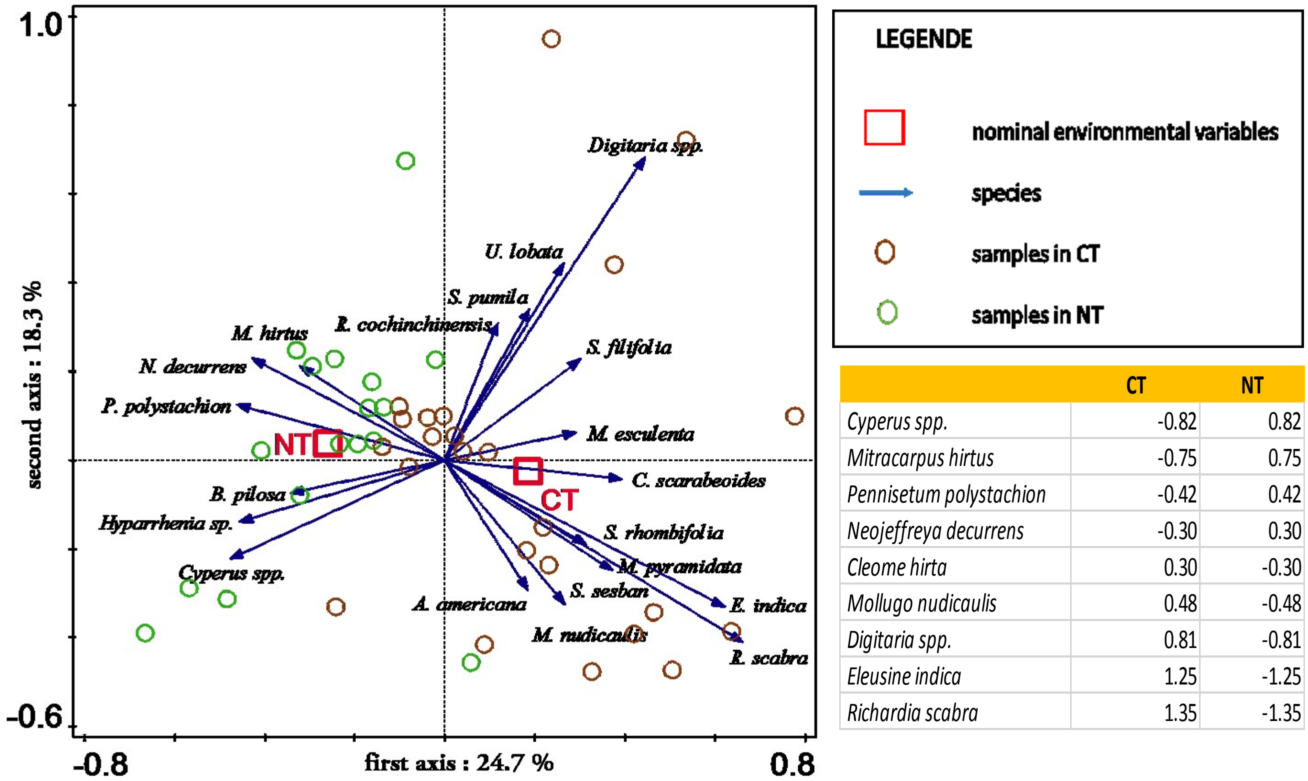
Table 4: Species classification by frequency and local cover (NT system, 60 DAS, weedy plots)

		Frequency of occurrence		
		100% -30%	**30% -10%**	**10% -0%**
Local cover	**100%-10%**	*Digitaria* spp., *Cyperus* spp.	*Richardia scabra*	*Heteropogon* sp.
	10% -5%	NONE	*Cleome hirta*, *Hyparrhenia* sp., *Pennisetum polystachion,*	*Hibiscus asper,*
	5%-0%	*Neojeffreya decurrens*, *Mitracarpus hirtus*	*Eleusine indica, Bidens pilosa*, *Ageratum conyzoïde*, *Setaria pumila,Melinis repens,*	OCCASIONNAL SPECIES

- NONE *means that no species has fallen in the class*
- *A complete species list is provided in supplementary material* 1

3.3.2 Weed community response to the NT system with stylosanthes

The ordination analysis showed that soil management had a significant effect on the weed community composition (p = 0.002). It explained 14.5% of the total variation of the species data at 60 DAS. The NT system was associated with high abundance of *Cyperus* spp. and *M. hirtus* and also *P. polystachion* and *N. decurrens* to some extent. The CT system was associated with high abundance of *R. scabra*, *E. indica* and *Digitaria* spp. and also to *M. nudicaulis* and *C. hirta* to some extent (Figure 2).



	CT	NT
Cyperus spp.	-0.82	0.82
Mitracarpus hirtus	-0.75	0.75
Pennisetum polystachion	-0.42	0.42
Neojeffreya decurrens	-0.30	0.30
Cleome hirta	0.30	-0.30
Mollugo nudicaulis	0.48	-0.48
Digitaria spp.	0.81	-0.81
Eleusine indica	1.25	-1.25
Richardia scabra	1.35	-1.35

Figure 2: Principle Components Analysis on weed community composition at 60 DAS, with supplementary explanatory variables soil management. Only the 20 species with the strongest contribution to the sample ordination were represented. Table on the right presents the strongest association observed between species and soil management type: the higher is the absolute value the stronger is the association, a positive score means a positive association and a negative score means a negative association

3.3.3 Effect of NT system with stylosanthes on weed cover and weed biomass

In weedy plots of 2017 weed cover was significantly lower in NT than in CT (p = 0.018, df = 1), an average difference of 47% was observed at 60 DAS (Figure 3). Comparable results were observed in the following sampling dates, 90 DAS and 120 DAS. It indicated an overall weed suppression effect by the no-till system with stylosanthes cover. In plots where farmers' management (FM) was applied, the weed cover was low and similar in both systems. It indicated that the farmer's intervention reduced weed infestation at the same level in both systems. In 2016 statistical analysis was not implemented because of the unbalanced number of fields between the two systems (12 in NT and only 5 in CT), the data however, indicated the same trend observed in 2017.

Total weed biomass at harvest was similar in the NT and CT averaging at 81 ± 8 g.m² dry matter. Grasses biomass was also similar, averaging at 64 ± 9 g.m², sedges biomass was meaningless 0.025 g.m² and not relevant for analysis. Broadleaved weeds biomass was significantly lower in NT than CT ($p=0.001$, df =1): 26 ± 5 g.m² and 7± 3 g.m² in CT and NT respectively.

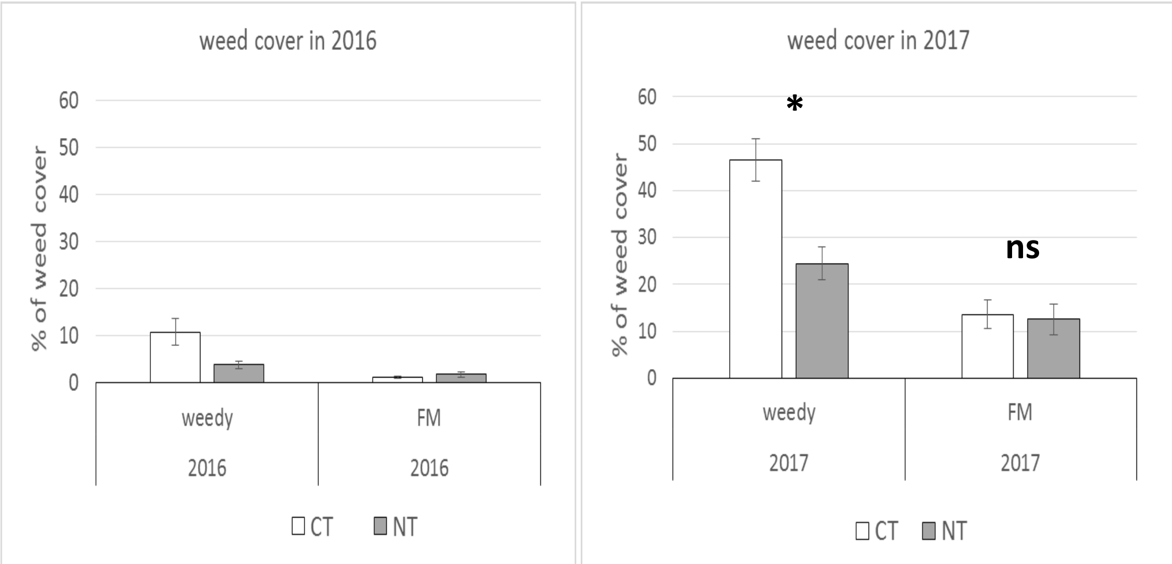


Figure 3: Effect of NT with stylosanthes on total weed cover at 60 DAS

`Liner mixed model was used to analyze the effect of soil management on weed cover in 2017, Response variable = weed cover, fixed factor = soil management, random factor = fields, the response variable was log transformed to improve residues distribution pattern.`
`Significance: * (p<0.05), n.s (p>0.05)`

3.3.4 Effect of NT system with stylosanthes on rice yield

The yields were relatively low mainly due to the lack or insufficient mineral fertilizers, the maximum yield was 2.87 $t.ha^{-1}$ recorded on NT weed-stylo-free plots in 2017. In general, the yield in 2016 was lower than the yield in 2017.

In 2016, the yield trend was inconsistent and no statistical analysis was implemented because of insufficient number of field managed in NT. In 2017, the rice yields were significantly higher in NT than in CT in weedy plots ($P = 0.037$, df = 1), and in farmers' plots ($P = 0.049$, df = 1). In weed-free plots no difference between the two systems was confirmed by statistical analysis (Figure 4).

To evaluate the impact of weed infestation on rice yield, yield loss due to weeds was evaluated in 2017. This was done separately for CT and NT fields. The two systems were considered as completely independent because a field was either managed in NT or CT. The result was summarized in Table 5. In the CT system, yield was lower in weedy and FM compared to weed-free. In the NT system yield was lower in weedy, higher in weed-stylo-free, and similar in FM in comparison to weed-free. This result indicated that weeds actually caused substantial yield losses in both systems, and also indicated that removing stylosanthes regrowth or not may affect the rice yield.

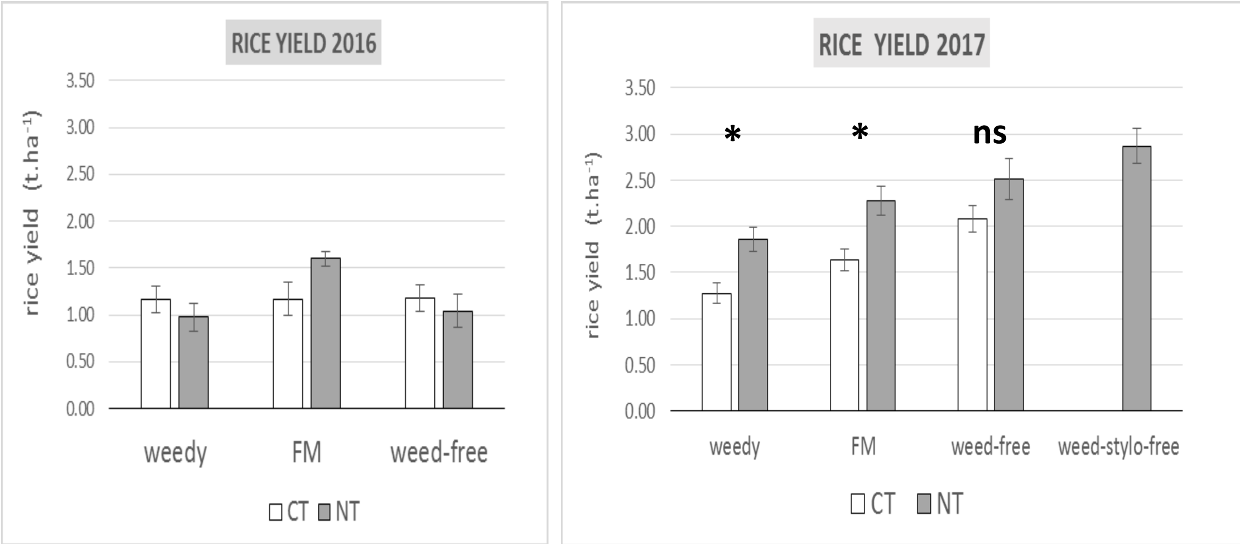


Figure 4: Effect of soil management on rice yield and effect of stylosanthes regrowth interference

Linear mixed model was used to analyze the effect of soil management on rice yield in 2017, Response variable = rice yield, fixed factor = soil management, random factor = fields.

Table 5: Rice yield losses due to weeds and stylosanthes regrowth interference in 2017

	Yield loss in CT compared to weed-free CT	Yield loss in NT compared to weed-free NT
weedy plots	- 39 %	- 26 %
FM plots	- 21 %	ns
weed – stylo – free plots		+ 14 %

Liner mixed model was used to analyze the effect of weed management on rice yield in 2017
The analysis was performed separately in each soil management level
Response variable = weed cover, fixed factor = weed management, random factor = fields
Signs meanings: (-) yield decrease, (+) yield increase, (ns) non-significant difference compared to the yield from weed-free plots.

3.4 Discussion

3.4.1 Weed community responses to the NT system with stylosanthes cover

The result of our study corresponds to what is related in the literature. A cover crop effect on weeds is species specifics (Teasdale 1996), which basically means that some species may be suppressed and some others can be possibly promoted, thus changing the weed flora and sometimes the total weed cover. Regardless of the stylosanthes mulch, the no-till component of the system may have played also a role in weed flora shift. Literature indeed report that weed species composition may differ between a no-till and a tilled system and some species are associated with the one or the other system (Blackshaw et al. 1994; Swanton et al. 1999).

The NT system with stylosanthes showed a suppressive effect on all dominant species in the CT system. I suppressed *R. scabra*, *E. indica*, *Digitaria* spp., and also suppressed *C. hirta* and *M. nudicaulis*. *Digitaria* spp. was highly dominant in both soil management systems, however its abundance was more associated to the CT system. This agroecological practice seems to be an interesting tool to managed fields infested by these above mentioned species. This suppressive effect should be due to either the tillage management or the stylosanthes mulch. Specific knowledge about each species' biology should bring some lights on this matter. In general, small-seeded and light-sensitive weed species are expected to be suppressed by the mulch (Teasdale 1996), and perennial weeds should be promoted in a no-till system because of low soil disturbance (Blackshaw et al. 1994; Nichols et al. 2015). The emergence of *M. hirtus* and *Cyperus* spp. in the NT with stylosanthes can be considered as the downsides of the system. Weeds in Cyperaceae family were reported to be weeds of lowlands in general (Rodenburg and Johnson 2009). It is possible that the humidity accumulated in the stylosanthes mulch stimulated *Cyperus* spp. growth as it offered the similar condition of the frequently wet lowland fields. Another possible explanation is that the low soil disturbance in the no-till system offers a better condition for *C. rotundus* or *C. esculentus* which are basically perennial weeds. *Cyperus* spp. in this study actually referred to a combination of three species (*C. esculentus, C. rotundus* and *C. cyperoides*), all three species perennials and very difficult to differentiate during the sampling. An annual *Cyperus* with a very different appearance was *C. amabilis* and this species was never included in the group of *Cyperus* spp. The promotion of Mitracarpus hirtus in NT system was unexpected and no explanation can be given so far, more study about this species is needed as literature does not provide information on it.

3.4.2 Effect of NT system with stylosanthes on weed cover and weed biomass

This study confirms previous studies in Laos and West Africa (Saito et al. 2006, 2010) which indicated that stylosanthes used as cover crop suppresses weeds in upland rice. It should be noted that the management of stylosanthes in those cited studies was different to what was done in the present study. In Laos and West African, stylosanthes was managed as an annual cover crop, while in Madagascar it was managed as a perennial living mulch.

The lower weed cover in NT with stylosanthes might be explained mainly by the stylosanthes mulch acting as a barrier limiting weed emergence. A literature review reported that a crop residues of 10 $t.ha^{-1}$ reduce significantly weed abundance and biomass regardless of climatic conditions, but 4 $t.ha^{-1}$ of dry matter and more may already suppress weeds. An estimation of stylosanthes residues on farmers' fields during the year of the experiment showed that the mulch biomasses were variable but high in general, ranging from 5 $t.ha^{-1}$ to 17 $t.ha^{-1}$. This is due to the capacity of the plant itself to produce an important biomass. One of the main features of cover crops weeds suppressive effect is that the amount of residues matters more than the type of residues as it act as a physical barrier on weeds (Teasdale 1996). On top of that, some other mechanism may have contributed: (i) the mulch limits radiation depressing weed seeds that require light to germinate (Teasdale 1996), (ii) the no-till does not disturb the soil, therefore weed seeds are not brought to the soil surface reducing their capacity to germinate (Chauhan 2012), (iii) an allelochemical substance produced by stylosanthes may suppress weed growth and germination (Khanh et al. 2006). Although allelochemicals may also have a negative effect on rice germination and growth, these effects are normally limited to the small-seeded weeds while the large-seeded crop seeds are not affected (Moonen and Bàrberi, 2006). The similarity in weed cover observed in NT and CT in farmers' plots (FM) should indicate that they spent more time in CT than in NT to remove weeds. There was supposed to be more weeds in CT as indicated by the weedy plots. In this context, time saving is likely one of the advantage of the NT system. Time is actually very limited at farm level during the period meant for weeding on upland rice (ref. Chapter 6).

The higher biomass of broadleaved weeds collected at harvest in CT compared to NT should be the reflection of a higher infestation of *R. scabra* in CT. In fact, the dominant grasses *Eleusine indica* and *Digitaria horizontalis* (the most important species in the group *Digitaria* spp. ref. Chapter 2) had already reached the senescence at harvest, according to observation during sampling. Therefore, grasses biomass at harvest poorly reflected the importance of weed-rice competition during the rice growth cycle. Because grasses are frequently the most important in term of biomass, the total weed biomass at harvest became also of less utility. *Cyperus* spp. also reached senescence before harvest. This species group is actually the only species that represents sedges. The other sedge in the genus *Fimbristylis* sp. was an occasional species. Thus sedge biomass at harvest is useless if one would like to evaluate the impact of this weed group on the yield. Collecting sedge biomass at 60 DAS or latest at 90 DAS should give more information on sedge infestation level.

3.4.3 Effect of the NT system with stylosanthes on rice yield

A recent survey in the Mid-West of Madagascar evaluated the average yield in upland rice of this region to be 1.6 $t.ha^{-1}$ with high variation of 62% (Razafimahatratra et al. 2017). This study showed an average yield of 1.17 $t.ha^{-1}$ and 1.64 $t.ha^{-1}$ in 2016 and 2017 respectively, recorded from the CT - FM plots. This indicated that the monitored fields were in the range of standard fields in the Mid-West.

The higher yield in NT compared to CT in both weedy plots and farmers' plots in 2017 indicated that the NT system with stylosanthes does not decrease the yield but may instead increase it. The higher yield in NT -FM might be explained by an improvement of soil physical properties (Chandra et al. 2006) and/or nitrogen accumulation by stylosanthes (Becker and Johnson 1998; Zemek et al. 2018). Indeed, weed removal by farmers reduced the infestation to such a low level that the weed cover at 60 DAS cannot explain anymore the difference in rice yield. Thus, the higher yield in NT - weedy plots should be explained by the combination of weed cover depletion and other benefits inherent to the system cited above. In weed-free condition however, there was no significant difference between CT and NT, it may indicate that if the plot is kept completely clean from weeds, the CT system produces as much yield as the NT system as there is no competition for the limited available nitrogen in the soil.

A similar weed cover was observed in FM plots in both systems. However, the weed impact was significant in CT but not in NT if they were compare to their respective weed-free plots. The possible explanation is that farmers removed the stylosanthes sprouts in FM while it was not removed in weed-free plots NT. In this case the rice in weed-free plots suffered from stylosanthes competition but not from weeds while the rice in FM suffered from weeds but not from stylosanthes leading to an even outcome in terms of rice yield. In CT, rice in weed-free had no competitors while rice in FM competed with subsequent emerging weeds after farmers' intervention resulting in a lower yield in the later than the former.

The higher yield in weed-stylo-free in NT compared to weed-free NT indicated that the emerging sprouts of the living mulch interfered with rice growth at least in some fields. It means that the stylosanthes was not fully controlled in those fields. Indeed, the fields having the highest stylosanthes biomass at harvest also showed a lower yield in weed-free if compared to its weed-stylo-free. That is, a direct link between stylosanthes regrowth and rice yield was difficult to establish because the yield differed considerably between fields due to other factors relative to the fields fertility, not only because of stylosanthes. In experiments in Laos stylosanthes was pruned if it grows early to minimize competition with rice (Saito et al. 2006). In reality, farmers in the Mid-West sometimes remove the stylosanthes regrowth during the weeding, especially if it grows too early (see chapter 06). This practice may undermine the good development of stylosanthes to the detriment of biomass production for the subsequent year, but allow to maintain rice yield in the current year.

