DISSERTATION

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Improving cropping systems of semi-arid south-western Madagascar under multiple ecological and socio-economic constraints

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Summary

Madagascar is the third poorest country in the world with more than 80% of the population living below the poverty line. The Mahafaly Plateau in the south-western region is particularly disadvantaged due to harsh climatic conditions, such as regular droughts and dry spells, low levels of infrastructure, rising insecurity, high illiteracy rates and crop damage due to locust outbreaks. Hence rural households are the most food insecure in the country. With 97% of the population working in agriculture, increases in cropping system productivity are at the base of improving livelihoods in the Mahafaly Plateau region, where traditional extensive cultivation practices without external inputs have led to cropland expansion and forest losses by 45% in the last four decades. Intensification of cropping systems is thus necessary due to dwindling land resources and soil fertility coupled with population growth. However, little is known about the performance of traditional and newly introduced cropping systems in this area. This research thus aimed at identifying constraints and opportunities and field-testing promising cropping system alternatives in farmers' fields.

The use of livestock manure was identified as a major opportunity for cropping system intensification, as manure is an unused resource readily available to most farmers. Likewise, charcoal, which is available in the study area in the form of residue from charcoal production, has potential to improve soil characteristics and crop yields, as has been demonstrated in previous studies from other semi-arid regions. The main staple crop grown by 99% of farmers is cassava (*Manihot esculenta* Crantz), which is able to resist dry spells and damage by locusts, and is the main food source in the lean season. We therefore investigated the effects of manure and charcoal amendments on cassava yields, as well as estimated the contribution of further factors limiting cassava yield in the study area. Furthermore, in the littoral zone where groundwater is available throughout the year, we investigated the potential for irrigated vegetable cultivation with manure and charcoal amendments during the dry season to diversify income and diet. Another focus of this research was the estimation of dew deposition and its contribution in the annual water balance by field-testing and calibrating a newly designed dew measurement device, as dew has been claimed to be of importance to natural vegetation and off-season crops, as well as a potential source of drinking water for the local population during the dry season.

Cassava was grown over three years in three trial fields in two villages on the Plateau, with applied zebu cattle manure rates of 5 and 10 t ha^{-1}, charcoal rates of 0.5 and 2 t ha^{-1}, and cassava planting densities of 4500 plants ha^{-1}. Tuber yields on unamended control plots across years ranged from 1 to 1.8 t dry matter (DM) ha^{-1} between fields. Manure did not affect yields in the first year, but led to tuber yield increases by 30 – 40% after three years in a continuously cropped field with low soil fertility. Fertilization

effects were more pronounced in plants uninfected by cassava mosaic virus (CMV) and were not observed in the other fields, which may be partly explained by sufficient soil nutrient stocks combined with relatively low demand by cassava. Charcoal did not affect yields across the whole trial period. Infection with CMV significantly affected yields in most cases and led to tuber yield depression by up to 30%. Plant stands were reduced by 4 to 54% of total across years and fields, presumably due to the occurrence of dry spells and low vigor planting material. While manure did not systematically increase yields and did not affect crop growth in the first year of application, nutrient amounts applied with 2.5 t ha^{-1} local livestock manure would be sufficient to replace nutrients extracted by cassava tubers and biomass at current yield levels.

Carrot (*Daucus carota* L. var. Nantaise) and onion (*Allium cepa* L. var. Red Créole) were grown in a field trial in the littoral village Efoetsy over two dry seasons with seeds obtained from a supplier of the regional capital Toliara. We tested the effects of local cattle manure applied at 40 t ha^{-1}, charcoal residue applied at 10 t ha^{-1}, as well as shading on vegetable yields. Plots were irrigated twice daily and manually with local well water, which had a salinity level of 7.65 mS cm^{-1}. Carrot and onion yields across treatments and seasons ranged from 0.24 to 2.56 t DM ha^{-1} and from 0.30 to 4.07 t DM ha^{-1}, respectively. Manure and charcoal amendments did not affect yields of both crops. Shading decreased carrot yields by 33% in the first year and enhanced yields by 65% in the second year, while onion yields were raised by 148% and 208% under shading in the first and second year, respectively. Seed germination experiments revealed that salinity of irrigation water as well as quality of seed lots from Toliara significantly reduced germination rates, leading to particularly low plant stands in onion plots. Returns to labor under the obtained yields and management system and taking into account local and regional produce market prices were highest for carrot cultivation under shade in the second year, but were generally too low to allow commercial production.

Dewfall in the littoral village Efoetsy amounted to 58 mm and represented 19% of total rainfall during the observation period of 18 months, thus indicating that dew indeed contributes to the annual water balance. Dew deposition was lower in the inland village than in the littoral village, and was also substantially lower in rainy season months compared to dry season months. Maximum daily values reached 0.48 mm. Regression analysis with local weather data revealed that factors most explaining daily dew amounts were mean wind speed, maximum values of differences between air temperature and dew point (T_{air}-T_{dp}) and the air temperature drop during the night (T_{max}-T_{min}), which is in line with findings of other studies. The tested dew balance device was able to reliably measure nightly dew fall on the metallic condensation plate, and correlation coefficients with several calibration methods ranged from 0.71 - 0.84. While the ecological significance of dew for the natural vegetation and crop species remains to be

investigated, dew harvesting on artificial condensation surfaces may be a viable option for additional water supply in the area.

Further discussion of yield limiting factors in the study area suggested that manure currently available in village livestock corrals may be of too low quality to be used in field trials and by farmers due to the long storage period and unfavorable storage conditions. Manures used in the presented studies had C:N ratios of up to 33, and the low or lack of yield increasing effects of manure application may be due to N immobilization after application. Hence, preferably freshly produced and appropriately stored or composted manure should be used in future investigation of the fertilization potential of local manure. Furthermore, manure is currently not available in sufficient amounts in the study area to be the sole source for cropland fertilization due to relatively low livestock densities compared to cropland areas. Other options for soil organic matter and nutrient replenishment are thus discussed as well as the need to increase water availability, access to adapted and high quality plant material, and socio-economic factors that are known to hamper cropping system intensification in south-western Madagascar. Finally, recommendations are given regarding future research approaches, namely concerning the need for better documentation of ongoing interventions, coordination between stakeholders, the necessity for on-farm trials that are designed appropriately and according to specific objectives, and the need for capacity building through participatory methods. In the absence of favorable conditions for cropping system intensification, alternative income activities may become increasingly attractive to farmers and drive the rural population out of farming. This trend is already observable in current household income diversification strategies and migration towards the regional capital Toliara, and should be addressed in development programs.

Zusammenfassung

Madagaskar ist das drittärmste Land der Welt, in dem mehr als 80% der Bevölkerung unterhalb der Armutsgrenze leben. Das Mahafaly Plateau in der südwestlichen Region ist besonders benachteiligt aufgrund der rauen klimatischen Bedingungen, vor allem regelmäßige Dürren und Trockenperioden, geringe Infrastruktur, steigende Unsicherheit, hohe Analphabetenrate und regelmäßige Zerstörung der Ernte durch Heuschreckenplagen. Daher sind die ländlichen Haushalte die am meisten von Ernährungsunsicherheit betroffenen des Landes. Da 97% der Bevölkerung in der Landwirtschaft tätig sind, ist eine Steigerung der Produktivität von Anbausystemen die Grundlage für eine Verbesserung der Lebensbedingungen in der Mahafaly Region, wo traditionelle extensive Anbaumethoden in den letzten vier Jahrzehnten zu Expansion von Ackerland und Waldverlusten um 45% geführt haben. Intensivierung von Anbausystemen ist daher notwendig aufgrund der schwindenden Bodenressourcen und Bodenfruchtbarkeit gekoppelt mit Bevölkerungswachstum. Jedoch ist wenig bekannt über die Produktivität von traditionellen und neu eingeführten Anbaumethoden in diesem Gebiet. Die Zielsetzungen der vorliegenden Arbeit waren daher, die limitierenden Faktoren und Möglichkeiten für vielversprechende alternative Anbaumethoden zu identifizieren und diese unter Feldbedingungen zu testen.