In 2016, the irregularity of rice yield showed the importance of factors which cannot be controlled in trials in real farms. The different cultivars used by farmers may have contributed in the source of variability, and the unbalanced number of fields managed in NT and CT limited the interpretation. Besides, the weed infestation level was very low during this year, as attested by the sampling at 60 DAS. It appeared that rice yield in weedy plots and weed-free plots were similar. It is possible that the weed infestation did not reached a harmfulness level, even though no theoretical threshold of harmfulness was established in this study. The low weed cover in 2016 may be linked to the previous year climatic condition. The rainfall amount in 2015 was extremely high (Chapter 1: Figure 4). It was reported that rainfall may impact the weed community (Fried et al. 2008). The result of Rakotoniriana (2015) showed a particularly high weed infestation during this year. It is possible that the weed seeds ready to germinate the following year has decreased. Another possible explanation is a low rainfall at the beginning of the cropping season 2016 (November –December) reducing weed emergence and rice development at the same time (Chapter 1: Figure 4).

3.5 Conclusion

The main results of this chapter confirmed all the hypotheses. The NT system with stylosanthes impact weed community composition. It suppressed all dominant weeds in CT (*R. scabra, Digitaria* spp*., E. indica*) and promoted other species (*Mitracarpus hirtus, Cyperus* spp.). It impacted also some less relevant species. The interesting result is that the final outcome showed a lower total weed cover in the NT system. Weed biomass at harvest showed a poor information on the crop-weed competition during rice growth as many important weeds species had already reached senescence (*D. horizontalis, E. indica, Cyperus* spp*.).* However, as broadleaved weeds persist (e.g. *R. scabra*) broadleaved biomass was always higher in CT than in NT. This agroecological practice did not appear to decrease rice yield, on the contrary, rice yield was higher in weedy conditions and in plots managed by farmers compared to the CT system. Nevertheless, stylosanthes regrowth seemed to interfere with rice grain production at least in some fields. If the cover crop grows early, pruning or removing its emerging sprouts maybe an option to avoid competition effect on rice.

Results obtained from 2016 cropping season were very inconsistent, and weed infestation during this year was very low. Thus, weed cover and yield interpretation was mostly focused in the result of 2017 cropping season. Even in this second year, the high yield variability between fields may have obscured some potentially interesting results. Such variability could be expected to exist in any experiment on real farms given the diversity of fields' history and management. An experiment on station was needed to reduce source of variability out of control. This was implemented and developed in the next chapter.

Chapter 4 : Field experiment on station to evaluate the effect of soil management and fertilization on weeds and rice yield

4.1 Introduction

Weed infestation is a major threat to crop production across the world (Oerke and Dehne 2004), It is particularly damaging in upland rice-based cropping systems in Africa, including Madagascar (Rodenburg and Johnson 2009). Weeds are strong competitors for the common pool of resources such as space, light and nutrients (Asif et al. 2014). Competition for nutrients is accentuated when these resources are limited in the weathered tropical soil of the Mid-West of Madagascar, on which upland rice is commonly cultivated. In this context, legume cover crops can be a solution because of their ability to fix nitrogen and suppress weeds at the same time (Lu et al. 2000). Nitrogen is indeed one of the most essential nutrient for plant growth and productivity (Ata-Ul-Karim et al. 2016).

In the previous chapter, the benefits from stylosanthes cover crop, managed as a living mulch, in upland rice cropping systems, was studied in experiments carried out in farmers' fields. Results tend to prove that this cover crop reduces total weed cover. This finding is supported by results of studies from other countries by Saito et al. (2006, 2010), the authors reported that stylosanthes fallow increased soil nitrogen available content (Saito et al. 2006). A recent study in Madagascar went further and quantified the nitrogen fixed by stylosanthes shoots to range from 96 to 122 kg $N.ha^{-1}$ (Zemek et al. 2018). It is well known that cultivated crops respond positively to an increase of soil available nutrients, but weeds are expected to respond as well. For instance, nitrogen and phosphorus application were reported to promote growth of several weed species (Blackshaw et al. 2002, 2004), and nitrophyl weeds are potential strong competitors for nitrogen (Lehoczky et al. 2013).

The results obtained from the previous chapter was mostly based on cropping systems without mineral inputs. A report on farmers' practice in the Mid-West of Madagascar however mentioned that some farmers apply mineral fertilizer at a low rate (Razafimahatratra et al. 2017). Therefore, the study on the no-till system with stylosanthes had to be extended to fields which received mineral fertilizer. A low mineral fertilizer rate had to be chosen for the study because a high rate application is a less probable scenario on real farms context. Farmers are not keen to apply a lot of fertilizers and hardly able to afford it. Furthermore, trial is also needed to determine if the addition of this small amount of mineral fertilizer, which farmers sometimes do, is necessary in this system, because literature reported that stylosanthes already supplies nitrogen to the crops. Therefore, a three year field experiment on-station was conducted from 2016 to 2018. The objective was to evaluate the effect of the NT system with stylosanthes, in combination with two levels of fertilization, on weeds and rice yield. The hypotheses were (i) The NT with stylosanthes suppresses weeds with or without mineral fertilizer application (ii) Mineral fertilizer increases weed cover and weed biomass in both CT and NT (iii) Mineral fertilizer increases rice yield in CT, but not necessarily in NT as stylosanthes already provides nitrogen (iv) The NT with stylosanthes and mineral fertilizer application affect weed community composition.

4.2 Materials and methods

4.2.1 Site description

A field experiment was carried out on an experimental station, in the Mid-West of Madagascar, during three growing seasons: 2016, 2017 and 2018. The station is managed by CAPES (Conservation Agriculture Plat-form for Ecosystem Services) a collaboration of many institutions led by the French research institution CIRAD and the Malagasy research institution FOFIFA. It was located at 19° 33' 26'' S and 46°24' 55'' E at an elevation of 930 m above sea level. The soil can be characterized as a clay-loam Oxisol (USDA) with a clay-silt-sand composition of 34–39-27% in the top layers (0–10 cm). The average temperature and rainfall in the Mid-West are respectively 23 °C and 1300 mm per year. The amount of rainfall is subject to some variation across years and between months, but the temperature is generally stable during the growing season (Chapter 1, Figure 4). Between November and March, which correspond to the growing season, the total amount of rainfall was 1220 mm, 1231 mm, 1241 mm in 2016, 2017 and 2018 respectively. The average rainfall during the growing season from the year 2006 to 2014 was 1099 ± 145 mm, thus the rainfall during the three years of experiment in the range of normal year. However, prior to the experiment, the rainfall reached 1715 mm in 2015, it was worthwhile to notify as such extreme events may impact weed infestation during the current year, and possibly affect the weed composition and abundance in the following year, through modification of weed seedbank.

4.2.2 Crop management in a rotation scheme

The experimental design was conducted in a bi-annual rotation scheme of rice – maize, both crops were present each year. In the conventional tilled system (CT), early plowing was done in May, between the two cereal growing seasons, and a superficial soil tillage just before sowing in October (Figure 1a). In the no-till system (NT), a perennial stylosanthes crop was present as a cover crop from April to October, and as a living mulch from November to April, during the rice growing season. Three stylosanthes rollings were done between the cereals growing seasons, two in June, with one week interval, and another one in September prior to the sowing period (Figure 1b), in order to reduce growth vigour and to flatten the cover crop before rice sowing, . Data from three years (2016, 2017, and 2018) of rice growing seasons were obtained with these same cultural operations.

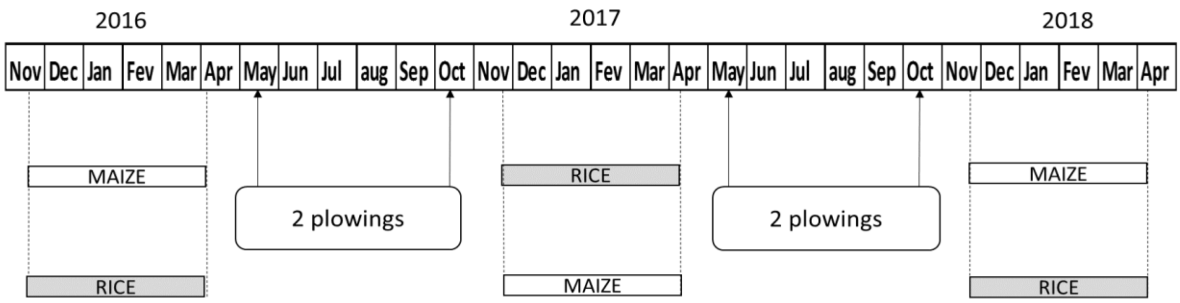


Figure 1a : Cropping calendar in CT system

The experiment was carried out in the rice plots, the maize plot were the rotation on which rice was grown the following year.

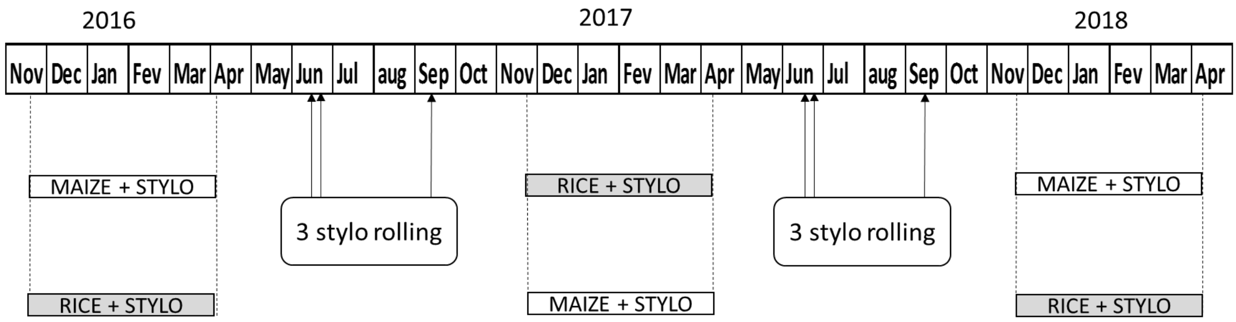


Figure 1b : Cropping calendar in NT system

The experiment was carried out in the rice + stylo plots, the maize + stylo plots were the rotation on which rice + stylo was grown the following year.

4.2.3 Experimental design

The experimental layout was a randomized complete block of six replications with a combination of three factors arranged in a split-split-plot design (Table 1). The field was positioned on a moderate slope (0 to 5%). Experimental replicates were laid out along this gradient with replicate 1 on the top and replicate 6 at the bottom of the slope. The soil management factor was introduced in the experimental fields since 2012 to conduct a previous study on its effect on the parasitic weed *S. asiatica* (Randrianjafizanaka et al. 2018). Thus, the soil management factors was five years old at the beginning of this study in 2016. The factor fertilization was introduced in 2016 especially for the present study. The mineral fertilizer rate used in the experiment can be categorized as low input. Only one farmer out of four uses mineral fertilizer in the Mid-West of Madagascar and applied it at a very low rate (Razafimahatratra et al. 2017). This strategy is mainly meant to prevent losing their investment in case of climatic hazards or other unexpected troubles. Anyway they cannot afford a lot of fertilizer. Thus the choice to use a low input in the experiment design was to imitate the rate a common farmer would use if he or she can afford the mineral inputs. An example of high input for upland rice would be 120 kg N, 26 kg P_2O_5 and 25 kg K_2O per hectare (Oikeh et al. 2010) while the rate applied in the experiment was only the equivalent of 20 kg N, 18 kg P_2O_5 and 13 kg K_2O per hectare (Table 1).

Table 1: Factors and treatments

	factors	levels	descriptions
main plot factor	soil management	CT	tillage without cover crops
		NT	no tillage with stylosanthes managed as a living mulch
sub-plot factor	fertilization	F1	10 t/ha of manure (dry matter)
		F2	F1 + 80kg of NPK + 25 Kg of urea
sub-sub-plot factor	weed management	weedy	no weeding from sowing date until harvest
		weed-free	weeds are weekly weeded but not stylo *(in the no-till system only)*
		weed-stylo- free	weeds and stylosanthes are weekly weeded

The weed management treatment was nested in the lowest level of the split-split-plot (Figure 2). The sub-sub-plots with different weed management moved each year because their disposition was chosen randomly inside the sub-plots, and also because of the rotation scheme. In fact, in 2016 and in 2018 the same plots were used while in 2017 the experiment was run on the rotation. Each plot size was 2.1 m by 3 m. The sub-sub-plots were used as quadrats for weed sampling and also for rice yield and weed biomass measurements at harvest. The whole study was conducted under naturally occurring weed population.

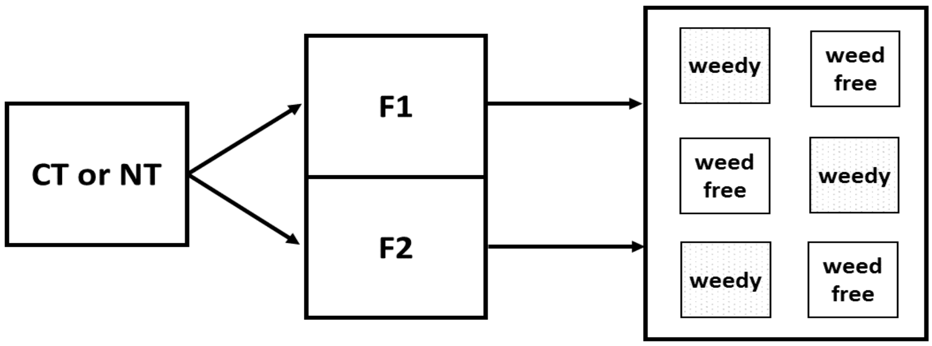


Figure 2: plots disposition nested inside each factor combination

Rice was sown on 27th, 17th and 25th of November in 2016, 2017 and 2018 respectively. The sowing was done in 20 cm x 30 cm grid. Rice grain seeds were put in a shallow hole dug by the *angady* and manure was applied in the hole at the same time. This method is similar to farmers' practice. The rice cultivar used was Nerica 4. Nerica, which stands for **New Rice for Africa,** is a cultivar group of interspecific hybrid developed by the Africa Rice Center. It was created from the wide cross between the *Oryza sativa* (L.) from Asia and the *Oryza glaberrima* (Steud.) (Rodenburg et al. 2009). The stylosanthes cultivar used was *Stylosanthes guianensis* CIAT 184 imported from Central America.

4.2.4 Data collection

Weed sampling was performed at 30 DAS, 60 DAS, 90 DAS and 120 DAS. Sampling of different dates were done inside the same quadrats (Figure 2). Rice grain yield, yield components and weed biomass were recorded at harvest, always in the quadrats of weed sampling. Rice grain yield was adjusted at 14% of humidity rate, weeds were weighted by group (grass, broadleaved weeds and sedge separately), and weed samples were oven dried 72h at 60 °C to calculate dry matter content. Yield components recorded were till number, panicle number, average grain weight and percentage of empty grains, measured from nine rice plants in a fixed position chosen in advance inside each quadrat.

4.2.5 Data analysis

Data collected during three years were analyzed separately because data from 2016 and 2018 were collected on the same plots while data from 2017 were collected on the adjacent plot, due to the rotation scheme. Therefore, data from the three years were not completely independent.

To characterize weed community composition. Weed species recorded in weedy plots were classified by frequency of occurrence and local cover. The frequency is the percentage of sampling units (quadrats) in which the species was present, the local cover is the average percentage of soil covered by the species inside the quadrats where it is present. This classification was adapted from method (Le Bourgeois and Merlier 1995). In this chapter, species having high frequency (> 30%) and high local cover (10%) were considered as dominant, whereas species with a low frequency (≤ 10%) and a low cover (≤ 5 %) were classified as occasional species. It referred to the famous 1-5 Braun-Blanquet cover-abundance scale (Braun-Blanquet 1932), where the threshold of 5% cover corresponds to the value '1' describing very scant species. That would separate species more relevant or less relevant in the weed-crop competition outcome. The other thresholds used to classify species were chosen arbitrarily, they were actually standardized with the thresholds used in the previous chapter (see Chapter 3). The species classification was done separately for CT and NT assuming a weed flora difference between the two systems (see also Chapter 3).

To observe weed species response to soil management and fertilization, ordination analyses were performed under CANOCO program version 5.2 (Ter Braak 2017). At the sight of the limited gradient (<3 standard deviation units) of the species composition in all three years, and the main interest in difference of abundances of the dominant weed species, data were analyzed with the linear response model. Blocks were inserted as covariables. In a first step, a RDA (Redundancy Analysis) with forward selection of the treatments based on the Monte-Carlo Permutation test was performed to assess which experimental factors significantly contributed to the variability in species composition. In a second step a PCA (Principal Component Analysis) was performed, and the significant treatments were superimposed in the ordination space, in order to express the maximum variability in species composition and the correlation with the treatments. The blocks were systematically added as a co-variable to account for any unwanted variability. Mean species abundance sampled at 60 DAS was calculated based on the three sub-samples taken per plot. Data were transformed to meet homogeneity of variances according to 2*arcsine (square-root (proportion weed cover)). The results presented, with respect to soil management and fertilization effect on weed flora, were from the sampling data at 60 DAS, because it presented a full expression of the weed community, and weeds has the biggest impact on rice yield in the period between 20 and 60 DAS (Chapter 5).

Analysis of variance (ANOVA) was used to quantify the effect of soil management and fertilization on weed cover and weed biomass, and the effect of soil management, fertilization and weed management on rice grain yield. The analysis was run under statistic R program ***lme*** function in the package ***nlme***

(**Pinheiro and al. 2016**) in R program version **3.3.2** (**R Core Team 2016**)**.** At first, a complete model was used to see each factor effect and a possible interaction. When the interaction was significant, a post-hoc test, also based on ***lme*** function, was used to determine the effect of fertilization inside each soil management level. It was done so because the fertilization factor was nested inside the soil management factor in the experimental design. Unless stated differently, raw data without transformation were used in these analyses.

4.3 Results

4.3.1 Characterization of weed community

A total of sixty-nine species were recorded during the three years of experiment. The species classification showed the dominant species in CT were *Digitaria* spp. and *Eleusine indica,* while in NT they were *Digitaria* spp. and *Mitracarpus hirtus* (Table 2 and Table 3). Species with low frequency but high local cover are species that occurs rarely but can become a threat if they grow uncontrolled in the cropped field (Kazi Tani et al. 2010). According to the threshold established, no such species exist in CT system, but in NT *Brachiaria* sp. appeared in this category.

Table 2: Species classification by dominance in CT

(Data from weedy plots during three years and all sampling dates)

		Frequency of occurrence		
		100% -30%	***30% -10%***	***10% -0%***
Local cover	***100%-10%***	*Digitaria* spp. *Eleusine indica*	*Cleome hirta* *Pennisetum polystachion*	NONE
	10% -5%	NONE	NONE	*Hyparrhenia* sp., *Brachiaria* sp., *Macroptilium atropurpureum, Neojeffreya decurrens, Rottboellia cochinchinensis, Melenis repens, Perotis patens,* *Bidens pilosa,*
	5%-0%	NONE	*Striga asiatica, Spermacoce filifolia, Mollugo nudicaulis Mitracarpus hirtus,* *Cyperus* spp. *Melochia pyramidata, Hyptis spicigera, Aeschynomene americana*	OCCASIONAL SPECIES

- NONE *means that no species has fallen in the class*
- *A complete species list is provided in supplementary material* 1

Table 3: Species classification by dominance in NT

(Data from weedy plots during three years and all sampling dates)

		Frequency of occurrence		
		100% -30%	***30% -10%***	***10% -0%***
Local cover	***100%-10%***	*Digitaria* spp. *Mitracarpus hirtus*	*Hyparrhenia* sp.	*Brachiaria* sp.
	10% -5%	NONE	*Pennisetum polystachion* *Cleome hirta*	*Bidens pilosa, Rottboellia cochinchinensis, Commelina africana, Cyperus amabilis, Macroptilium atropurpureum, Setaria pumila, Melenis repens*
	5%-0%	*Neojeffreya decurrens* *Eleusine indica* *Ageratum conyzoides* *Cyperus* spp.	*Hyptis spicigera* *Spermacoce filifolia* *Mollugo nudicaulis*	OCCASIONAL SPECIES

- NONE *means that no species has fallen in the class*
- *A complete species list is provided in supplementary material* 1

The principal Components Analysis (PCA) showed that the block accounted for 24%, 11% and 15 % of the variability in species composition in 2016, 2017 and 2018 respectively. After this correction, the forward selection showed that soil management explained an important part of the variability in weed community composition in all three cropping seasons, while fertilization explained a small part of the variability, its effect was significant only in 2018 (Table 5). During the three cropping seasons, *Digitaria* spp. and *Eleusine indica* were consistently associated with the CT while *Mitracarpus hirtus, Neojeffreya decurrens* and *Ageratum conyzoides* were consistently associated with the NT (Figure 3 and Table 4). Regarding fertilization, only *Digitaria* spp. appeared to respond to the mineral input by increasing its abundance while *Spermacoce filifolia* seemed to have a preference for the plots with manure only.

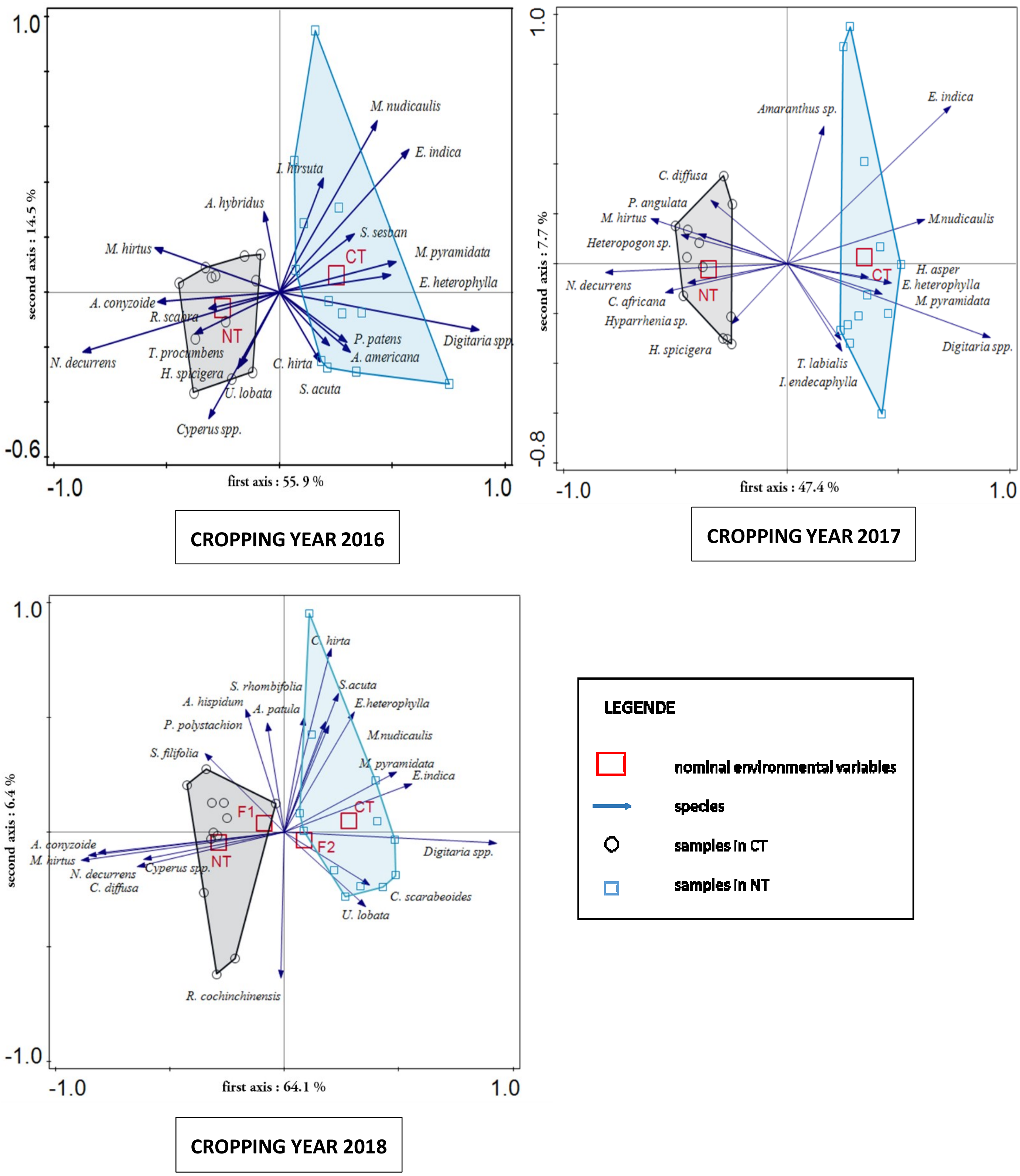


Figure 3: Principle Components Analysis (PCA) on weed community composition at 60 DAS with supplementary explanatory variables soil management and fertilization in case they resulted to affect the weed community composition significantly based on the Monte-Carlo Permutation test. Only the 20 species with the strongest contribution to the sample ordination were represented.

Table 4: Species scores representing the highest association with soil management and fertilization from principal components analysis (the higher is the absolute value of the score the stronger is the association, a positive score means a positive association and a negative score means a negative association).

CROPPING YEAR 2016

Species name	CT	NT
Neojeffreya decurrens	-0.90	0.90
Mitracarpus hirtus	-0.86	0.86
Cyperus spp.	-0.52	0.52
Ageratum conyzoides	-0.45	0.45
Euphorbia heterphylla	0.40	-0.40
Melochia pyramidata	0.42	-0.42
Mollugo nudicaulis	0.65	-0.65
Eleusine indica	1.48	-1.48
Digitaria spp.	3.18	-3.18

CROPPING YEAR 2017

Species name	CT	NT
Mitracarpus hirtus	-0.96	0.96
Neojeffreya decurrens	-0.95	0.95
Commelina africana	-0.80	0.80
Ageratum conyzoides	-0.64	0.64
Hyparrhenia sp.	-0.05	0.05
Mollugo nudicaulis	0.53	-0.53
Eleusine indica	2.66	-2.66
Digitaria spp.	3.99	-3.99

CROPPING YEAR 2018

Species name	CT	NT
Mitracarpus hirtus	-1.56	1.56
Neojeffreya decurrens	-0.67	0.67
Ageratum conyzoides	-0.67	0.67
Cyperus spp.	-0.60	0.60
Cleome hirta	0.38	-0.38
Melochia pyramidata	0.44	-0.44
Eleusine indica	0.93	-0.93
Digitaria spp.	4.30	-4.30
Species name	**F1**	**F2**
Digitaria spp.	1.56	-1.56
Spermacoce filifolia	-0.39	0.39

Table 5: Percentage of variability of the weed community composition explained by the treatment

treatment	2016		2017		2018	
	Explain (%)	P -value	Explain (%)	P -value	Explain (%)	P -value
soil management	47.3	0.002	59.3	0.002	63.9	0.002
Fertilization		n.s		n.s	7.9	0.006

% of variability explained by the factor and p-value,
Determined by interactive forward selection of Redundancy Analysis (RDA), with CANOCO 5.2

4.3.2 Effect of soil management and fertilization on weed cover and weed biomass

Preliminary analysis showed that there was a year effect (p =0.001, df = 2) on weed cover. Therefore, the analyses were done separately for each year. This year effect indicated that the weed cover was lower in 2016 compared to both year 2017 and 2018 which were similar (Table 7).

The result showed that soil management effect on weed cover was significant in 2017 and 2018 throughout the growing season, while in 2016 it was significant only at 60 DAS. Fertilization effect was not significant in 2016, but significant in 2017 at 60 DAS, and significant throughout the growing season in 2018, except at harvest date (Table 6). An interaction between soil management was also observed in 2018 at 60 DAS and 90 DAS.

Table 6: Effect of soil management and fertilization on weed cover

cropping season	2016			2017				2018			
sampling date	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
soil management	**	n.s	n.s	***	***	*	**	***	***	**	*
fertilization	n.s	n.s	n.s	n.s	*	n.s	n.s	**	***	*	n.s
soil x fertilization	n.s	n.s	n.s		n.s			n.s	*	*	

- Analysis model: Weed cover = soil + ferti + soil x ferti, random: block/soil/ferti
- Significance: * (p<0.05) , ** (p<0.01), *** (p<0.001), n.s (p>0.05)
- Sampling was not performed at 30 DAS in 2016
- Log transformation was applied on 2016(60DAS) and 2018(30DAS)
- Permutation test (not ANOVA test) was used on 2017(30 DAS, 90 DAS, 120 DAS) and 2018 (120DAS) because there was not enough variability (almost all cover in NT was as low as 0 or 1% at 30 DAS, and almost all cover in CT reached 100% in at 90DAS and 120 DAS), interactions between factors cannot be investigated.

Table 7: Weed cover actual values (%) in different treatments, cropping seasons and sampling dates

Weed covers were averaged when there is no significant difference between treatments

<table>
<tr><th rowspan="2"></th><th colspan="3">2016</th><th colspan="4">2017</th><th colspan="4">2018</th></tr>
<tr><th>60 DAS</th><th>90 DAS</th><th>120 DAS</th><th>30 DAS</th><th>60 DAS</th><th>90 DAS</th><th>120 DAS</th><th>30 DAS</th><th>60 DAS</th><th>90 DAS</th><th>120 DAS</th></tr>
<tr><td>CT F1</td><td rowspan="2">34 ± 23</td><td rowspan="4">53 ± 22</td><td rowspan="4">74 ± 20</td><td rowspan="2">23 ± 11</td><td>80 ± 17</td><td rowspan="2">96 ± 09</td><td rowspan="2">100 ± 00</td><td>11 ± 07</td><td>66 ± 15</td><td>93 ± 09</td><td rowspan="2">99 ± 02</td></tr>
<tr><td>CT F2</td><td>87 ± 12</td><td>19 ± 10</td><td>93 ± 08</td><td>99 ± 02</td></tr>
<tr><td>NT F1</td><td rowspan="2">11 ± 10</td><td rowspan="2">01 ± 02</td><td>20 ± 14</td><td rowspan="2">66 ± 25</td><td rowspan="2">85 ± 15</td><td>02 ± 01</td><td>20 ± 11</td><td>45 ± 18</td><td rowspan="2">68 ± 19</td></tr>
<tr><td>NT F2</td><td>29 ± 19</td><td>03 ± 02</td><td>31 ± 21</td><td>64 ± 15</td></tr>
</table>

Whenever there was a significant soil management effect, the weed cover was lower in NT than in CT. Whenever there was a fertilization effect, the weed cover was higher in F2 than in F1. In case of interaction between the two factors (2018 at 60 DAS and 90 DAS), the interaction effect had to be taken into account. The fertilization effect must depended on soil management. The post-hoc analyses showed that: at 60 DAS the fertilization effect was stronger in CT than in NT, but at 90 DAS the fertilization effect was weaker in CT than in NT (Table 6 and Table 7).

The analysis on weed biomass collected at harvest showed that the factor soil management affected grasses weeds, broadleaved and total weeds in all three cropping seasons, except in 2016 for broadleaved weeds. Fertilization effect was not significant in 2016 and 2017, but significant on total weeds and grasses in 2018 (Table 8). No interaction was observed between the two factors.

The total weeds biomass was reduced by 65% - 71%, and grasses biomass reduced by 73% - 79% in NT compared to CT. Total weed biomass increased by 15% - 27%, and grasses biomass increased by 17%-37% in F2 compared to F1, it was observed only in 2018 cropping season when fertilization effect was significant. Broadleaved weeds biomass was two to three times higher in NT compared to CT system (Table 9), but broadleaved weeds represented only a small portion of total weed biomass in both systems in a way that total weed cover was always higher in CT. Sedges represented the smallest portion of total weed biomass (< 2 g.m²), this weed group did not grow very much in the experimental field, and in upland rice cropping systems in general. Besides, the only important sedge *Cyperus* spp. had already reached senescence at harvest, thus statistical analysis on sedge biomass was judged irrelevant.

Table 8: Effect of soil management and fertilization on weed biomasses at harvest

cropping season	2016			2017			2018		
weed group	total weeds	grasses	broadleaved	total weeds	grasses	broadleaved	total weeds	grasses	broadleaved
soil management	**	**	ns	*	**	*	***	***	*
fertilization	ns	ns	ns	ns	ns	ns	**	**	ns
soil x fertilization	ns	ns	ns	ns	ns	ns	ns	ns	ns

- Analysis model: Weed biomass = soil + ferti + soil x ferti, random: block/soil/ferti
- Significance: * ($p<0.05$) , ** ($p<0.01$), *** ($p<0.001$), n.s ($p>0.05$)

Table 9: Average weed biomasses in different treatments and cropping seasons

(g.m² dry matter at harvest)

Weed biomasses were averaged when there is no significant difference between treatments

cropping season	2016			2017			2018		
weed group	total weeds	grasses	broadleaved	total weeds	grasses	broadleaved	total weeds	grasses	broadleaved
CT F1	209 ± 268	171 ± 223	34 ± 70	305 ± 357	292 ± 338	13 ± 78	281 ± 293	272 ± 284	9 ± 37
CT F2							324 ± 334	317 ± 331	
NT F1	75 ± 133	43 ± 92		102 ± 170	64 ± 132	38 ± 64	83 ± 133	63 ± 107	19 ± 33
NT F2							105 ± 154	86 ± 130	

4.3.3 Effect of soil management and fertilization on rice yield

The analysis was separated for weedy plots and weed-free plots to investigate the factors effect in case of weed interference condition in one hand, and to estimate the rice potential yield of each system without weed interference, in the other hand.

- **In weed-free plots** :

There was no *year* effect but interactions between *year* and other factors. The analysis was done separately for each year. The results showed that there was a fertilization effect in all three years. There was no soil management effect in 2016 and 2017, but in 2018 there was a soil management effect and an interaction between soil management and fertilization (Table 10 and Table 11).

Table 10: Effect of soil management and fertilization on rice yield in weed-free plots

	2016		2017		2018	
	p-value	df	p-value	df	p-value	df
Soil management	0.509	1	0.694	1	0.015 *	1
fertilization	0.000 ***	1	0.043 *	1	0.005 **	1
Soil x ferti	0.163	1	0.937	1	0.027 *	1

Model: Yield= soil + ferti + soil x ferti, random: block/soil/ferti
Symbol Significance: * ($p<0.05$), ** ($p<0.01$), *** ($p<0.001$), no symbol ($p>0.05$)

In 2016 and 2017, the yield was higher in F2 than in F1 but soil management did not affect yield. In 2018 there was an interaction between the two factors to be taken into account: as fertilization is nested inside soil management according to the experimental design, it can be said that the soil management NT globally increased the yield, fertilization effect was different inside each soil management level: F2 increased yield in CT but did not increase significantly yield in NT.

Table 11: Average rice grain yield from weed-free plots ($t.ha^{-1}$)
Yields were averaged when there was no significant difference between treatments

treatment	2016	2017
CT - F1	1.72 ± 0.9	2.07 ± 0.9
NT - F1		
CT - F2	2.73 ± 0.9	2.47 ± 0.8
NT - F2		

treatment	2018
CT – F1	1.42 ± 0.7
CT – F2	2.17 ± 0.7
NT – F1	2.62 ± 0.7
NT – F2	

- **In weedy plots :**

There was a year effect on rice yield and also interaction between year and soil management. Therefore, the analysis was done separately for each year. The result showed that there was no factor effect in 2016. There was an effect of both fertilization and soil management in 2017, and there was an effect of soil management, fertilization and an interaction effect in 2018 (Table 12).

Table 12: Effect of soil management and fertilization on rice grain yield weedy plots

	2016		2017		2018	
	p-value	df	p-value	df	p-value	df
Soil management	0.585	1	0.017 *	1	0.007 **	1
fertilization	0.120	1	0.005 **	1	0.046 *	1
Soil x ferti	0.552	1	0.518	1	0.033 *	1

Model: Yield= soil + ferti + soil x ferti, random: block/soil/ferti
Transformation was applied on yield :(log + 1) for 2016 and 2017, and (log) for 2018
Symbol Significance: * ($p<0.05$), ** ($p<0.01$), *** ($p<0.001$), no symbol ($p>0.05$)

In 2016, the yield can be considered as similar in all treatments. In 2017, the yield was globally higher in NT than CT. The yield was higher in F2 than F1 both in CT and NT. In 2018, the soil management globally increased yield. Fertilization effect was different in CT and NT: in CT fertilization decreased the yield due to an increase of weed infestation whereas in NT it did not affect neither positively or negatively the yield.

Table 13: Average rice grain yield from weedy plots ($t.ha^{-1}$)
Yields were averaged when there is no significant difference between treatments

treatment	2016	2017
CT - F1	1.26 ± 0.9	0.15 ± 0.2
NT - F1		1.13 ± 0.8
CT - F2		0.46 ± 0.4
NT - F2		1.46 ± 0.9

treatment	2018
CT – F1	0.38 ± 0.2
CT – F2	0.22 ± 0.2
NT – F1	1.71 ± 0.9
NT – F2	

In NT, the yield from weed-free and weed-stylo-free plots were compared in order to evaluate if removing the stylosanthes regrowth can increase significantly the yield (Figure 4). The result showed that rice yield was higher in weed-stylo-free plots than in weed-free plots in 2016 ($p = 0.005$, df =1) and 2018 ($p = 0.041$, df =1), but no difference was confirmed in 2017 ($p = 0.069$, df=1).

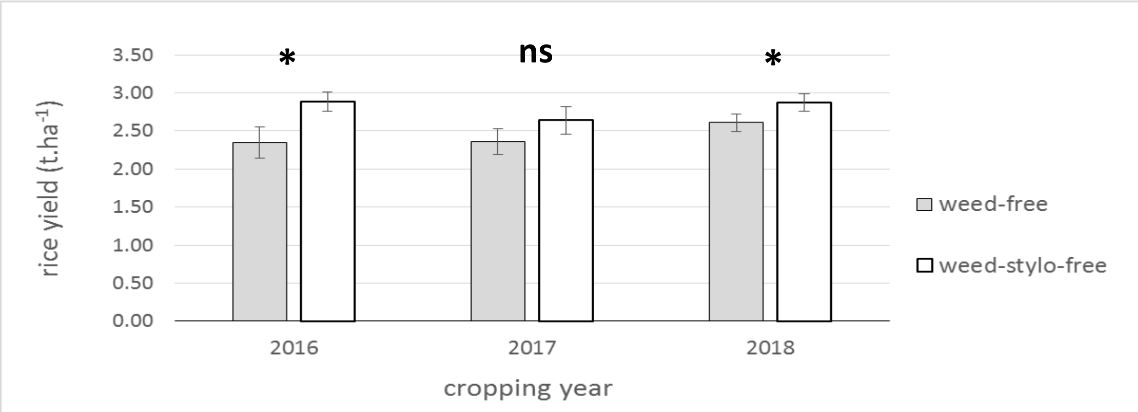


Figure 4: Effect of stylosanthes regrowth removal in weed-free plots in NT system
Model: Response variable = yield, fixed factor = stylo management, random factor = block/soil/ferti
Code meanings: **(*)** p < 0.05, **(ns)** p > 0.05

4.4 Discussion

4.4.1 Weed community response to soil management and fertilization

An important response of the weed community to soil management was observed during the three years of study. This confirm the hypothesis that soil management affect weed community composition. This factor explained a high percentage of the variability in weed species composition. The most conspicuous effect is that highly dominant *Digitaria* spp. and *E. indica* of CT system were suppressed in NT, while *M. hirtus, A. conyzoides* and *Cyperus* spp. were promoted. Some other species were also affected by the soil management (Table 4). Preadapted weed species are those that are resident in an agroecosystem within dispersal distance of a crop and come to predominate through a change in management practice (Rao et al. 2007). It appeared to be the case of *M. hirtus* or *Cyperus* spp. This result is in line with the literature which reported that cover crops suppressive effect on weeds is species specific (Teasdale 1996).

Fertilization effect on weed composition did not appear to be strong, and sometimes not expressed. In Swanton et al. (1999) an application of nitrogen up to 200 kg.ha^{-1} did not influence the weed community. Nevertheless, in our study *Digitaria* spp. was observed to respond to the mineral input by increasing its abundance. Other studies reported that several weed species respond to fertilization by increasing their growth (e.g. Blackshaw et al. 2002, 2004). Regarding this low effect of fertilization observed in this study some explanations can be speculated i) the weed community composition is in general less sensitive to fertilization, but if one dominant species responds, its effect becomes significant, ii) fertilization effect is dependent of soil management, i.e., its effect in CT system maybe stronger than its effect in NT system as this last system seemed to suppress the fertilization effect sometimes iii) the effect of fertilization is dependent of the cropping season, i.e., the climatic condition of each year and 2018 was favorable for its expression iii) fertilizer effect on weed community composition builds up slowly in time, and since the fertilizer treatment was newly imposed within the design in 2016 its effect was not yet expressed in the first year but in 2018 it started to show up. Besides, the mineral input applied was low rate, equivalent to 20 kg.ha^{-1} of nitrogen, 18 kg.ha^{-1} of phosphorus and 13 kg.ha^{-1} of potassium. It is unlikely that it would affect strongly the weed community at the first year. The study should be prolonged in order to confirm the cumulative effect of mineral fertilization in the long term. The clear effect of soil management on the weed community composition can be explained by the fact that this factor was already in place since 2012, and therefore reached its full expression. Besides, the plowing in the CT system has an immediate effect on the weed community by destroying the present weeds before sowing.

4.4.2 Soil management effect on weed cover and weed biomass

The lower total weed biomass and cover observed in NT confirmed our hypothesis that the NT system with stylosanthes cover crop suppresses weeds with or without mineral fertilizer. It is in agreement with the general assumption that cover crops reduce weed infestations (Teasdale 1996; Lu et al. 2000; Hartwig and Ammon 2002), and results of specific studies which proved that stylosanthes reduces weed infestation (Saito et al. 2006, 2010). In 2016, the effect of soil management on weeds was not no more expressed at the end of the cropping season. It is in line with general assumption that the weed suppression effect of cover crops occurs mainly at early season but not for the duration of the growing season (Teasdale 1996; Lu et al. 2000). The higher broadleaved biomass observed in NT system is certainly due to the emergence of *M. hirtus* in this system.

The result also indicated that fertilization increased weed biomass and cover, mainly due an increase of grass weeds or more precisely *Digitaria* spp. as observed in weed composition pattern. It confirmed the hypothesis that mineral fertilizer increases weed cover and biomasses. Nevertheless, it should be noticed that fertilization effect is less consistent across years and not necessarily on all weed species, or maybe it needs time to build up to be fully expressed.