Die Verwendung von Viehdung wurde als bedeutender Ausgangspunkt für die Intensivierung der Landwirtschaft identifiziert, da Dung eine ungenutzte Ressource, jedoch für die meisten Bauern leicht zugänglich ist. Ebenso hat Holzkohle, die im Untersuchungsgebiet in Form von Rückständen aus Holzkohle-Produktion vorhanden ist, das Potenzial, Bodenbeschaffenheit und Ernteerträge zu verbessern, wie es in früheren Studien in anderen semi-ariden Regionen nachgewiesen wurde. Die Hauptanbaufrucht, die von etwa 99% der Bauern angebaut wird, ist Maniok (*Manihot esculenta* Crantz), die tolerant gegenüber Trockenperioden und nicht von Heuschreckenschäden betroffen ist. Maniok ist somit das Hauptnahrungsmittel, besonders in der Hungerperiode. Wir untersuchten daher die Auswirkungen von Mist und Holzkohle auf Maniokerträge sowie die Beiträge von weiteren Faktoren, die im Untersuchungsgebiet ertragslimitierend sind. Darüber hinaus wurde in der Küstenregion, wo Grundwasser das ganze Jahr über zur Verfügung steht, das Potenzial für bewässerten Gemüseanbau mit Mist und Holzkohle untersucht, um zu einer Diversifizierung von Einkommen und Ernährung beizutragen. Ein weiterer Schwerpunkt dieser Arbeit war die Schätzung von Taubildung und deren Beitrag in der Jahreswasserbilanz durch Testen und Kalibrierung eines neu entworfenen Taumessgerätes, da der Taubildung eine Bedeutung für die natürliche Vegetation und Nebensaisonkulturen, als auch als potentielle Trinkwasserquelle für die Bevölkerung während der Trockenzeit, eingeräumt wurde.

Maniok wurde über drei Jahre und in drei Versuchsfeldern in zwei Dörfern auf dem Plateau angebaut, mit applizierten Zeburindermistraten von 5 und 10 t ha^{-1}, Holzkohleraten von 0,5 und 2 t ha^{-1} und Maniokpflanzdichten von 4500 Pflanzen ha^{-1}. Maniokknollenerträge auf Kontrollflächen im Versuchszeitraum erreichten 1 bis 1,8 t Trockenmasse (TM) ha^{-1}. Mistdüngung hatte keinen Einfluss auf die Erträge im ersten Jahr, führte aber zu einer Steigerung der Knollenerträge um 30 - 40% nach drei Jahren in einem kontinuierlich bewirtschafteten Feld mit geringer Bodenfruchtbarkeit. Düngewirkungen waren stärker ausgeprägt in Pflanzen, die nicht von Cassava-Mosaikvirus (CMV) infiziert waren. In den anderen Versuchsfeldern konnten keine signifikanten Düngeeffekte beobachtet werden, was teilweise auf ausreichende Bodennährstoffvorräte in Verbindung mit relativ geringen Ansprüchen von Maniok erklärt werden kann. Holzkohle hatte keinen Einfluss auf die Ernten über den gesamten Testzeitraum. Infektion mit CMV hatte meist einen signifikanten Einfluss auf Pflanzenerträge und führte zu Ertragseinbußen um bis zu 30%. Pflanzenbestände wurden felder-und jahresübergreifend um 4-54% des vollen Bestandes reduziert, was vermutlich auf das Auftreten von Trockenperioden und geringe Vitalität von Pflanzmaterial zurückzuführen ist. Während Dung nicht zu systematischen Ertrağssteigerungen führte und keine Auswirkungen im ersten Versuchsjahr zu verzeichnen waren, sind aufgebrachte Nährstoffmengen mit 2,5 t ha^{-1} lokalem Dung ausreichend, um bei momentanen Erträgen Nährstoffexporte durch Maniokknollen und -biomasse zu ersetzen.