The interaction between soil management and fertilization with regard to weed cover indicated that fertilization effect maybe more or less expressed depending on the soil management, and may dependent also on sampling date. At early season, the suppressive effect of the cover crop mulch reduced the effect of fertilization. Later on, when the mulch began to decompose weeds grew faster in the NT system than in CT system as indicated by the interaction effect (Table 7).

The most important weed suppression effect of NT system with stylosanthes actually occurred at the beginning of the growing season (Table 7). At this period, the stylosanthes mulch was still thick and its regrowth negligible. In the experimental field, stylosanthes biomass was estimated to be 16 ± 4 $t.ha^{-1}$ dry matter at sowing date and stylosanthes cover in weedy plots was only 2 ± 1% at 30 DAS, 5 ± 7 % at 60 DAS, but reached 17± 16% at 90 DAS. It should indicate that the weed suppression was mainly due to the mulch, not the competition between stylosanthes regrowth and weeds. In other words, it is not the smothering mechanism reported in some scientific literature (Lu et al. 2000). Some studies demonstrated that crop residues of 10 $t.ha^{-1}$ or more reduces significantly weed emergence and weed biomass (Ranaivoson et al. 2018). Mulch was reported by the literature to provide a physical barrier that impedes the emergence of weed seedlings after germination, and to limit radiation for weed light-sensitive seeds germination (Teasdale 1996; Lu et al. 2000). Besides, the allelopathic effect of stylosanthes on weeds may have also contributed to undermine weed germination. Allelopathic compound in stylosanthes was already identified in bioassay (Khanh et al. 2006), but its effectiveness in real field is not yet well known.

The lower weed cover in 2016 compared to the two following years might be explained by the climatic condition of the year prior to the experiment. The rainfall amount in 2015 was extremely high (Chapter 1: Figure 4) and it was reported that rainfall may impact weeds (Fried et al. 2008). The result of Rakotoniriana (2015) showed a particularly high weed infestation in the Mid-West of Madagascar in 2015. It is possible that the weed seeds ready to germinate the next year had decreased. Another possible explanation is a low rainfall at the beginning of the cropping season (November –December) reducing weed emergence and rice development at the same time (Chapter 1: Figure 4).

4.4.3 Fertilization effect on rice yield in CT and NT systems

The higher yield observed on weed-free plots that received mineral fertilizer confirmed that rice responds positively to fertilization both in CT and NT in a no weed interference context. The higher yield observed on weedy plots that received mineral fertilizer in 2016 and 2017 still confirmed that rice responds positively to fertilization both in CT and NT in a weedy context. However, when fertilization increased significantly weed infestation, it may decrease the yield as observed in 2018 CT.

The positive effect of the NT system on yield in weed-free observed in 2018 indicated that this system may provide a better condition to rice development excluding its contribution on weed suppression. It is frequently related in literature that legume cover crops provide an extra nitrogen supply (Saito et al. 2006; Zemek et al. 2018), or play other agroecological role such as erosion control, water regulation and soil organic matter enhancement (Lu et al. 2000; Ranaivoson et al. 2017). However, the positive effect of NT on yield may not be expressed in weed-free as observed in 2016 and 2017. Therefore, a higher yield in NT compared to CT cannot be taken for granted in a weed-free context, maybe a further research is needed to understand in which situation it occurs. Several factors may interact, for example it was observed that the difference between yield from NT and CT was reduced when mineral fertilizer was applied (Table and Table). It can also be interpreted another way: rice responds better to mineral fertilizer in CT system because nitrogen limitation was alleviated. In this case the system with stylosanthes is more interesting when nitrogen is scarce and therefore more adapted to the low input cropping system in the real farms of the Mid-West of Madagascar.

The higher yield observed in NT weedy plots is mainly the result of a lower weed infestation, probably combined by some benefits inherent to the NT system. The higher yield in NT can be interpreted as the expression of a lower yield loss, or an important yield loss due to weeds in CT. By comparing the yield from weedy plots in NT and CT with their respective weed-free plots, it can be said that yield losses in CT ranged from 81% to 93% whereas it ranged from 33% to 54% in NT. This yield loss in NT system is pretty low as potential yield losses due to weeds in rice cropping systems are usually very high, and may reach 100% in case of no-weed control (e.g. Chauhan and Johnson 2011; Singh et al. 2014). The absence of yield difference between CT and NT in 2016 was clearly due to the low weed infestation during this year resulting in a non-significant weed suppressive effect of stylosanthes until the end of the cropping season, and the absence of fertilization effect is probably linked to the fact that this factor was introduced in the experimental design in 2016 for the first time. These results indicated that the system with stylosanthes is interesting to counteract negative effect of weeds when the infestation level is high and farmers cannot perform weeding.

The higher yield in weed-stylo-free NT compared to weed-free NT observed in 2016 and 2018 indicated that stylosanthes regrowth may interfere with rice growth. In experiments in Laos, stylosanthes was pruned when it grows too early in order to minimize competition with rice (Saito et al. 2006). In the Mid-West of Madagascar, farmers sometimes remove stylosanthes regrowth during the weeding, especially if it grows too early (see chapter 06). This practice may undermine the good development of stylosanthes, and may negatively affect the biomass production for the subsequent year, but it allows farmers to avoid yield loss due to stylosanthes interference the current year.

The yield loss in this study in CT under weedy conditions was higher than the yield loss reported in lowland rice, for example a yield losses of 49% was observed in Johnson et al. (2004). In general, yield losses in unweeded plots showed to be higher in experiments similar to this study, 96% (Chauhan and Johnson 2011), 85 % (Anwar et al. 2012) in comparison to experiments in lowland irrigated or flooded rice systems. It confirmed that weeds constitute a more biotic constraint in upland rice.

4.5 Conclusion

The result of this field experiments highlighted that the most dominant weed species in CT system were *Digitaria* spp. and *Eleusine indica*. The NT system promoted some species like *M. hirtus* but it suppressed *Digitaria* spp. and *E. indica* along with few other species. Consequently the total weed cover was reduced and the yield loss caused by weeds is lower in NT compared to CT.

Application of mineral fertilizers increased total weed biomass and cover, *Digitaria* spp. was identified to respond to the mineral input by increasing its abundance. These were observed only at the last year of the experiment, maybe the fertilization effect took time to accumulate before being expressed. Without weed interference, mineral input increased rice yield in both CT and NT systems. Interaction between soil management and fertilization, observed in 2018 weed-free plots, suggested that rice responds less to fertilization in the NT system compared to a CT system. It is possible that the stylosanthes, as a legume cover crop, provided already nitrogen. In weedy condition, the fertilizer impact on rice yield depends on its effect on weed infestation and the soil management. The rice yield may decrease instead of increasing if the fertilization promotes strongly weed biomass. The NT system however may reduce the weed promoting effect of fertilization at least at yearly stage of rice growth, this interaction can maintain the yield despite the negative effect of fertilization which promotes weed infestation and total weed biomass.

These findings suggest that the NT system with stylosanthes is more interesting when weeds cannot be controlled correctly in a low input rice cropping system. They also suggest that in a conventional tilled system, farmers have to prepare to remove seriously weeds to obtain an acceptable yield, and cannot invest on mineral inputs if weeds are not correctly controlled.

Chapter 5 : Critical period of weed interference

5.1 Introduction

The knowledge of the critical period of weed interference (CPWI) is one of the key aspects of integrated weed management (Swanton and Weise 1991). It can be defined as the period in the crop growth cycle during which weeds must be controlled to prevent yield losses (Knezevic et al. 2002). During the recent years some studies were published on the CPWI of rice. This period was reported to be between 15 and 58 DAS in Chauhan and Johnson (2011) but may change with sowing row spacing. It was between 14 and 42 DAS in (Amadou et al. 2013) but may change considerably with rice cultivars. Finally, it was between 12 and 83 DAS in Singh et al. (2014) but may change with rice cultivars and influenced by weed infestation level of the cropping year. Facing this variability, knowing the CPWI in a specific context is important to formulate a suitable weed management schedule.

In the context of small-scale farmers in the Mid-West of Madagascar herbicides are not commonly used (Razafimahatratra et al. 2017), weed control is done mainly by hand. Hand-pull weeding is a time consuming work requiring about 30 days/ha (Husson et al. 2013). Furthermore, farmers are overloaded by agricultural tasks at the beginning of the rainy seasons. November, December and January are a very busy time as many activities has to be achieved, namely transplanting of irrigated rice and planting of all upland crops (Chapter 6). This situation leaves the household labor force a very little time to deal with weeds, thus they often grow freely in the crop field. The knowledge of the exact timing of crop-weed competition is a helpful information to adjust activities planning and set priorities. Besides, the introduction of the NT system with stylosanthes cover in the Mid-West of Madagascar may offer an opportunity to delay weed emergence thanks to the thick mulch of stylosanthes that covers completely the soil. This may give farmers extra time, and schedule flexibility for weed removal. Moreover, the literature does not provide much information on the CPWI in a NT system with cover crop by comparison to conventional tilled systems.

Therefore, this study was conducted to determine the CPWI in a low-input upland rice cropping system, in order to optimize the timing of weeding. It was implemented in two contrasted cropping systems: no-till system with stylosanthes cover crop (NT) and conventional tilled systems (CT). The hypothesis is that the cover crop can delay the beginning of the CPWI by delaying weed emergence.

5.2 Materials and methods

5.2.1 Description of the experiment

Field experiments were carried out during the 2017 and 2018 cropping seasons at the experimental station called Ivory in the Mid-West of Madagascar (19°33.29’S, 46° 24.913'E). The experimental site is characterized by rainfall averaging at 1300 mm, a monthly average temperature around 24.5 °C during the growing season (November – April), and soil type classified as a clay-loamy Oxisol (USDA). In 2017 a field experiments were performed in CT system. In 2018 the experiment in CT system was repeated and an experiment in NT system with stylosanthes cover was added. The three experiments were setup on different fields, but they were close to each other afar from 60 m. Topography and pedoclimatic conditions were similar but each field history such as crop sequence and crop management were different.

5.2.2 Crop management

The experimental layout for all experiments was a randomized complete block with four replications (Figure 1). Two series of weeding regimes were tested: (a) an increasing duration of weed interference and (b) an increasing duration of weed-free period. The first series aimed to determine the beginning of the CPWI. It included a weedy, a weed-free control and three levels of weeding regimes: left weedy until 20 DAS, 40 DAS or 60 DAS, after which plots where maintained weed-free until harvest. The second series aimed to determine the end of CPWI, using the weedy and weed-free control mentioned previously, and three levels of weeding regimes: weeded until 20 DAS, 40 DAS and 60 DAS afterward subsequent emerging weeds were allowed to grow until harvest. Consequently, 8 treatments were studied in each block, each treatment allocated in a plot of 25 m² in 2017, reduced to 16 m² in 2018. Experiments were carried out under naturally occurring weed population. Weeding was performed every five days respecting the different weeding regime, it was done exclusively by hand and a spade-like tool called *angady* to mimic the real farms methods in the Mid-West of Madagascar.

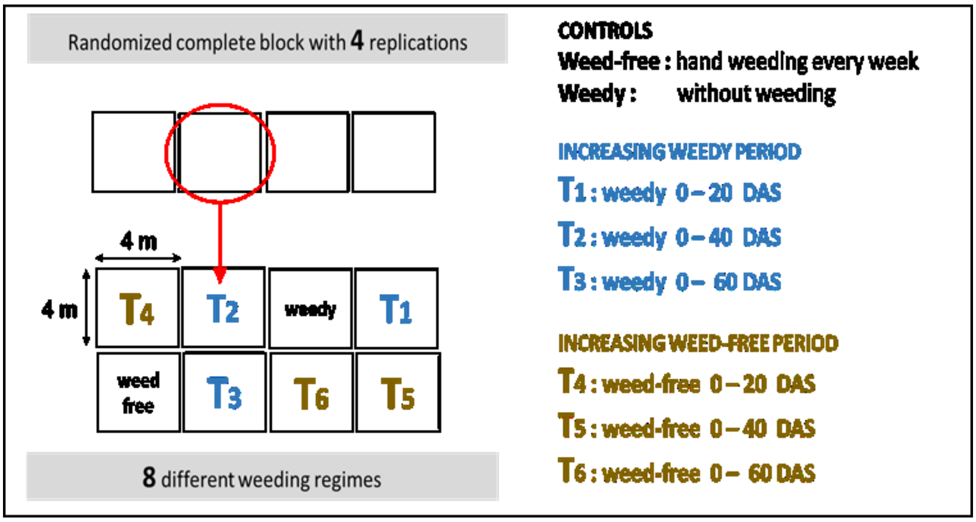


Figure 1: Experimental design and treatments

The cultivar used was Nerica 4 which is already widely spread in farmers' fields and showed a good adaptation to the pedoclimatic condition of the study area. Its growth cycle is around 120 days in the Mid-West of Madagascar. Rice was sown in November, two-three weeks after the beginning of the rainy seasons, and harvested in March-April (Table 1). The sowing was done by hand at 20 cm x 30 cm, and cattle manure was applied at the same time directly in the hole with the seeds at 5 $t.ha^{-1}$ rate of dry matter. In the CT system, the field was plowed 20 cm depth before sowing. In the NT system, stylosanthes was grown alone the previous cropping season and rolled down by *rolo-faca* three times during the dry season (Mai – October). After the rolling, the stylosanthes became a sleeping mulch through which rice was directly sown in November. The system with stylosanthes was not established the previous year, the fields were managed in no-till with stylosanthes since 2012 therefore the systems can be considered as already stable.

Table 1: Previous crop and rice growth cycle

experiment	previous crop	sowing date	harvest date
CT – 2017	rice + bean	22/11/2016	21/03/2017
CT – 2018	peanuts	28/11/2017	04/04/2018
NT – 2018	stylosanthes	27/11/2017	29/03/2018

5.2.3 Data collection

Weed sampling was done at 20 DAS, 40 DAS, 60 DAS and 90 DAS using the whole plot as quadrat, by excluding two outer rows considered as borders. The sampling objective was to make an inventory of all species growing in the experimental fields, to determine the dominant ones, and to have the total weed cover and weed biomass in each treatment which can be used to explain the yield loss. A sample of twelve rice plants were defined in advance inside each plot (Figure 2) to measure plant height and tiller number at 20 DAS, 40 DAS and 60 DAS. Plants nitrogen status was estimated using a non-destructive Chlorophyll meter (SPAD-502) at 70 DAS. Chlorophyll meter readings were measured from the three uppermost fully expanded leaves of ten randomly selected plants from each plot. The Chlorophyll meter was proved to be a robust, reliable and rapid diagnostic tool for estimation of plant nitrogen status (Ata-Ul-Karim et al. 2016). These measurements were to evaluate the effect of weed competition on plant growth and nitrogen available resource.

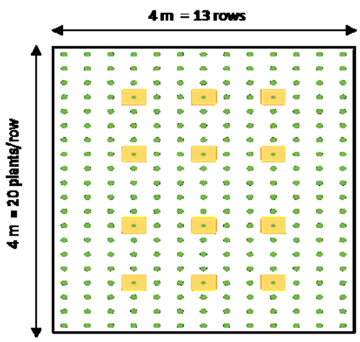


Figure 2: Rice plants spatial arrangement in a plot (samples for plants height and tiller in yellow color)

Weed biomass was removed and weighted inside the quadrat for sampling at 20, 40 and 60 DAS for the treatment T1, T2 and T3 respectively (Figure 1). Fresh samples were collected to estimate humidity rate and convert the fresh biomass into dry matter. Just before harvest, rice yield components were recorded using the sample of 12 rice plants mentioned previously (Figure 2). The tillers number, panicles number, average grain weight and % of empty grains were measured. At harvest, rice grain, rice shoot biomass and weed biomass were weighted inside the same quadrat used for weed sampling. Weeds were separated by weed groups (grass, broadleaved weeds and sedge). Stylosanthes regrowth was also removed and weighted in NT system. Samples of rice grains, rice shoot, weeds, and stylosanthes were collected to estimate humidity rate at harvest. They were dried up in oven 72 hours at 60°C. Rice grain yield were converted to t. ha^{-1} and adjusted at 14% moisture content, for the others the fresh biomass was converted into dry matter.

5.2.4 Data analysis

Weed species were classified according to their frequency of occurrence and their local cover, thus the species having the highest frequency and cover were considered as dominant species. Frequency is the proportion of sampling unit (quadrats) that contains the species and local cover is the average cover of a weed species in the samples where it is present. This classification was adapted from method presented in Le Bourgeois and Merlier (1995). In this chapter, species having a high frequency (> 30%) and a high local cover (10%) were considered as dominant, whereas species having a low frequency (≤ 10%) and a low cover (≤ 5 %) were classified as occasional species. It referred to the famous 1-5 Braun-Blanquet cover-abundance scale (Braun-Blanquet 1932), where the threshold of 5% cover corresponds to the value '1' describing very scant species. That would separate species more relevant or less relevant in weed-crop competition outcome. The other thresholds used to classify species were chosen arbitrarily. They were actually standardized with the thresholds chosen in the previous chapter (see Chapter 4).

Analysis of variance (ANOVA) were performed with R program version **3.3.2** (**R Core Team 2016**) using the ***lme*** function in the package ***nlme*** (**Pinheiro and al. 2016**) in order to determine treatment effect on rice grain yield and its components. Post hoc test were performed afterward with the ***multcomp*** package (Hothorn et al. 2018) using the Tukey's all pair comparison method. Logistic equation in ***stat*** package of R program was used to determine the beginning of CPWI. Gompertz equation in ***minpack.lm*** package (Timur et al. 2016) was used to determine its end. These two equations are the most common approach for data analysis of CPWI in literature (Knezevic et al. 2002).

<u>Logistic equation structure:</u>

Y = a / (1+exp [-(x - b)/c])

Y *= relative yield (% weed free)*
x *= growing degree days after emergence (minimal growth temperature for rice considered to be 10°C, rice emergence 7 days after sowing)*
a, ***b*** and ***c*** : *Parameters estimated with package stats.R , function nls and Self Starting NLs Logistic model (SSlogis)*

Gompertz équation structure :

Y = a exp (- b * exp (- k * x))

Y = *relative yield (% weed free)*
x *= growing degree days after emergence (minimal growth temperature for rice considered to be 10°C, rice emergence 7 days after sowing)*
a, ***b*** and ***c*** : *Parameters estimated with package minpack.lm.R based on Levenberg-Marquardt Nonlinear Least-Squares Algorithm*

The CPWI has been determined by using relative rice yield (% of weed-free control) and growing degree days (GDD) as quantitative variable in the regression analysis. Rice emergence was used as starting point for accumulation of GDD. That was 7 - 8 days after sowing dates. The base temperature for rice growth was set at 10°C, the most commonly used in literature (eg. Counce et al. 2009). The CPWI was determined based on the threshold 5% yield loss which was also the standard threshold in literature (Knezevic et al. 2002).

5.3 Results

5.3.1 Weed community characterization

A total of forty-two weed species were recorded in CT system experiments 2017 and 2018. There was some differences in terms of weed community composition between the two cropping seasons. In 2017, the dominant species were *Richardia scabra, Cleome hirta and Digitaria* spp. (Table 2). In 2018, the community was strongly dominated by *Richardia scabra* which was present in all sampling quadrats of all sampling dates, and covered on average 34% of the ground. *Cleome hirta* and *Digitaria* spp. had a high frequency but an average cover and so end up in a lower class, while *Euphorbia heterophylla* emerged and reached also the class of species with average cover and high frequency. *Rottboellia cochinchinensis* almost disappeared to fall in the category of occasional species (Table 3). In the NT system, twenty-three species were recorded. The community was highly dominated by *Bidens pilosa* (Table 4).

Table 2: Classification of weed species in CT system 2017

		Frequency of occurrence		
		100% -30%	**30% -10%**	**10% - 0%**
Local cover	**100%-10%**	*Cleome hirta, Richardia scabra, Digitaria* spp.	NONE	NONE
	10% -5%	*Eleusine indica, Rottboellia cochinchinensis*	NONE	*Ipomoea eriocarpa, Setaria pumila, Hyparrhenia* spp.*, Melenis repens, Indigofera hirsuta*
	5%-0%	*Mollugo nudicaulis*	*Euphorbia heterophylla, Hibiscus asper, Mitracarpus hirtus, Acanthospermum hispidum, Urena lobata,*	OCCASIONNAL SPECIES

NONE *means that no species has fallen in the class*
Data used were from all sampling in the group of treatment early weed competition
A complete species list is provided in supplementary material 1

Table 3: Classification of weed species in CT system 2018

		Frequency of occurrence		
		100% -30%	**30% -10%**	**10% -0%**
Local cover	**100%-10%**	*Richardia scabra*	NONE	NONE
	10% -5%	*Cleome hirta,* *Digitaria* spp. *Eleusine indica* *Euphorbia heterophylla*	NONE	*Pennisetum polystachion,* *Setaria pumila*
	5%-0%	*Mollugo nudicaulis*	*Acanthospermum hispidum* *Hibiscus asper*	OCCASIONNAL SPECIES

NONE *means that no species has fallen in the class*
Data used were from all sampling in the group of treatment early weed competition
A complete species list is provided in supplementary material 1

Table 4: Classification of weed species in NT system 2018

		Frequency of occurrence		
		100% -30%	**30% -10%**	**10% -0%**
Local cover	**100%-10%**	*Bidens pilosa*	NONE	NONE
	10% -5%	*Cleome hirta*	*Pennisetum polystachion* *Digitaria* spp. *Rottboellia cochinchinensis* *Euphorbia heterophylla*	*Setaria pumila*
	5%-0%	*Mitracarpus hirtus*	*Commelina africana* *Brachiaria* sp., *Cyperus* spp. *Ageratum conyzoides* *Urena lobata, Richardia scabra* *Spermacoce filifolia*	OCCASIONNAL SPECIES

NONE *means that no species has fallen in the class*
Data used were from all sampling in the group of treatment early weed competition
A complete species list is provided in supplementary material 1

5.3.2 Weed cover

The result of sampling in weedy control plots at different dates indicated that total weed cover increased as growing degree days was accumulating through the growing season (Figure 3). In the field experiments in CT system, the dynamics of weed cover was similar in 2017 and 2018: it increased quickly from the beginning of the cropping season and reached almost 100% at mid-growing season. The percentage of weed cover cannot go beyond 100% as the methodology imposed, but weed biomass may still increase. In NT system, the dynamics of weed cover showed a delay of weed emergence at early date, then weeds grew steadily to cover around 70% of the quadrats at rice harvest. At all sampling dates, the weed cover was significantly lower in NT than in CT.