Karotten (*Daucus carota* L. var. Nantaise) und Zwiebeln (*Allium cepa* L. var. Red Créole) wurden in einem Feldversuch im Küstendorf Efoetsy über zwei Trockenzeiten angebaut. Saatgut wurde von einem Lieferanten aus der Landeshauptstadt Toliara bezogen. Wir testeten die Auswirkungen von lokalem Rindermist mit einer Rate von 40 t ha^{-1}, Holzkohle mit einer Rate von 10 t ha^{-1}, sowie Beschattung auf die Gemüseernteerträge. Versuchsflächen wurden zweimal täglich per Hand mit lokalem Brunnenwasser bewässert, dessen Leitfähigkeit 7,65 mS cm^{-1} betrug. Karotten- und Zwiebelerträge über alle Behandlungen und Jahre erreichten 0,24 bis 2,56 t TM ha^{-1} bzw. 0,30 bis 4,07 t TM ha^{-1}. Dünger und Holzkohle hatten keinen Einfluss auf die Erträge beider Kulturen. Beschattung verringerte die Karottenerträge um 33% im ersten Jahr, während sich die Erträge im zweiten Jahr um 65% erhöhten. Zwiebelerträge wurden unter Beschattung um 148% und 208% im ersten und zweiten Jahr erhöht. Keimungexperimente zeigten, dass die Salinität des Bewässerungswassers sowie die Qualität des Saatgutes aus Toliara die Keimraten deutlich reduzierten, was zu besonders niedrigen Zwiebelpflanzenbeständen führte. In Anbetracht der erzielten Erträge und des Bewirtschaftungssystems des Versuchsfeldes, und unter Berücksichtigung der lokalen und regionalen Marktpreise, waren die Renditen am höchsten für Karottenanbau unter Beschattung im zweiten Jahr. Diese waren aber in der Regel zu gering, um eine kommerzielle Produktion zu ermöglichen.

Taubildung im Küstendorf Efoetsy betrug 58,4 mm und repräsentierte damit 19% der Niederschlagsmenge innerhalb des gesamten Beobachtungszeitraum von 18 Monaten. Dies weist darauf hin, dass Tau in der Tat einen wichtigen Beitrag zur jährlichen Wasserbilanz darstellt. Taumengen waren im Landesinneren geringer als im Küstendorf, und waren auch wesentlich geringer in den Regenzeitmonaten im Vergleich zu Trockenzeitmonaten. Tageshöchstwerte erreichten 0.48 mm. Die Regressionsanalyse mit lokalen Wetterdaten ergab, dass die folgenden Faktoren am meisten die täglichen Taubeträge erklärten: mittlere Windgeschwindigkeit, Maximalwerte der Differenzen zwischen Lufttemperatur und Taupunkt (T_{Luft} - T_{TP}) und der Lufttemperaturabfall während der Nacht (T_{max} -T_{min}). Dies ist im Einklang mit Ergebnissen anderer Studien. Die getestete Tau-Waage-Vorrichtung war in der Lage, die nächtliche Taubildung auf der metallischen Kondensationsplatte zuverlässig zu bestimmen, und Korrelationskoeffizienten mit mehreren Kalibrierungsmethoden erreichten 0,71 bis 0,84. Während die ökologische Bedeutung von Tau für die natürliche Vegetation und Nutzpflanzenarten noch untersucht werden muss, kann Tausammlung auf küntlichen Kondensationsflächen eine realisierbare Option für zusätzliche Wasserversorgung in der Region sein.

Eine weitere ausführliche Diskussion über limitierende Faktoren weist darauf hin, dass Dünger, der derzeit in dörflichen Viehpferchen vorhanden ist, aufgrund der langen Lagerzeit und ungünstigen Lagerbedingungen womöglich von zu geringer Qualität ist, um in Feldversuchen und von Bauern als Düngemittel verwendet werden. Mist in den vorgestellten Versuchen hatte C:N-Verhältnisse von bis zu 33, und die niedrigen oder fehlenden ertragssteigernden Effekte der Düngerausbringung kann auf N-Immobilisierung nach Aufbringung zurückzuführen sein. Daher sollten in zukünftigen Untersuchungen vorzugsweise frischer und angemessen gelagerter oder kompostierter Dung verwendet werden, um das Düngepotenzial von lokalem Mist beurteilen zu können. Darüber hinaus ist im Untersuchungsgebiet aufgrund relativ geringer Viehdichten im Vergleich zu Ackerflächen Mist nicht in ausreichender Menge vorhanden, um die einzige Quelle für die Düngung von Kulturflächen zu sein. Weitere Optionen für die Verbesserung der Bodenfruchtbarkeit werden somit ebenso diskutiert wie die Notwendigkeit, die Wasserverfügbarkeit und Zugang zu angepasstem und qualitativ hochwertigem Pflanzenmaterial zu verbessern, als auch sozio-ökonomischen Faktoren, die die Intensivierung von Anbausystemen in südwestlichen Madagaskar behindern. Abschließend werden Empfehlungen für zukünftige Forschungsansätze gegeben, in Bezug auf die Notwendigkeit einer besseren Datenerhebung über laufende Maßnahmen, der Koordinierung zwischen den Akteuren, angemessener und zielgerichteter On-farm-Versuche, und der Stärkung von Kapazitäten durch partizipative Methoden. In Abwesenheit von günstigen Bedingungen für die Intensivierung der Landwirtschaft können alternative Einkommensaktivitäten immer attraktiver für Bauern werden und zu zunehmender Landflucht führen.