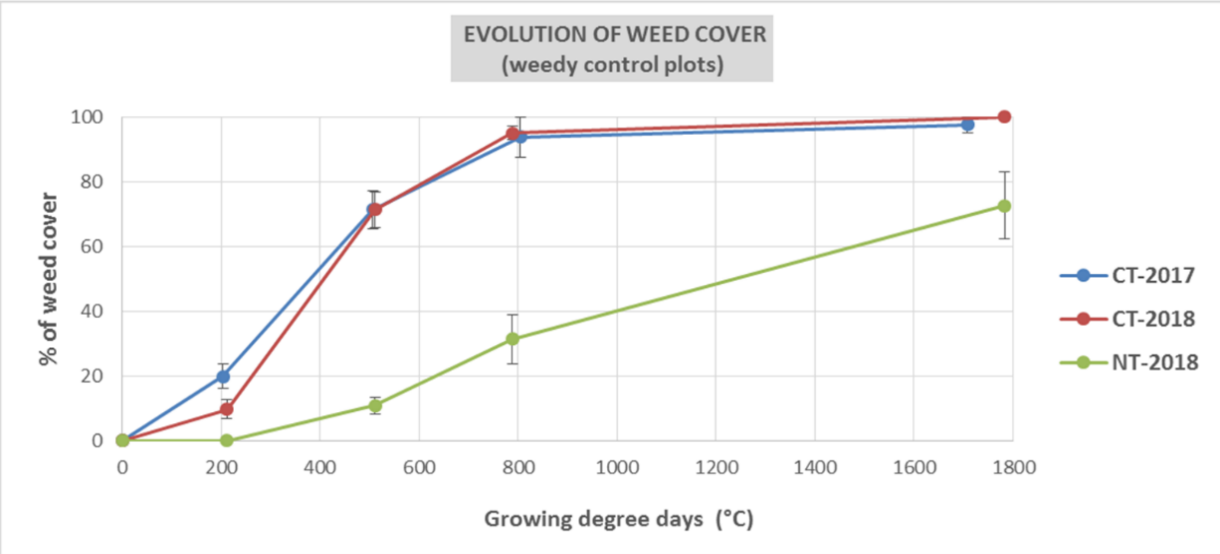


Figure 3: Dynamics of total weed cover

5.3.3 Effect of different weeding regime on rice grain yield

Rice grain yield was significantly influenced by weed competition in all experiments. Rice yield decreased when weedy period increased, and inversely it increased when the weed-free period increased. However, the speed of the yield decrease varied considerably from one experiment to another (Table 5). In CT-2017, it appeared that the rice field can be left unweeded until 20 DAS without significant yield loss, while in CT-2018, weed interference until 20 DAS caused already a significant loss. In contrast weeding can wait until 60 DAS without serious risk of yield loss in NT-2018. For all three experiments, it appeared that the rice field should be maintained weed-free until a certain date between 40 DAS and 60 DAS to avoid substantial yield loss (Table 6).

Rice yields were generally low in all experiments even in weed-free control, this was due to the absence of mineral inputs. Actually, the Nerica 4 cultivar has an yield potential up to 5 t.ha^{-1} (JICA 2006). Anyway, this low yield reflected correctly the real farms situation in Madagascar. In weedy control CT system, the rice grain harvested was as low as 10 - 50 kg.ha^{-1} indicating a 99.6% and 97.8% yield losses in 2017 and 2018 respectively by comparison to their respective weed-free control. The NT weedy control produced 1190 kg.ha^{-1} indicating a 53 % yield loss compared to the weed-free control.

Table 5: Effect of an increasing duration of weedy period on rice grain yield

weeding regime	rice grain yield (t.ha^{-1})		
	CT - 2017	**CT - 2018**	**NT - 2018**
weed-free control	2.02^{a}	2.21^{a}	2.52^{a}
weedy 0 - 20 DAS	1.91^{a}	1.71^{b}	2.46^{a}
weedy 0 - 40 DAS	0.80^{b}	0.87^{c}	2.31^{a}
weedy 0 - 60 DAS	0.27^{c}	0.68^{c}	2.12^{a}
weedy control	0.01^{c}	0.05^{d}	1.19^{b}

Within column, means sharing same letters are not significantly different at *P = 0.05*

Table 6: Effect of an increasing duration of weed-free period on rice grain yield

weeding regime	rice grain yield ($t.ha^{-1}$)		
	CT - 2017	**CT - 2018**	**NT - 2018**
weedy control	0.01^{d}	0.05^{d}	1.19^{d}
weed-free 0 - 20 DAS	0.74^{c}	0.74^{c}	1.46^{cd}
weed-free 0 - 40 DAS	1.23^{b}	1.45^{b}	1.96^{bc}
weed-free 0 - 60 DAS	1.83^{a}	1.71^{ab}	2.07^{ab}
weed-free control	2.02^{a}	2.21^{a}	2.52^{a}

Within column, means sharing same letters are not significantly different at *P = 0.05*

5.3.4 Critical period of weed interference

Preliminary analysis was performed to identify if the relative yield differ between experiments. When there was a significant difference, the regression curves were presented separately for each experiment, otherwise data from different experiments were pooled to drawn a unique curve. It turned out that the year relative yield in CT system of the treatment series "*increasing duration of weed-free period"* were similar, therefore a unique curve were presented for the two years. All the others were different so their curves were presented separately (Figure 4 and Figure 5).

The result showed that the CPWI started at 155 GDD (18 DAS) and 45 GDD (11 DAS) in 2017 and 2018 respectively in the CT system. It started at 342 GDD (29 DAS) in NT system. The end of the CPWI was at 1157 GDD (84 DAS) in both cropping season 2017 and 2018 CT system, and 1282 GDD (94 DAS) in the NT system (Figure and Figure).

After the parameters of the models were estimated, the following equations were used to draw the curve of the CPWI.

- Logistic curve for CT 2017 : ***y = 107/(1+exp[-(x-448)/-143])***
- Logistic curve for CT 2018 ***: y = 265/(1+exp[-(x+224)/-462])***
- Gompertz curve for CT 2017 and CT 2018 : ***y = 99.3 exp (-2.534 * exp (- 0.0035 * x))***
- Logistic curve for NT 2018 : ***y = 107/(1+exp[-(x-1554)/-586])***
- Gompertz curve for NT 2018= ***y = 104 exp (-0.8 * exp (- 0.0017 * x))***

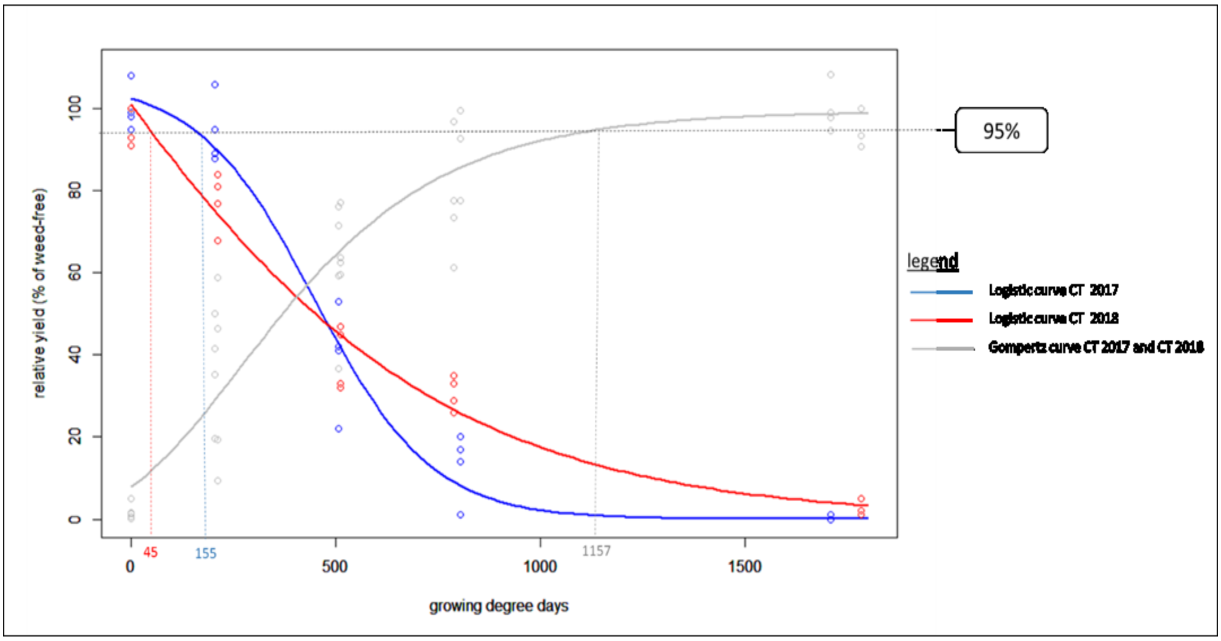


Figure 4: The beginning and end of the CPWI in CT system

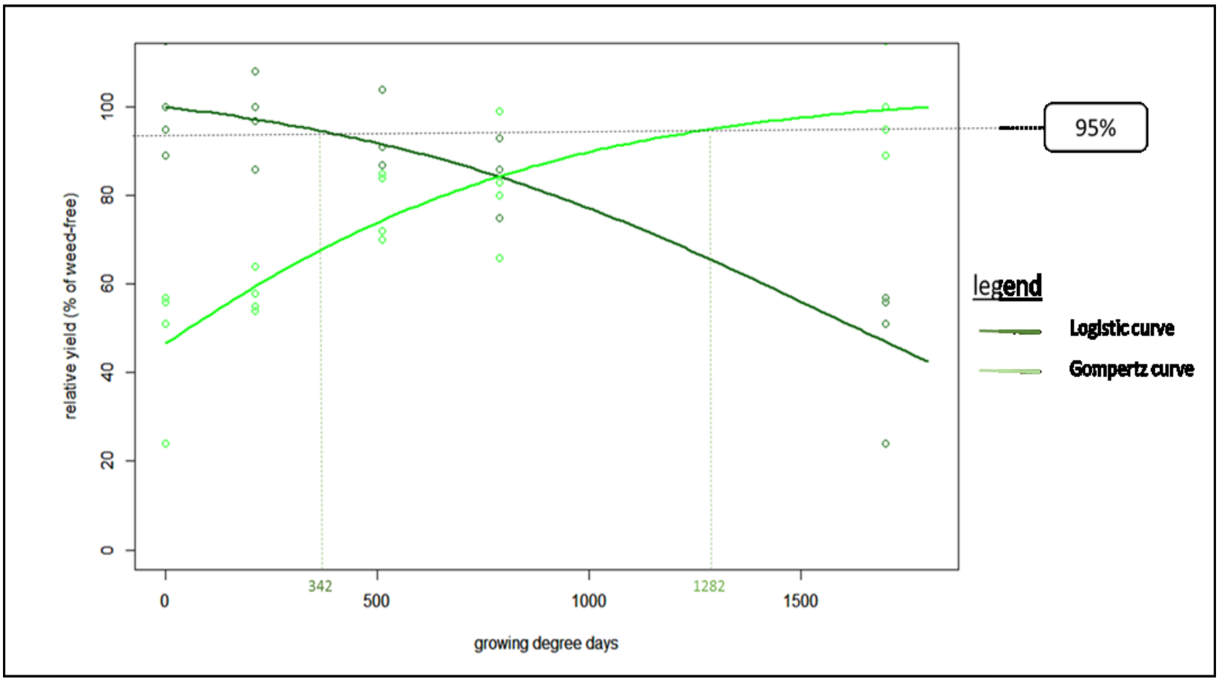


Figure 5: The beginning and end of the CPWI in NT system with stylosanthes

5.3.5 Correlation between rice yield, yield components and weed biomass

The result indicated that there was correlations between rice yield, yield components and weed biomass collected at harvest. The correlation matrix showed that rice grains and rice shoot biomass were strongly and positively correlated. Both were negatively correlated with grass weeds, broadleaved and total weeds, the highest correlation was however with broadleaved weeds. Tiller number, panicle number and full grains weight were positively correlated with grain yield, and negatively correlated with broadleaved weeds, but not correlated with grass (Table 7a and Table 7b).

Table 7a: Rice yield, yield components and weed biomass in CT system

weeding regime	tiller number	panicle number	grass (g/m²)	broadleaved (g/m²)	sedge (g/m²)	tot.weeds (g/m²)	weight of full grains (g/200grains)	% empty grains	rice shoot (t/ha)	rice grain (t/ha)
weedy 0 - 20 DAS	112 ± 10	102 ± 11	03 ± 03	05 ± 02	0.00	8 ± 4	5.01 ± 0.2	16 ± 7	1.41 ± 0.2	1.81 ± 0.2
weedy 0 - 40 DAS	101 ± 21	80 ± 12	51 ± 29	51 ± 18	0.00	102 ± 41	4.82 ± 0.3	15 ± 7	0.89 ± 0.3	0.83 ± 0.2
weedy 0 - 60 DAS	92 ± 20	77 ± 20	116 ± 52	171 ± 69	0.00	287 ± 104	4.84 ± 0.3	27 ± 21	0.59 ± 0.2	0.47 ± 0.3
weedy control	52 ± 67	54 ± 76	468 ± 152	226 ± 87	0.00	694 ± 259	4.60 ± 0.4	18 ± 12	0.03 ± 0.0	0.03 ± 0.0
weed-free 0 - 20 DAS	107 ± 39	82 ± 21	115 ± 72	160 ± 83	0.01 ± 0	275 ± 39	4.83 ± 0.2	12 ± 5	0.77 ± 0.5	0.74 ± 0.4
weed-free 0 - 40 DAS	120 ± 26	106 ± 17	34 ± 36	22 ± 14	0.01 ± 0	56 ± 29	4.99 ± 0.2	17 ± 5	1.36 ± 0.5	1.34 ± 0.4
weed-free 0 - 60 DAS	114 ± 43	99 ± 41	06 ± 03	08 ± 04	0.02 ± 0	14 ± 6	5.02 ± 0.2	17 ± 6	1.60 ± 0.5	1.77 ± 0.3
weed-free control	116 ± 33	109 ± 33	0	0	0.00	0	5.02 ± 0.2	14 ± 4	1.92 ± 0.5	2.12 ± 0.2

- Data averaged from 2017 and 2018 cropping season CT systems
- Tiller number and panicles number are the number counted from the sample of 12 rice plants just before harvest
- Weight full grains is the weight of 200 grains taken randomly from the sample of 12 plants
- Grass, broadleaved and total weeds were weed biomass collected at harvest, and during the first weeding of T1, T2 and T3

Table 7b: Pearson matrix correlation between rice yield and yield components with weed biomass

Variables	tiller number	panicle number	grass	broadleaved	total weeds	weight full grains	% empty grains	rice shoot	rice yield
tiller number	**1.00**								
panicle number	0.91	**1.00**							
grass	-0.21	-0.14	**1.00**						
broadleaved	-0.34	-0.40	0.58	**1.00**					
total weeds	-0.28	-0.25	0.95	0.80	**1.00**				
weight full grains	0.39	0.39	-0.17	-0.33	-0.24	**1.00**			
% empty grains	-0.11	-0.09	0.03	0.30	0.13	-0.11	**1.00**		
rice shoot	0.53	0.51	-0.57	-0.73	-0.70	0.51	-0.11	**1.00**	
rice yield	0.43	0.45	-0.60	-0.80	-0.74	0.49	-0.18	0.90	**1.00**

The number in red indicates a significant correlation (P < 0.05) between corresponding variables

5.3.6 Weeding regime effect on rice plant growth

The result from experiments in CT system showed that weed infestation affected rice development during vegetative phase (Table 8). In weed-free control, the rice plant height was 49 ± 7 cm and number of tillers 10 ± 4 at 60 DAS; and the chlorophyll meter displayed a score of 41 ± 2, at 70 DAS. No year effect was detected, therefore the data across two years were averaged. Significant plant height reduction was observed in weedy control, weedy until 60 DAS and weedy until 40 DAS. Significant tillering reduction was detected in weedy control and the weedy until 60 DAS. Significant reduction of nitrogen status, as estimated by the chlorophyll meter, was detected in the following plots: weedy control, weedy 0 - 60 DAS, weedy 0 - 40 DAS and weed-free 0 – 20 DAS.

Similar analysis run on data collected from NT system with stylosanthes showed that there was no significant effect of weeding regime on plant height and tillering. However, the chlorophyll meter displayed a lower score on weedy control compared to weed-free ($p = 0.023$), but no effect on chlorophyll meter score was detected in the other weeding regime.

Table 8: Weed competition effect on rice plant height, tillering and nitrogen status

weeding regime	tiller number	plant height (cm)	SPAD scores
weedy 0 - 20 DAS	10.4 ± 4	48 ± 8	40 ± 3
weedy 0 - 40 DAS	09.0 ± 4	39 ± 8 *	37 ± 2**
weedy 0 - 60 DAS	08.0 ± 4 *	34 ± 8 ***	28 ± 5***
weedy control	07.0 ± 4 ***	36 ± 9 ***	25 ± 3***
weed-free 0 - 20 DAS	09.4 ± 4	46 ± 8	37 ± 3**
weed-free 0 - 40 DAS	11.2 ± 4	50 ± 8	41 ± 2
weed-free 0 - 60 DAS	11.4 ± 4	49 ± 7	39 ± 3
Weed-free control	10.0 ± 4	49 ± 7	41 ± 2

Symbols (*) following the means show difference compared to the weed-free control
Significance meaning: ns $p > 0.5$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Data from 2017 and 2018 CT system, tiller number and plant height recorded at 60 DAS, nitrogen status estimated by the chlorophyll meter (SPAD-502) at 70 DAS on Last extending leave, 10 plants plot, 3 measures/plant

Mixed linear model: $y = ax + b$, random = block

- *y = rice development parameter (tiller, height, nitrogen status)*
- *x* = weeding regime effect
- *b* = intercept, average value of the response variable in weed-free control
- *a* = parameter estimated by lme function in nlme package
- *Degree of freedom for the analysis on each variables = 7*

5.4 Discussion

The CPWI begun later in the NT system compared to the CT system. This result confirms our hypothesis. The delay of weed-crop competition in NT can be explained by a lower weed infestation in this system. Singh et al. (2014) also observed that the CPWI depends on weed infestation level. The lower weed infestation level in NT was certainly the consequence of a late weed emergence. In fact, at 20 DAS there was no weeds to sample in the NT system because they did not emerge yet. At this date, rice plants was already 21 ± 3 cm tall. The stylosanthes mulch was as high as 23 $t.ha^{-1}$ which covered completely the soil, providing a formidable physical barrier at early date of the cropping season. A literature review reported that a crop residues of 10 $t.ha^{-1}$ is enough to reduce weed emergence and biomass (Ranaivoson et al. 2018). The possibility for rice to emerge from this barrier is thanks to the sowing method. To put rice seeds in the soil, a hole about 7 cm deep was made with a spade-like tool called *angady*. By digging the soil, this manual tool cut through the mulch above, thus reduces the barrier on the very place where the rice plant will emerge later (see Chapter 1: Photo 3).

During the rainy season, the mulch decomposes progressively as time went by and weeds will eventually manage to emerge. In the experiments, weed emergence in the NT system started at a certain time between 20 DAS and 40 DAS, rice plants had already a very important size advantage. A very basic feature of crop-weed competition is that if the emergence of crops occurs before weeds, they will be able to use much of the limited resource (Asif et al. 2014). This should explain that there was no negative effect of weeds on rice at early date of the growing season in the NT system.

From farmer viewpoint, such delay of rice-weed competition must be very useful, especially in case of work overload at the period for weeding. It actually happened very frequently as attested by farmers (Chapter 6). It gives time to accomplish other activities without risking a substantial yield loss on the upland rice fields. Furthermore, if it happens that the farmers did not have time to remove weeds throughout the growing season, they can still expect around 47% of the potential yield according to our result. In CT system, if the rice fields are left unweeded the farmer will harvest almost nothing.

The rice-weed competition timing also differed across years in the conventional system. The higher early weed competition in 2018 may be related to weed community composition. The weed species *Richardia scabra* was suspected to cause this strong competition effect. Indeed, this species dominated the weed community in 2018 (Table 4). This argument is in line with farmers' perception. They consider *Richardia scabra* to be highly competitive than other weed species such as *Digitaria* spp. (ref. Chapter 05). Furthermore, broadleaved weeds showed a negative and higher correlation with rice yield than grasses which always pointed out at the broadleaved *Richardia scabra* (Table 8b). The importance of some particular weed species in weed-crop competition was also reported in literature, it was indeed observed that the presence of *Oryza longistaminata* has a negative effect on rice growth even at a low level of infestation (Johnson et al. 2004). The origin of the difference in weed community composition may be attributed to the field weed seedbank which should be linked to the fields' history, because agroecological condition (soil, rainfall and temperature) were similar.

The negative correlation between weed biomass and yield components indicated that the tillering ability, the panicle production capacity and grains maturation phase were impacted negatively by weeds, mainly broadleaved. Thus resulting in a lower shoot biomass and grain yield. Besides, the significant effect of weeding regime on the chlorophyll meter scores indicated that there was a strong competition for nitrogen which begins already between 20 DAS and 40 DAS. This competition for nutrients, and probably for other resources, undermined rice plant height, and at a certain level impacted also the tillering ability.

The ANOVA showed that the fields must be kept weed-free at a certain date between 40 DAS and 60 DAS for all experiments to avoid significant yield loss, afterward subsequent emerging weeds cannot impact rice anymore. The first weeding intervention to avoid significant yield loss however vary considerably: i) It should be performed before 20 DAS in case of strong infestation of competitive weed species like *Richardia scabra* ii) It can be postponed but no later than 40 DAS in case of a combination of dominant species *Digitaria* spp*., Cleome hirta, Richardia scabra* and others iii) It can be postponed even after 40 DAS in a NT system with stylosanthes. All this indicated that the weed-crop competition timing is dependent of the cropping system and the weeds species composition.

Literature added that the weed-crop competition pattern varies with rice cultivars, planting row spacing, weed infestation, weed species and other cultural practices and environmental factors (Knezevic et al. 2002; Johnson et al. 2004; Anwar et al. 2012; Amadou et al. 2013; Singh et al. 2014). Results from all these studies showed a different time span of the CPWI. One of the results reported by Singh et al. (2014) was very close to the result of the experiment CT system in 2018 in the present study, but in general the results are always different from one study to another. This confirms that precise knowledge of the cropping system context is necessary to predict the CPWI.

5.5 Conclusion

The study was done on upland rice field under naturally weed occurring population. Weed infestation impacted negatively rice development such as plant height, tillering and nitrogen supply resulting in a lower rice grain yield, shoot biomass and other yield components. The main result also indicated that the rice – weed competition timing differs across cropping season and between cropping system. This is linked to difference of weed infestation level and the difference of weed flora composition. The presence of aggressive weeds such as *Richardia scabra* may prompt the rice-weed competition, while a no-till system with cover crop may delay this competition by reducing weed infestation at early date.

Farmers should check the main weed species that grows on the field to decide for the date of weeding as competition may begin to occur before or after 20 DAS in conventional tilled system. The no-till system with stylosanthes cover crop may be an option to reduce the yield losses in case of a limited time availability for weeding intervention at farm level.

Chapter 6 : Farmers' perception on weeds and stylosanthes

6.1 Introduction

Interaction with stakeholders is essential in a research processes. Farmers have certainly a central position in any agronomic research. Local farmers' perception and knowledge on specific topic of the study should help to adjust the research trajectory, but it can also explain results obtained from experiments and can be compared with the general scientific assumption in the literatures.

First step in a participatory approach methodology is to define participants. This question must be addressed, especially in view of the fact that different groups may have developed different knowledge and opinion (Bergold and Thomas 2012). For instance, men and women may think differently on the addressed topic, therefore a gender approach should be taken into consideration (World Bank 2007). The method used to collect information may involve techniques such as focus group and interviews. Ranking and scoring implemented during interviews can elicit participant's opinion. The specific objectives of these methods are in general to determine or identify one, or a few items, as being the most important from the respondent perception (Abeyasekera 2001). They can provide numerical data which could be explored by statistical analysis. Qualitative information can also be obtain with open questions, and may support and explain the trends in numerical data.

Recent survey in the Mid-West of Madagascar (Razafimahatratra et al. 2017) indicated that 72% of farmers grow upland rice in a conventional tilled system (CT), which means that a large portion of the population is potentially concerned by weed issues in upland cropping system. However, those who has experienced with cover crops where only 2% of the total households. The topic addressed in this study was the close relation between weeds and stylosanthes cover crops as a possible tool for weed management. Therefore participants who can provide information based on their experience from practices on the no-till system with stylosanthes cover crop (NT) were particularly needed. To gather this information a survey was conducted. It was only a first step to explore the possibility to include farmers in the research process. The next step should be an inclusive participatory research with farmers and other stakeholders to formulate weed management strategy.

The aim of the survey was to map farmers' knowledge of and opinion about weeds and stylosanthes in upland rice- based cropping systems. The research questions were: i) which weed species are the most abundant in upland rice and what are their main traits? ii) What are the difficulties farmers have in defining and applying a successful weed management strategy? iii) Do farmers consider the NT system with stylosanthes as an interesting option for weed management and other aspect of the cropping system improvement?

6.2 Material and methods

6.2.1 Study area and data collection

The survey was conducted in Mandoto District, Mid-West of Madagascar. Individual interviews and group sessions were used to collect farmer's knowledge and opinion on different topic related to weeds in upland rice and stylosanthes. The participants' selection was based on their knowledge and experience with the no-till system with stylosanthes. Participants where therefore not chosen randomly but preselected. They were actually farmers who were followed since a few years ago by the DP-SPAD (a collaboration of research and development institutions plate-form working in this area). Researchers interacted with these farmers in order to understand how small-scale farms are operating, and sometimes farmers accept to test innovation techniques. These households were similar to any standard farms in the Mid-West of Madagascar, except that they have more experienced with innovation techniques such as the use of stylosanthes as a cover crop.

The individual interviews were conducted from April to May 2016, 20 men and 20 women were interviewed to avoid that the responses were biased toward one gender. The data collected were scores on dominant weed species regarding six main weed traits: (1) frequency of occurrence, (2) capacity to cover the ground (3) harmfulness on rice growth and yield (4) weeding difficulty, (5) dissemination capacity, and (6) possible valorization. These traits were defined in advance by the researchers. The traits *frequency*, *cover* and *dissemination* were chosen as they can be associated with the parameters *frequency* and *cover* used during weed sampling (see previous Chapters). Therefore they can enable comparison with result from field experiments. The trait *harmfulness* is particularly important as it is directly linked to rice yield. The traits *weeding difficulty* was chosen to refer to weed management problem. Finally, the trait *valorization* was included because it is reported that many species commonly seen as weeds are sometimes used by the local population for different purpose (Stepp 2004; Rodenburg et al. 2012). The scoring was based on a scale of 1 to 10. Fifteen weed species were chosen in advance to be attributed scores. The species selection was based on preliminary results of weed sampling data on farmers' fields (Chapter 2) and the result of a floristic recording in the Mid-West of Madagascar done the previous year (Rakotoniriana 2015). Stylosanthes was included among the list of weed species to be scored, in order to evaluate the farmers' perception on this species. Pictures of each weed species were shown to farmers to be sure they all talked about the same species (Photos 1).

The group sessions were carried out in June 2016 and June 2017. The same farmers who participated in the individual interviews were invited to attend to the sessions, some other members of their family who participate in farming activities were invited as well. The sessions were also supported by weed species pictures to avoid misunderstanding about the species in question (Photos 1).

Forty-eight farmers participated to the first session. General topics about weeds were addressed including: weeds history in the district, weeds dissemination, weeds relationship with soil fertility, trade-off between weeds harmfulness and valorization, and the benefits from stylosanthes and limits. On each topic farmers expressed their knowledge and viewpoints, and ultimately a vote was made to evaluate the number of participants who agreed upon the same ideas. Finally farmers were asked to make some comments about the preliminary results from the individual interviews (see also supplementary material 3).

During the second session, the same farmers from the first session were invited to discuss new topics. Twenty-four responded to the call. Questions about weed management at farm level were addressed: the peak workloads narrowing farmer's availability for weeding activities, the priority crop for weeding, the most urgent weed species to be removed, the critical period of weed interference, the effect of agronomical practices such as crop rotation, intercropping and fertilization on weed infestation, the effect of stylosanthes on weeds and rice yield. Questionnaires based on ranking, multiple choice questions and quantification estimation were used to collect data, participants were allowed to discuss between each other and explain their opinion on each specific topic. The ranking was applied to the most important crops, and most harmful weeds to identify which crops the farmers prioritize for weeding and which weed species is prioritized to be removed first. The scale was 1 - 5, one for the highest priority and 5 for the lowest priority (see also supplementary material 4).

Individual interview based on weed pictures to be sure that the respondents understand which species we were talking about

Group session also with visual support. After explanation of the specific topic addressed, ideas exchange between participants were allowed

Photos 1: Individual interviews and group session (**Rafenomanjato A., 2016**)

6.2.2 Data analysis

Analysis of variance (ANOVA) were performed on the score data with R program version **3.3.2 (R Core Team 2016)** using the function ***aov*** integrated in R program in order to identify the species having the highest scores for each weed traits studied. Post hoc test were performed afterward with the ***multcomp*** package (Hothorn et al. 2018) using the Tukey's all pair comparison method. A non-parametric analysis Kruskal-Wallis test was used to analyze ranking data, followed by a Dunn post-hoc test for pairwise comparison with the package ***dunn.test*** (Dinno, 2007). Analyses were run with statistic

R program version 3.3.2 (R Core Team 2016). Data analysis were based on the methods for scores and ranks described in (Abeyasekera 2001).

6.3 Results and discussion

6.3.1 Farmers' perception on most important weed species

Results from scoring during the individual interviews are presented in Figure 1a and Figure 1b. The species that received the highest score of *frequency* were *E. indica*, *R. scabra* and *Digitaria* spp*.* The species that received the highest score of *cover* were *R. scabra, E. indica and S. guianensis*. The highest scores for dissemination capacity were attributed to *R. scabra, S. guianensis*, *E. indica, S. asiatica* and *C. hirta*. In theory, when one species obtain a high score for these three traits, it should be a dominant species. *Cover* and *frequency* are actually popular parameters used by weed scientists to make an evaluation of a species abundance/dominance (Nkoa et al. 2015), and species with high dissemination capacity are very likely to reach this position in the community. Regarding *E. indica* and *R. scabra* farmer's perception correspond to result from sampling on farmers' fields showing that those two weeds were dominant species in conventional tilled systems (Chapter 2). It was however unexpected that the dominant species *Digitaria* spp*.* observed during weed sampling was not considered by farmers to have a particularly high cover or dissemination capacity.

The highest score for *weeding difficulty* was attributed to *E. indica*, *R. scabra*, *Digitaria* spp. and S. *asiatica*. Farmers' comments highlighted that *R. scabra* is difficult to manage, as after the first weeding intervention, it reinfest quickly the field requiring another weeding. *Eleusine indica* and *Digitaria* spp*.* are difficult to remove from the field because of their stem elongation and developed root system. *Striga asiatica* cannot be controlled with hand weeding as it develops underground and appears on the surface only when the damage on rice was already done, which makes its management very difficult.

The most harmful weeds causing the highest damage on rice were *S. asiatica* followed by *R. scabra* and *E. indica.* Indeed, the parasitic weed species *Striga* spp*.* were reported to inflict rice yield loss up to 80% throughout Africa (Teka 2014), such enormous damage must be perceived by malagasy farmers and consequently they attributed a very high score of harmfulness on this parasitic weed. The high harmfulness of *R. scabra* and *E. indica* may be associated with their dominant traits but also a high competitiveness characteristics. *Digitaria* spp*.* was not regarded as highly harmful compared to the previous cited species. Farmers' comments added that *Digitaria* spp. is not causing too much damage on rice unless the infestation level is particularly high.

Farmer's perception on each species competitiveness is particularly useful, because it is very difficult to evaluate the competitiveness of a single weed species through field experiments (Rao et al. 2007), but farmers can be assumed to perceive approximately the damaged caused by a given species thanks to their daily experience on the field.

Highest score for valorization was attributed to *S. guianensis* and *E. indica.* Digitaria spp., *M. nudicaulis* and *B. pilosa* have also some usefulness. Farmers' comments highlighted that the high valorization of *Stylosanthes guianensis* is related to its possible use as cover crop and sometimes for cattle feeding, and most importantly its ability to enhance soil fertility. *Digitaria* spp*.* and *E. indica* are also used for cattle feeding with a more preference to *E. indica*. *Mollugo nudicaulis* is used for traditional medicines to treat several types of human disease, and *B. pilosa* can be consumed as human food.

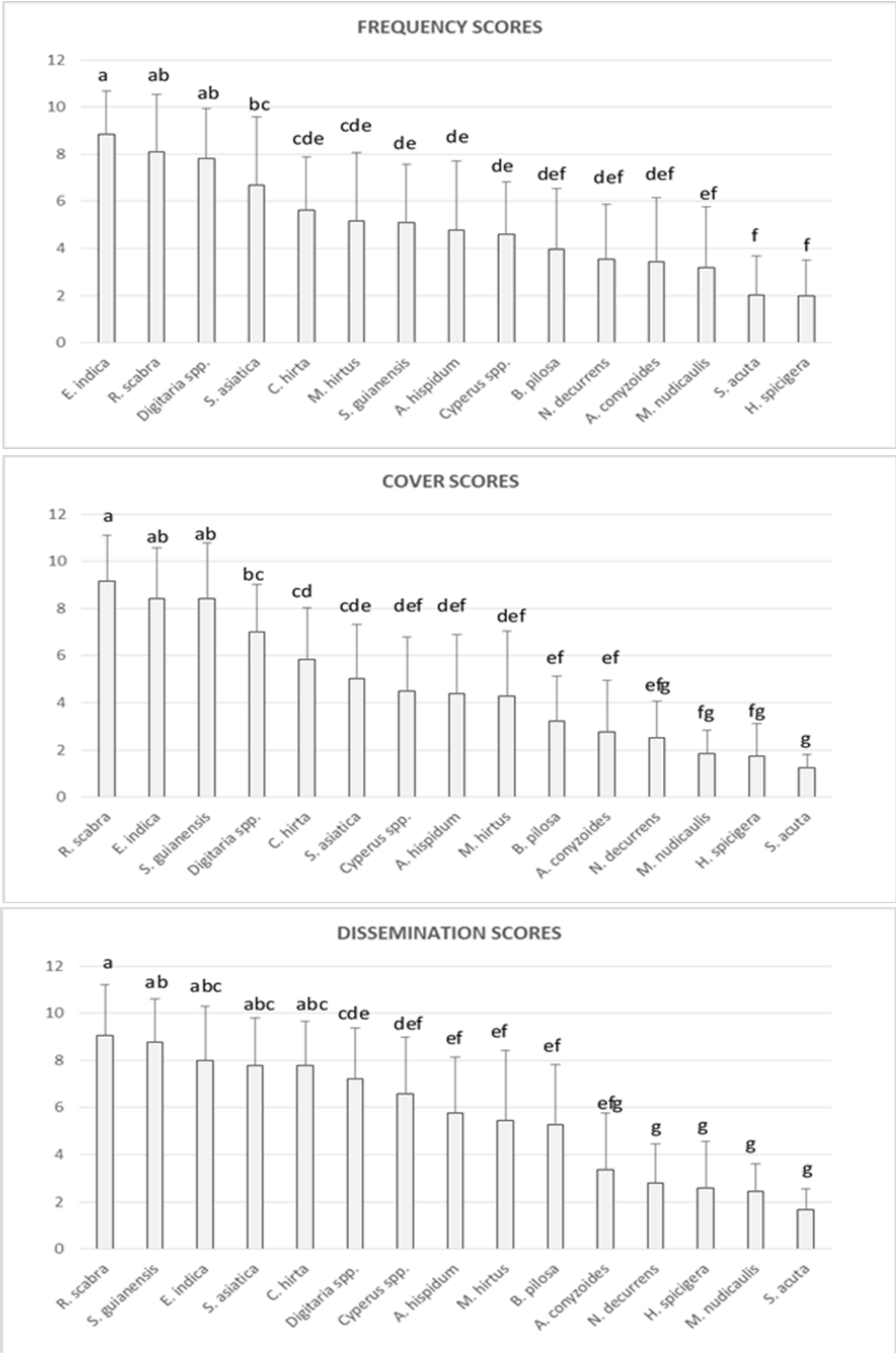


Figure 1a: Average scores of frequency, cover and dissemination
(The score scale was one to ten, means with the same letter are not significantly different)

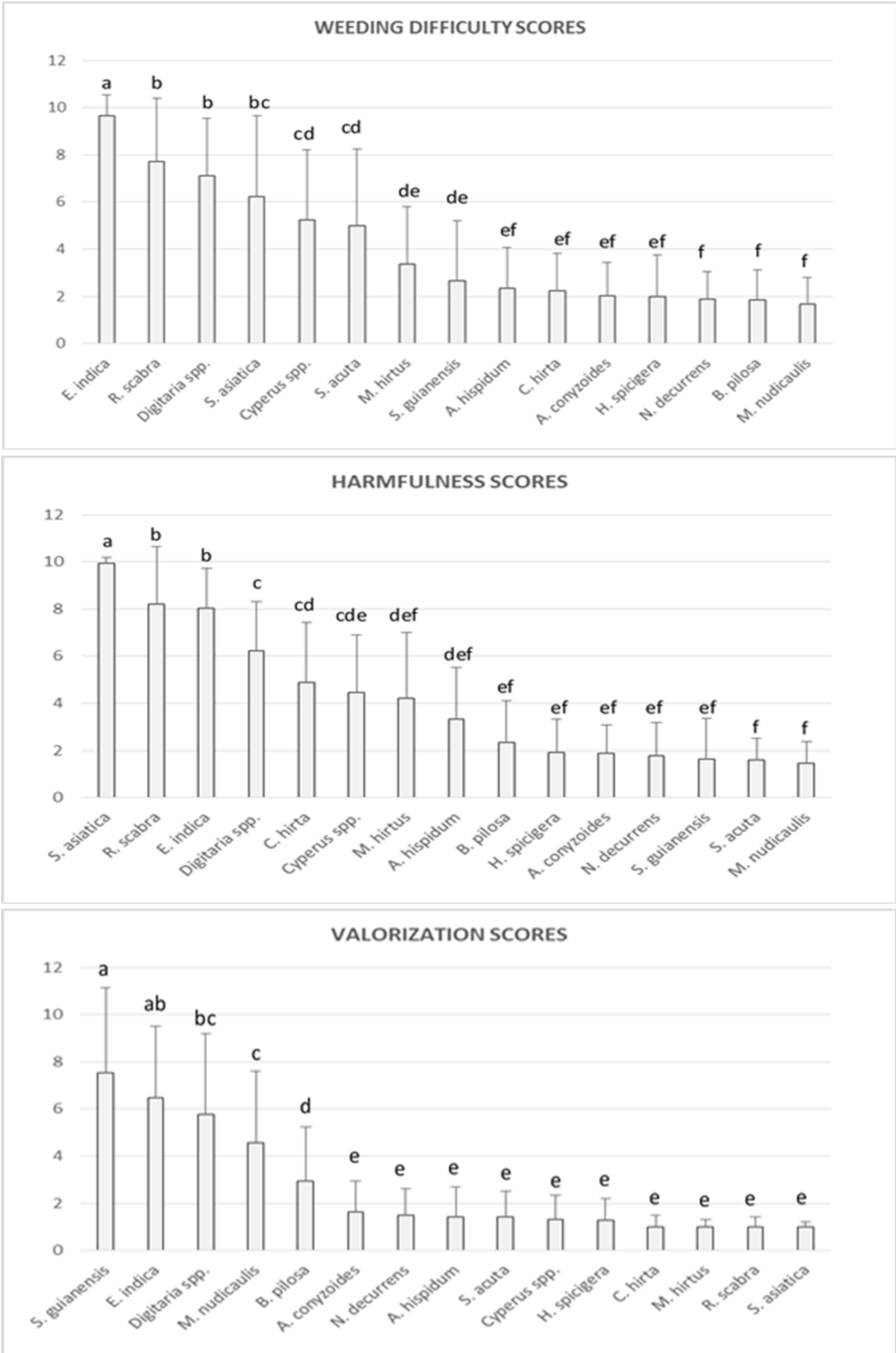


Figure 1b: Average score of weeding difficulty, harmfulness and valorization

The score scale was 1 – 10, means with the same letter are not significantly different

6.3.2 Weed species history, relation with soil fertility

Among the most frequent weeds, the following infested upland cropping systems in the Mid-West as far as farmers remember: *Digitaria* spp*., S. asiatica, E. indica, N. decurrens, M. nudicaulis, A. hispidum, Cyperus* spp*., A. conyzoides, B. pilosa, S. acuta, H. spicigera.* The newest weed species is *Richard scabra* which was seen in the region for the first time around the year 2005, and quickly colonized many upland crop fields. No one seemed to know where it came from. *Richardia scabra* can be regarded as an invasive species in the Mid-West of Madagascar, some speculation about invasive species is the decrease in regulation by natural enemies, resulting in a rapid increase in distribution and abundance, a theory largely discussed by scientists (Keane and Crawley 2002).

Most farmers begun to know the existence of *S. guianensis* between 2006 and 2011. The cover crop can be considered as relatively new in the land scape. Regarding the relation between weeds and soil fertility, the proportion of participants that perceive weeds to favor fertile soil was (50%), unresponsive to soil fertility (44%), and favor poor soil (6%). Farmers commented that *S. asiatica* shows some preference to poor soils. This is in line with what is frequently reported in the literature about this parasitic weeds (e.g. Teka 2014).

6.3.3 Farmers' perception on weed management at farm level

The survey about agricultural activities at farm level showed an important workload in November, December and January. The peak is in December (Figure 2). In the Mid-West of Madagascar, the rain usually starts to fall at early November, thus at mid-November the soil have got enough moisture, appropriate for upland rice sowing. In December, farmers move down to the lowlands in order to transplant irrigated rice. They mentioned that when upland rice should be weeded, workforce are already engaged in the lowlands to prepare rice seedlings transplantation. It leads to a work overload situation. December is particularly a bottleneck of time and workforce availability. Unfortunately during this period, the still young upland rice plants are mostly vulnerable to weed competition. In Madagascar, like in most African countries, hand weeding is the most widely applied intervention against weeds. While it is effective in reducing direct competition and preventing weeds from producing and shedding seeds (Rodenburg and Johnson 2009), this method is extremely labour demanding, requiring 30 days of works per hectare in conventional tilled system (Husson et al. 2013). According to some participants' comments, they cannot achieve the first weeding in upland rice correctly because of this peak workload and the incredible amount of labour required by hand weeding. Many farmers chose to postpone the weeding intervention despite a clear awareness that there will be a yield loss.

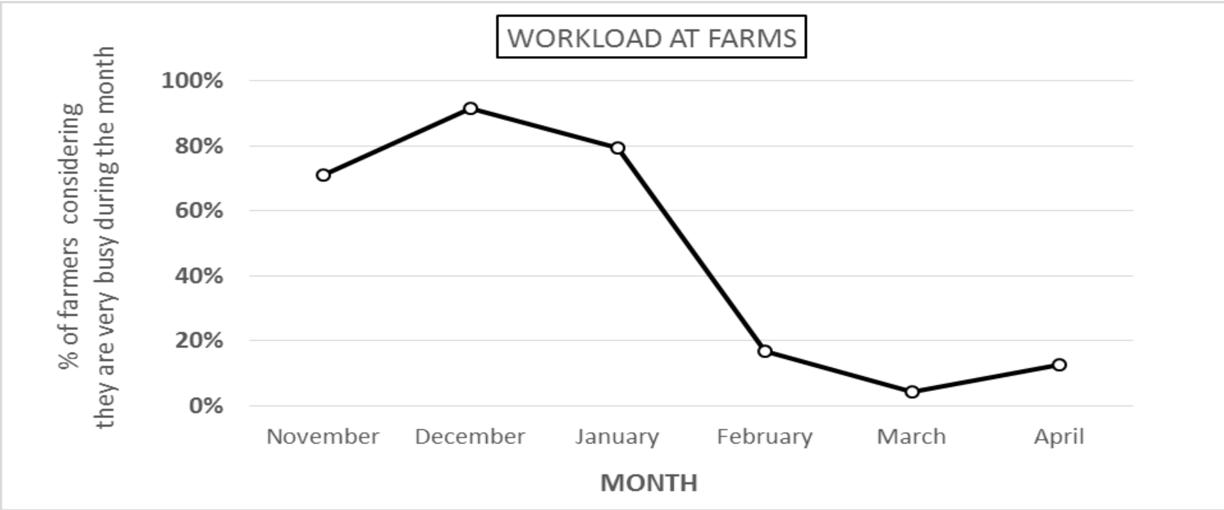


Figure 2: Workload at farm level

Most important upland crops in the Mid-West of Madagascar were identified as rice, maize, peanuts, cassava and groundnut by a recent survey (Razafimahatratra et al. 2017). Among those crops, farmers consider rice as priority for weeding and groundnuts is the last to be weeded (Table 1). Farmers' comments highlighted that this choice is due to the importance given to rice as the staple food, they mentioned as well that rice is less competitive against weeds compared to the other crops, which is also reported in some literature (Rodenburg and Johnson 2009).

Table 1: main crop ranked by priority for weeding

crops	mean based on farmers' rank
rice	1.3 [a]
maize	2.5 [b]
peanuts	3.2 [bc]
cassava	3.6 [bc]
groundnuts	3.9 [c]

Kruskal Wallis test (df = 4, n = 24) followed by Dunn post-hoc test, the mean based on rank followed by the same letter are not significantly different

If hypothetically, only one of the five most harmful weeds infests each upland rice field, farmers would chose to deal firstly with *Richardia scabra* (Table 2). This species presents the most urgent threat from their viewpoint, because the species has a high harmfulness level, this was already stated in the individual interviews. Some farmers would also choose to remove *Eleusine indica,* it is also perceived as a very harmful weed. Farmers added that if *E. indica* is given time to reach stem elongation and flowering stage, its enormous root system will damage all the surrounding rice plants when they try to uproot the weed. This characteristic of *E. indica* was already mentioned in Le Bourgeois and Merlier (1995). *Striga asiatica* was not ranked due to its peculiar phenology, this parasitic weed emerges aboveground after 60 DAS (Randrianjafizanaka et al. 2018) while farmers usually perform weeding between 20 DAS and 60 DAS.

Table 2: Weed species ranked by urgency to be removed

Weed species	mean based on farmers' rank
Richardia scabra	1.8 [a]
Eleusine indica	2.2 [b]
Cyperus spp.	3.0 [bc]
Digitaria spp.	3.6 [bc]
Cleome hirta	4.0 [c]

Kruskal Wallis test (df = 4, n = 24) followed by Dunn-post hoc test, the mean based on rank followed by the same letter are not significantly different

Farmers first weeding date on upland rice occurred in average at 25.2 DAS, despite the fact that they think the actual rice - weed competition begins on average at 21.8 DAS. It showed that farmers realize their intervention is slightly late, and weeds have already begun the competition before they are removed. The result from our experiments (Chapter 5), determined the beginning of the CPWI at 12 - 18 DAS in conventional tilled system. This is earlier than farmers perceive. It is possible that the 5% of yield loss on which the threshold of the critical period of weed interference in scientific literatures is commonly based, is not perceived by farmers as serious yield loss.

When asked about the effects of cultural practices on weeds (Table 3), 46 % of the participants responded that both crop rotation and intercropping decrease weed infestation, while 54% and 46% considered crop rotation and intercropping respectively not to have any effect on weeds. Eight percent mentioned that intercropping increases weed infestations. Comments from farmers pointed out that the cause of weed suppression is linked to the differential weed management of the successive crops, not because of the crop rotation or intercropping practices itself. This was already mentioned in other studies in Africa (Le Bourgeois and Merlier 1995). The vast majority of 83 % perceived that manure application increases weed infestation. Cattle manure from cows (zebu) is the most common fertilizer used by farmers on upland rice. They do think however that it is a source of weed seeds. *Eleusine indica, Digitaria* spp. and *Cyperus* spp. were explicitly mentioned by participants as species spread by cattle manure. Literature also reported that many viable weed seeds subsist in cattle manure (e.g. Pleasant and Schlather 1994).

Table 3: Farmer's perception on the effect of cultural practice on weed infestation

cultural practice	effect of weed infestation	% of answer
crop rotation	increase	00
	decrease	46
	no effect	54
intercropping	increase	08
	decrease	46
	no effect	46
cattle manure application	increase	83
	decrease	00
	no effect	17

6.3.4 Farmers perception on stylosanthes, weeds and upland rice

All participants, without exception agreed on the yield increase, their estimation varied from 20% to 100% more rice grains in a no-till system compared to a conventional till system. Regarding the weed suppression effect, the lowest estimation was a weed decrease of 50% and the highest 90%. Two farmers out of twenty-four however did not agree and perceived a weed infestation increase in the no-till system. It may concern some specific cases: an emergence of species well adapted in the no-till system (ref. Chapter 3 and Chapter 4), or a thin mulch of stylosanthes biomass which did not provide an effective physical barrier to control weeds. In fact, a review reported that a low residue biomass may stimulate weed emergence instead of suppressing it (Ranaivoson et al. 2017).

To understand farmers' management of the stylosanthes, it was asked if they removed the stylosanthes regrowth. Eight out of twenty responses were affirmative. Comments from the participants highlighted that the stylosanthes sprouts removal was not systematic. It is done only if the living mulch regrows too early or too much, and the farmer is afraid that cover crop is going to interfere with rice development. It is unclear what causes the early growth of stylosanthes but one possible explanation is the quality of the rolling during the land preparation, another possibility is a low mulch biomass accelerating stylosanthes germination from previous years seeds (Husson et al. 2013).

Finally, farmers were asked to make an inventory of the most important benefits and limits of the system with stylosanthes adoption (Figure 3a and Figure 3b). It turned out that farmers have a very positive opinion towards the system due to its ability to enhancement soil fertility. The most important limit of adoption is seeds availability. A study report mentioned that stylosanthes seeds production is easy but collecting the seeds requires a lot of time (30 – 40 days/ha) for 100 kg of seeds (Husson et al. 2013).

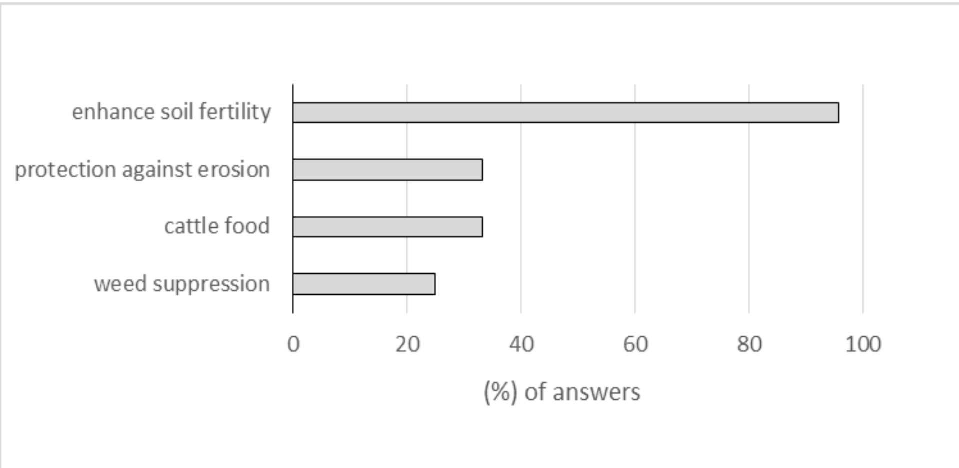


Figure 3a: Most important benefits from stylosanthes according to farmers

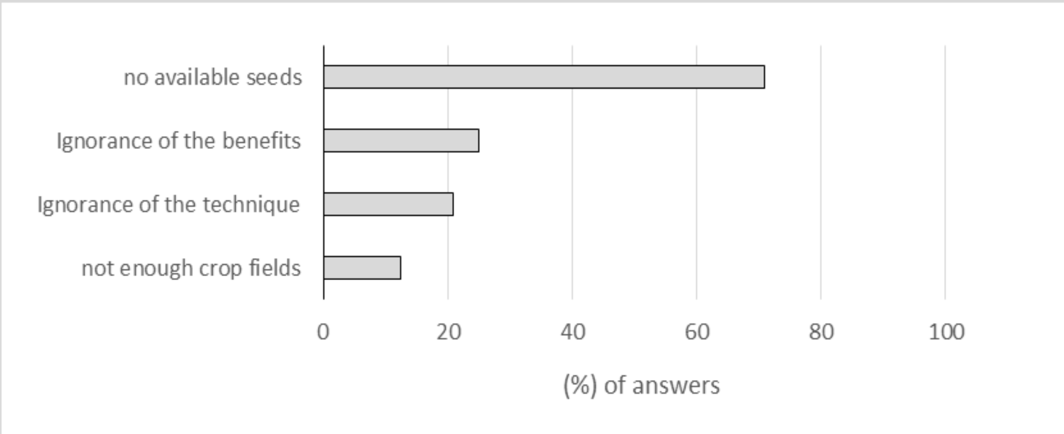


Figure 3b: Most important limits that hinders stylosanthes adoption

6.4 Conclusion

According to farmers the most harmful weeds is *S. asiatica*, followed by *R. scabra* and *E. indica*. Those species cause the highest yield losses in upland rice fields. *Digitaria s*pp. cause yield loss only when its infestation level is high. *Richardia scabra* has newly arrived in the region and therefore can be considered as an invasive species. *Striga asiatica* was identified as a species of low fertile soil. An important peak workload occurs in November, December and January at farm level, which frequently leads to a weeding intervention delay on upland rice, resulting in considerable yield loss. Manure is an important source of weed dispersal. *Digitaria* spp. and *E. indica* are suspected to be spread by this popular organic fertilizer in the Mid-West. The no-till system with stylosanthes is perceived by farmers as a cultural practice which may suppress weeds and increase rice yield. Weeds are real problems in upland rice-based cropping systems in the Mid-West of Madagascar, and farmer's perception on the agroecological practice is generally positive. However, some limits such as the seed availability issue should be alleviated to encourage the adoption of this innovative cropping system.

Chapter 7 : General discussion

The general discussion is focusing on the comparison of main results from each chapters and their implication and limits in weed management.

7.1 Effect of no-till system with stylosanthes on weed community

The total number of weed species recorded in all samplings during this work was 102. This should be taken only as an indicative figure, because some species which are difficult to differentiate were grouped (*Digitaria* spp. and *Cyperus* spp.). The definition of weeds within the framework of this study was: *Any species which was not planted deliberately by the farmer in the current cropping season was to be counted as a weed*. Therefore, six of the weed species were actually crops or cover crops (*Cucurbita* sp., *Psidium guajava*, *Sorghum bicolor, Vigna subterranean, Zea mays, Stylosanthes guianensis, and Mucuna pruriens*). Those lasts had a very low occurrence to interfere on the study focus which concern the actual weeds. Two occasional species were not identified so far, they were given pseudo-names during the samplings. This highlighted the need for a further identification work if one is interested in occasional species of the Mid-West of Madagascar.

The weed flora was dominated by broadleaved weeds in term of species richness, but in term of cover grass and broadleaved were fairly balanced on farmers' fields. Sedge occurrence was very low, this group was represented only by two gender (*Cyperus* and *Fimbristylis*). The most consistent dominant species across samplings in all experiments was *Digitaria* spp. This species was dominant in both the no-till system with stylosanthes cover crop and the conventionally tilled system, but appeared to be more abundant in the conventional system, and respond positively to mineral input by increasing furthermore its abundance. The other dominant species were *R. scabra* and *E. indica* in conventional systems on one hand, and *M. hirtus* and *Cyperus* spp. in the innovative on the other hand. During the surveys, farmers also considered that *E. indica* and *R. scabra* are dominant species because of their high frequency, cover and dissemination ability. *Digitaria* spp. was perceived only as a frequent species and less harmful compared to *E. indica* and *R. scabra*. Maybe it is possible that farmers overestimated the presence of species that they are afraid of, and consequently underestimated *Digitaria* spp. presence as it seems to be less competitive and pose less threat.

The dominant species in the no-till system were not particularly noticed by farmers, maybe because there exist only few fields managed in this system, compared to the conventionally tilled fields, at regional scale in the Mid-West of Madagascar. A recent survey reported that stylosanthes is grown only on 2% of upland rice fields in the region (Razafimahatratra et al. 2017).

In general, the weed flora in farmers' fields and on-station experiments presented the same species composition. However, an important difference was observed regarding *R. scabra*. This species was rarely present in the split-plots experimental field on-station, but was consistently dominant in farmers' fields and in the experiments for critical period of weed interference. This is not abnormal as some farmers' fields were strongly infested by *R. scabra* while others were strongly infested by *Digitaria* spp. (Chapter 2). The reason behind this difference is unclear and may need a further research, by testing for example different manure, as this organic fertilizer is a source of weed seeds. It should be noted that the experiment on station was biased toward two dominant species, *Digitaria* spp. and *E. indica,* and missed the other important species of conventional tilled system, *R. scabra*.

7.2 Effect of no-till system with stylosanthes on weed cover and weed biomass

The total weed cover was lower in the no-till system than in conventional system. The results from the experiments on farms and on station were consistent. This confirms the general hypothesis that the no-till system with stylosanthes, managed as a living mulch, suppresses weeds. Our result joins the findings of previous researches on stylosanthes in Laos and Benin (Saito et al. 2006, 2010).

The weed suppressive effect of this innovative system is mainly attributed to the stylosanthes mulch that limits weed emergence at the beginning of the cropping season. During all experiments, stylosanthes mulch was evaluated to be between 5 - 23 $t.ha^{-1}$ dry matters at sowing date. According to a recent review, 10 $t.ha^{-1}$ or more of crop residues suppresses significantly weed abundance and biomass (Ranaivoson et al. 2018). Weed suppressive effectiveness of stylosanthes was quantified by farmers to be between 50% - 90%. The experiment on farms showed an average weed suppressive effect of 47% at 60 DAS, and the experiment on station showed a weed suppressive effect of 80% - 93% at 30 DAS. The farmer's perception corresponds to the result from experiments, considering the fact that they perform the first weeding around 30 DAS.

7.3 Effect of no-till system with stylosanthes on rice

Results obtained from all experiments showed that rice yield was similar in the conventionally tilled system and the innovative system, or higher in the innovative system in several cases mainly in weedy plots. This confirms the general hypothesis that the NT system with stylosanthes pose no threat to rice yield. It may increase yield instead or reduce yield loss due to weeds. The results joined the findings from other experiments conducted on stylosanthes in Laos and Benin (Saito et al. 2006, 2010). In weedy plots, the higher yield observed in the no-till system was mainly attributed to a lower weed cover. In weed-free plots it should be attributed to a general improvement of the soil fertility such as a nitrogen fixation by the legume cover crop, improved soil structure and water infiltration. This can occur through different mechanisms reported in the literature (Teasdale 1996; Lu et al. 2000; Hartwig and Ammon 2002).

During the survey, all farmers agreed that the no-till system with stylosanthes does not reduce rice yield compared to the conventional tilled system, but increase yield instead. Farmers' perception was in general in line with the results from experiments on this matter. They estimated a rice yield increase between 20% up to 100%, while the result from trials on-farm in 2017 showed a yield increase of 39% if weeds are managed in farmer's way. It indicated that the increase in yield actually occurs though

100% increase might be overestimated. In the effort to encourage farmers to adopt the innovative technique, some development projects praised stylosanthes, which may have influenced some farmers' perception, leading to a yield overestimation compared to the reality in their fields.

In weedy plots, the higher yield in the innovative system should be interpreted as a reduction of yield losses due to weeds. Yield losses in the conventional system were very high in case of strong weed infestation: 80% in 2017 and 93% in 2018 experiment on station, and only 33% to 54% in the innovative system in the same experiments. The experiment on farms in 2017, showed a smaller difference: 39% and 26% yield loss in conventional system and the innovative system respectively, surely because weed infestation was lower. Finally, in 2016 on farms and on-station, there was no difference of yield loss between the two systems as weed infestation was very low. It indicated that the benefits from the innovative system with respect to yield is more expressed in a situation of a high weed infestation.

In weed-free plots, a higher yield in the innovative system was observed only once in all experiments, the 2018 on-station experiment without mineral input. It indicated that if weeds are correctly removed the no-till system with stylosanthes is expected to increase yield mainly in a low input condition.

In sum, it is possible that the innovative system does not increase yield if weeds are correctly removed and a certain rate of mineral fertilizer is applied. Conversely, it produces a higher yield than the conventional system when weed pressure is high, and fertilization is low. It may explain why farmers are mostly interested in this innovative system for its capacity to enhance soil fertility (Chapter 6). It may also confirm that stylosanthes, as a legume crop, provides nitrogen in the soil to the benefits of cultivated crops (Zemek et al. 2018).

It was observed both on farms and on station that removing stylosanthes regrowth in the no-till system may increase rice yield. Literature reported indeed that a living mulch present a potential risk to compete with the crops (Teasdale 1996). This may explain why farmers sometimes remove or prune stylosanthes sprouts. During the survey, 40% of the participants declared to do this practices from time to time, not systematically. The overgrowth of stylosanthes sprouts may linked to a less effective rolling during land preparation, or a thin mulch which trigger stylosanthes seeds germination (Husson et al. 2013). Pruning may alleviate this problem but will surely require an extra-time. This practice was already implemented in Laos (Saito et al. 2006).

Rice yield from farmers' fields and from the experiment on-station was generally comparable. Average yield obtained for all experiments were globally low, it ranged from 1.18 $t.ha^{-1}$ to 2.56 $t.ha^{-1}$ in weed-free plots, excluding plots were mineral fertilizer was applied. This last situation does not reflect the actual yield on real farms because farmers rarely use mineral inputs and if so at a very low rate. According to a recent survey, the standard yield of upland rice in the region is 1.6 $t.ha^{-1}$ with a variation coefficient of 60% (Razafimahatratra et al. 2017) and in Sub-Saharan Africa upland rice yield ranges from 1-3.5 $t.ha^{-1}$ (Balasubramanian et al 2007). That is to say the low yield in all experiments is similar to the reality in the Mid-West and in Africa in general. This is obviously due to low external inputs. The rice cultivar Nerica 4 is actually able to produce up to 5 t.ha^{-1} in the best growing condition (JICA 2006)

7.4 The critical period of weed interference

It was highlighted during the survey that an important work overload occurred in November, December and January at farm level. This work overload period correspond to the critical period of weed interference in upland rice in conventional system (Chapter 5). As the upland rice sowing occurs between the middle and the end of November, the first weeding should occurred during the peak of workload in December. Frequently, farmers have to postpone the weeding because of other activities, and sometimes they do not have time for weeding at all. In this context, a cropping system that provides time flexibility or suppress weeds by itself should be an interesting option. The no-till system with stylosanthes appeared to answer to these requirements. It was indeed observed that this system suppressed weed emergence, especially at the beginning of the growing season. Literature reported as well that an early season weed control is one of the main features of a cover crop (Teasdale 1996). Furthermore, it was reported that the weeding requires 30 days/ha in conventional system, which can be reduced to 5 days/ha if the system with stylosanthes is correctly implemented (Husson et al. 2013).

Competitive weed species like *Richardia scabra* may prompt the start of the CPWI. This was also perceived by farmers. They considered this species as a very harmful weed, only the parasitic weed *Striga asiatica* out-matches the damage caused by *Richardia scabra* according to the survey scoring results. Furthermore, farmers stated that *R. scabra* is the most urgent species to be removed from the field. During the interviews, some farmers displayed anxiety at the sight of *R. scabra* or *S. asiatica* photos, indicating a psychological effect of the species. The point is that farmer's perceive the potential damage that can be inflicted by each weed species, an important knowledge that scientists should explore, because ranking the comparative damage done by a single species through a field experiment is very difficult given the interaction of factors and processes in weed-crop competition and the related economic damage (Rao et al. 2007).

7.5 Potential limits of the no-till system with stylosanthes

Despite all the benefits from the no-till system with stylosanthes, there are some limits that may hinder its adoption by overall farmers. This system was introduced on real farms in the Mid-West of Madagascar in 2004, and nowadays, it covers only 2% of total upland rice fields in the region, according to a recent survey (Razafimahatratra et al. 2017). A few reasons may explain the poor adoption rate of this agroecological practice in real farms up to now. During the collective interview farmers expressed mainly seeds availability issue, ignorance of the benefits from the system, ignorance of management technical skill needed, and insufficient crop fields to establish the new cropping system. In our opinion, the three first obstacles can be alleviated by means of stylosanthes seeds subsidies, and information and teaching campaign on stylosanthes and its management and the benefits it can provide. The present study hopefully will provide a lot of contribution in these matters. The last limit is more challenging. Firstly , stylosanthes establishment requires time to fully express its potential, four to five years is generally needed (Husson et al. 2013). During this transition, the food produced by the field is low and may discourage some farmers. Secondly, when the system is well established, stylosanthes has to be grown alone or with another crop during one cropping season, prior to each rice cultivation. This other crop is usually maize sown at low density (1 m x 1 m). It allows stylosanthes to develop correctly and produce an important biomass to be rolled into mulch for the coming rice cultivation. That is, the maize suffers from stylosanthes competition and produce a low yield (Rodenburg et al. in press). Farmers may not be inclined to have one season non-productive or less productive. For these reasons, a few agronomists working in the region projected that the no-till system with stylosanthes will not be adopted by farmers who owned less than 3 ha of land, because they cannot afford the one season fallow period, it would impact significantly their food production of the current year (Suarez and Penot, 2010 ; Razafimahatratra et al. 2012).

7.6 Conclusion and perspective

Weed pressure in upland cropping systems is an important limit that undermine upland rice production in the Mid-West of Madagascar. The introduction of the no-till system with stylosanthes cover crop offered a new perspective for weed management. This study was then conducted to investigate the effect this agroecological practices on the weed community composition, total weed cover, rice yield and the critical period of weed interference. The methodology was based on weed sampling on farmers' fields, field experiments on farms and on station, combined with interviews with farmers. All the studies were conducted in the Mid-West of Madagascar from 2016 to 2018. The study area covered three administrative units, *commune* Vinany, Ankazomiriotra and Inanantonana stretching over 30 km.

The weed sampling showed that the most dominant weeds on upland rice fields managed in the conventional tilled system were *Digitaria* spp*., Richardia scabra* and *Eleusine indica*. The agroecological system suppressed these three dominant weeds along with other species such as *Euphorbia heterophylla, Melochia pyramidata* and *Mollugo nudicaulis,* resulting in a decrease of the total weed cover and biomass. This weed suppression effect was mostly attributed to the stylosanthes mulch that limits weed emergence and growth at early date of the growing season. It was however observed that the no-till system with stylosanthes increased the abundance of *Mitracarpus hirtus*, and also promoted some other species such as *Ageratum conyzoides*, *Neojeffreya decurrens,* and *Cyperus* spp. indicating that the weed suppression effect is species specific. Mineral inputs combine with manure increased weed cover and weed biomass compared to manure alone. It increased particularly the abundance of *Digitaria* spp.

The result from harvest from field experiments showed that, in weed free condition, rice yield was not reduced by the innovative system but was observed to be increased in some cases. This should be attributed to nitrogen supply by the legume cover crop and general improvement of soil texture and water regime. In weedy condition, the yield loss due to weeds was considerably reduced in the innovative system compared to the conventional system as a consequence of the weed suppression effect. Mineral input was observed to increase rice yield in general, but may decrease the yield if it promote strongly weed infestation. It was also observed that the suppression effect of weed emergence by the stylosanthes mulch delayed the critical period of weed interference in upland rice, and the presence of highly competitive weed species such as *Richardia scabra* may prompt the start of weed-crop competition at early date.

The farmers' general perception is in agreement with the results of the experiments on the fact that the innovative system decreases the total weed cover and pose no threat to rice yield, but may increase the yield instead. It also highlighted that farmers are overloaded by agricultural activities in November, December and January, thus the weeding on upland rice field is not always correctly achieved. In this context there is another benefit of the innovative system as it delay the beginning of the critical period of weed interference which should alleviate the work overload that farmers have to deal with during some period of the year.

The main limit of the innovative system are: the time necessary for the system to reach its full potential (4 to 5 years), the investment on the tool necessary for its management, and the one of two year fallow period required by stylosanthes to accumulate enough biomass for the following rice cropping season. It is possible that farmers with limited crop fields and resources cannot afford the investment, the fallow period and the time required for the innovative system establishment.

This research showed many characteristic of a legume cover crop managed as a living mulch in a no-till system: it may suppress weeds but this suppressive effect is species specific and attributed mainly to the mulch, the weed biomass and weed cover reduction result in a lower crop yield loss due to weed-competition, and it may change the critical period of weed interference by delaying the weed-crop competition timing. The result also indicated a possible interaction between soil management and fertilization leading to a variable outcome of weed infestation level and yield, and it confirmed also the assumption that some weed species respond to fertilization. The interview with farmers indicated that they can provide valuable information mainly on the competitiveness of a given weed species.

The potential benefits of stylosanthes, managed as a living mulch, highlighted in this study should be tested in other countries wherever stylosanthes can be grown correctly, local population may be interested. The possibility to use other species of cover crops in weed management should be tested in the Mid-West of Madagascar in order to diversify the weed management strategy. A particular focus should be oriented to the weed species *Richardia scabra* given the fact that it is relatively new and a very problematic weed, questions like why it strongly infested some fields and not others must be addressed, no valid explanation can be speculated so far. The physiology of the most important weed species should be studied as it can provide a complementary information to set up weed management strategy. Finally, a participatory approach including farmers should be implemented more effectively in the next research process. The social approach in the present study was only a first step to collect basic information on weeds problem and weed management but may open the gate for an actual participatory process.

Information provided in this research work should improve the knowledge about weeds in Madagascar and can also be used to feed the data base of the web site WIKWIO (Weed Identification and Knowledge in Western Indian Ocean) for international exchange on weeds in tropical countries.

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SUPPLEMENTARY MATERIALS

Supplementary material 1: Weed species full list

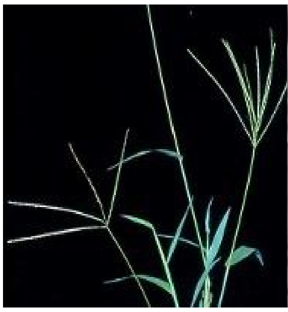
(List of all weed species observed in farmers' fields and experimental fields during the study)

Species scientific name	Family	local name	group	life form
Acanthospermum australe (Loefl.) Kuntze	*Asteraceae*	anamalaonalika, kidoron' alika	broadleaved	annual
Acanthospermum hispidum DC.	*Asteraceae*	hisabazaha, bakakely	broadleaved	annual
Aeschynomene americana L.	*Fabaceae*	anjananjana, ramianoka	broadleaved	annual
Aeschynomene patula Poir.	*Fabaceae*		broadleaved	annual
Ageratum conyzoides (L.) L.	*Asteraceae*	hanitrimpatsaka	broadleaved	annual
Alysicarpus monilifer (L.) DC.	*Fabaceae*		broadleaved	annual
Alysicarpus ovalifolius (Schum.) Leonard	*Fabaceae*		broadleaved	annual
Amaranthus hybridus L.	*Amaranthaceae*	anapatsamena, jakimena,	broadleaved	annual
Amaranthus sp.	*Amaranthaceae*		broadleaved	annual
Arachis hypogaea L.	*Fabaceae*		broadleaved	annual
Aristida sp.	*Poaceae*	bozaka	grass	annual
Aristolochia sp.	*Aristolochiaceae*		broadleaved	annual
Bidens pilosa L.	*Asteraceae*	tsipolitra, anatsinahy	broadleaved	annual
Brachiaria sp.	*Poaceae*		grass	annual
Brachiaria umbellata (Trin.) Clayton	*Poaceae*	volonondry, fandrodahy	grass	annual
Cajanus scarabaeoides (L.) Thouars	*Fabaceae*	tsimbatrimbatry	broadleaved	annual
Chamaecrista mimosoides (L.) Greene	*Fabaceae*		broadleaved	annual
Celosia argentea L.	*Amaranthaceae*		broadleaved	annual
Celosia trigyna L.	*Amaranthaceae*	fotsimbarinakoho	broadleaved	annual
Chrysanthellum americanum (L.) Vatke	*Asteraceae*		broadleaved	annual
Cleome hirta (Klotzsch) Oliv.	*Cleomaceae*	akondronjaza, anantsifotra	broadleaved	annual
Commelina africana L.	*Commelinaceae*	moravelona, tsimativonoina	broadleaved	annual
Commelina benghalensis L.	*Commelinaceae*	moravelona, tsimativonoina	broadleaved	annual
Commelina diffusa Burm.f.	*Commelinaceae*	andrenahake	broadleaved	annual
Conyza sumatrensis (S.F.Blake) Pruski & G.Sancho	*Asteraceae*	ahibahiny, maintsoririnina	broadleaved	annual
Corchorus olitorius L.	*Malvaceae*		broadleaved	annual
Crassocephalum crepidioides (Benth.) S.Moore	*Asteraceae*	anandrambo, Mampody	broadleaved	annual
Crotalaria juncea L.	*Fabaceae*		broadleaved	annual
Cucurbita sp.	*Cucurbitaceae*	voatavo	broadleaved	annual
Cynodon dactylon (L.) Pers.	*Poaceae*		grass	perennial
Unidentified 1	*Cyperaceae*	karepoka	Sedge	annual
Cyperus amabilis Vahl	*Cyperaceae*	karepoka	Sedge	annual
Cyperus rotundus L.	*Cyperaceae*		Sedge	perennial
Cyperus cyperoides (L.) Kuntze	*Cyperaceae*		Sedge	perennial
Cyperus esculentus L.	*Cyperaceae*	karepoka	Sedge	perennial
Cyperus (unidentified N° 1)	*Cyperaceae*	karepoka	Sedge	perennial
Desmodium sp.	*Fabaceae*		broadleaved	annual
Digitaria horizontalis Willd	*Poaceae*	ratsanakoho	grass	annual
Digitaria bicornis (Lam.) Roem. & Schult.	*Poaceae*	ratsanakoho	grass	annual
Digitaria ciliaris (Retz.) Koeler	*Poaceae*	ratsanakoho	grass	annual
Echinochloa colona (L.) Link	*Poaceae*	ahibary, akatandrano	grass	annual
Elephantopus mollis Kunth	*Asteraceae*	tambakombako	broadleaved	annual
Eleusine indica (L.) Gaertn.	*Poaceae*	tsipihipihina, ahitromby	grass	annual
Eragrostis aspera (Jacq.) Nees	*Poaceae*		grass	annual

species name	Family	local name	group	life form
Eragrostis cilianensis (All.) Janch.	*Poaceae*		grass	annual
Eragrostis patula (Kunth) Steud.	*Poaceae*		grass	annual
species X (unidentified n° 2)			broadleaved	annual
Euphorbia heterophylla L.	*Euphorbiaceae*		broadleaved	annual
Euphorbia hirta L.	*Euphorbiaceae*		broadleaved	annual
Fimbristylis sp.	*Cyperaceae*	haravolo, kiforomboalavo	Sedge	annual
Galinsoga parviflora Cav.	*Asteraceae*		broadleaved	annual
Heteropogon sp.	*Poaceae*	danga	grass	annual
Hibiscus asper Hook.f.	*Malvaceae*		broadleaved	annual
Hyparrhenia sp.	*Poaceae*		grass	annual
Hyptis pectinata (L.) Poit.	*Lamiaceae*	mampivena	broadleaved	annual
Hyptis spicigera Lam.	*Lamiaceae*	mampivena	broadleaved	annual
Hyptis suaveolens (L.) Poit.	*Lamiaceae*		broadleaved	annual
Indigofera endecaphylla Jacq. ex Poir.	*Fabaceae*	akondro-jaza	broadleaved	annual
Indigofera hirsuta L.	*Fabaceae*		broadleaved	annual
Ipomoea bolusiana Schinz	*Convolvulaceae*		broadleaved	annual
Ipomoea eriocarpa R. Br.	*Convolvulaceae*		broadleaved	annual
Jacquemontia tamnifolia (L.) Griseb.	*Convolvulaceae*		broadleaved	annual
Lantana camara L.	*Verbenaceae*	radrika	broadleaved	annual
Leonotis nepetifolia (L.) R.Br.	*Lamiaceae*		broadleaved	annual
Macroptilium atropurpureum (DC.) Urb.	*Fabaceae*		broadleaved	annual
Manihot esculenta Crantz	*Euphorbiaceae*	mangahazo	broadleaved	perennial
Melinis repens (Willd.) Zizka	*Poaceae*	apollo, volombavan-tasaka	grass	annual
Melinis minutiflora P.Beauv.	*Poaceae*		grass	annual
Melochia pyramidata L.	*Malvaceae*		broadleaved	annual
Mitracarpus hirtus (L.) DC.	*Rubiaceae*	fengalala	broadleaved	annual
Mollugo nudicaulis Lam.	*Molluginaceae*	aferotany	broadleaved	annual
Mucuna pruriens (L.) DC.	*Fabaceae*		broadleaved	annual
Neojeffreya decurrens (L.) Cabrera	*Asteraceae*	salakan' ny mpiosy	broadleaved	annual
Oldenlandia sp.	*Rubiaceae*		broadleaved	annual
Paspalum scrobiculatum L.	*Poaceae*		grass	annual
Pennisetum polystachion (L.) Schult.	*Poaceae*		grass	annual
Perotis patens Gand.	*Poaceae*		grass	annual
Physalis angulata L.	*Solanaceae*		broadleaved	annual
Portulaca oleracea L.	*Portulacaceae*	ahi-kisoa	broadleaved	annual
Psidium guajava L.	*Myrtaceae*	goavy	broadleaved	perennial
Richardia scabra L.	*Rubiaceae*	ahiboanjo, ahibokotra	broadleaved	annual
Rottboellia cochinchinensis (Lour.) Clayton	*Poaceae*	veromalay	grass	annual
Senna occidentalis (L.) Link	*Fabaceae*		broadleaved	annual
Sesbania sesban (L.) Merr.	*Fabaceae*		broadleaved	annual
Setaria pumila (Poir.) Roem. & Schult.	*Poaceae*		grass	annual
Sida acuta Burm.f.	*Malvaceae*	fanory, kisindahorina	broadleaved	annual
Sida rhombifolia L.	*Malvaceae*	kisindahorina	broadleaved	annual
Sida urens L.	*Malvaceae*	kisindahorina	broadleaved	annual
Solanum lycopersicum L.	*Solanaceae*	voatabia	broadleaved	annual
Sorghum bicolor (L.) Moench	*Poaceae*		grass	annual
Spermacoce alata Aubl.	*Rubiaceae*		broadleaved	annual
Spermacoce filifolia (Schumach. & Thonn.) J.-P.Lebrun & Stork	*Rubiaceae*		broadleaved	annual
Spermacoce pusilla Wall.	*Rubiaceae*		broadleaved	annual

species name	**Family**	**local name**	**group**	**life form**
Oldenlandia tenelliflora (Blume) Kuntze	*Rubiaceae*		broadleaved	annual
Oldenlandia tenelliflora (Blume) Kuntze	*Rubiaceae*		broadleaved	annual
Spilanthes costata Benth.	*Asteraceae*	anamalaody	broadleaved	annual
Striga asiatica (L.) Kuntze	*Orobanchaceae*	arema, ahitra menakely	broadleaved	annual
Stylosanthes guianensis (Aubl.) Sw.	*Fabaceae*		broadleaved	perennial
Tephrosia linearis (Willd.) Pers.	*Fabaceae*		broadleaved	annual
Teramnus labialis (L.f.) Spreng.	*Fabaceae*		broadleaved	annual
Tridax procumbens (L.) L.	*Asteraceae*	angamay, kelivoloina	broadleaved	annual
Urena lobata L.	*Malvaceae*	salenjy	broadleaved	annual
Vigna subterranea (L.) Verdc.	*Fabaceae*	voanjobory	broadleaved	annual
Vigna umbellata (Thunb.) Ohwi & H.Ohashi	*Fabaceae*		broadleaved	annual
Waltheria indica L.	*Malvaceae*	kisindahorina	broadleaved	annual
Zea mays L.	*Poaceae*	katsaka	grass	annual

Supplementary material 2: The most frequent weed species in upland rice in the Mid-West of Madagascar



Digitaria spp.

Richardia scabra

Striga asiatica

Mitracarpus hirtus

Eleusine indica

Cleome hirta

Neojeffrey decurrens

Mollugo nudicaulis

Acanthospermum hispidum

Cyperus spp.

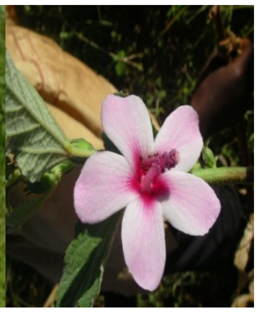
Bidens pilosa

Ageratum conyzoides

Rottboellia cochinchinensis

Euphorbia heterophylla

Commelina diffusa



Urena lobata

Supplementary material 3: First group session with farmers

After a few minutes of idea exchange on a specific topic, the number of farmers who agreed on the same opinion was written down on a board with any relevant information from the discussion

<u>Supplementary material 4</u>: Questionnaire used during the second group session with farmers

Name ***: …***
Age ***: …***
Gender ***: …***
village of origin ***: …***

Questions:

1. ***In which months does your household have a work overload? cross the corresponding month***

☐ *November* ☐ *December* *January* ☐ *February* ☐ *March* ☐ *April*

2. ***Rank the following crops by priority for weeding,***
number one for the most priority and so on (ties are allowed).

☐ *maize* ☐ *cassava* ☐ *groundnuts* ☐ *rice* ☐ *peanuts*

3. ***Rank the following weeds species by priority to be removed from the field,***
number one for the most priority and so on (ties are allowed).

☐ *Digitaire* ☐ *Eleusine* ☐ *Richardia* ☐ *Cleome* ☐ *Cyperus*

4. ***How many days after the sowing date do you think the first weeding should be performed?***

…….

5. ***How many days after the sowing date do you actually perform weeding in your fields?***

…..

6. ***According to your experience, what is the effect of intercropping on weed infestation?***

☐ *increase* ☐ *decrease* ☐ *no effect*

7. ***According to your experience, what is the effect of crop rotation on weed infestation?***

☐ *increase* ☐ *decrease* ☐ *no effect*

8. ***According to your experience, what is the effect of increasing fertilization rate on weed infestation?***

☐ *increase* ☐ *decrease* ☐ *no effect*

9. ***If 10 baskets of weeds grows in a rice field managed in CT,***
how many baskets do you think have grown in this field if it was managed in NT with stylosanthes?
(The figure given by each farmer were averaged to obtain an estimation of weed suppressive effect by the NT system)
……..

10. ***If 10 bags of rice was produced by a rice field managed in CT,***
how many bags do you think have been produced if it was managed in NT with stylosanthes?
(The figure given by each farmer were summed up to obtain an estimation of the average of yield increase in the NT system)
………

11. ***Do you remove stylosanthes regrowth in our fields managed in no-till system with stylosanthes cover crops?***
……….

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