Dieser Trend ist bereits beobachtbar in aktuellen Diversifizierungsstrategien von Haushaltseinkommen, inlusive Migration in die Landeshauptstadt Toliara.

Resumé

Madagascar est le troisième pays le plus pauvre du monde, avec plus de 80% de la population vivant au-dessous du seuil de pauvreté. Le Plateau Mahafaly dans la région Sud-Ouest est particulièrement défavorisé en raison des conditions climatiques difficiles, tels que des périodes de sécheresse régulières, du faible niveau d'infrastructure, de l'insécurité croissante, des taux élevés d'analphabétisme et des dégâts aux cultures dû aux invasions de criquets. Ainsi les ménages ruraux souffrent de l'insécurité alimentaire la plus haute dans le pays. Avec 97% de la population active dans l'agriculture, l'augmentation de la productivité des systèmes de culture est à la base de l'amélioration des conditions de vie dans la région du Plateau Mahafaly, où des pratiques culturales traditionnelles, extensives et sans utilisation d'intrants ont conduit à une expansion des terres cultivées et de la déforestation par 45% dans les quatre dernières décennies. L'intensification des systèmes de culture est donc nécessaire en raison de la diminution des surfaces disponbiles et la fertilité des sols accompagnée par la croissance démographique. Cependant, peu est connu sur la performance des systèmes de culture traditionnels et nouvellement introduits dans cette région. Cette recherche visait donc à identifier les contraintes et opportunités concernant des pratiques culturelles alternatives prometteuses et à réaliser d'essais sur terrain au milieu paysan.

L'utilisation du fumier d'élevage a été identifiée comme une opportunité majeure pour l'intensification des systèmes de culture, car celui-ci est une ressource facilement disponible pour la plupart des agriculteurs, cependant il est actuellement pas encore utilisé. Egalement, le charbon de bois, qui est disponible dans la zone d'étude sous forme de résidus de la production de charbon de bois, a le potentiel d'améliorer les caractéristiques du sol et le rendement des cultures, ce qui a été démontré antérieurement dans d'autres régions semi-arides. La principale culture de base qui est cultivée par 99% des agriculteurs est le manioc (*Manihot esculenta* Crantz), qui est capable de résister à la sécheresse et n'est pas attaqué par les criques. Ainsi, il est la source principale de nourriture dans la période de soudure. Nous avons donc étudié les effets de fumier et de charbon de bois sur les rendements de manioc, ainsi que'estimé la contribution d'autres facteurs limitant le rendement du manioc dans la zone d'étude. En outre, dans la zone littorale où l'eau souterraine est disponible toute l'année, on a investigué le potentiel de la culture de légumes irrigués avec du fumier et charbon de bois pour diversifier les revenus et l'alimentation au cours de la saison sèche. Un autre objectif de cette recherche était l'estimation de la quantité de rosée et sa contribution dans le bilan hydrique annuel, comme il était suggéré que la rosée est importante pour la végétation naturelle et les cultures de contre saison, ainsi que comme une source potentielle d'eau potable pour la population locale pendant la saison sèche. Dans ce but, un dispositif de mesure de rosée nouvellement conçu était testé et évalué dans la région.

Le manioc a été cultivé pendant trois années dans trois champs d'essai dans deux villages sur le plateau, avec les taux de fumier de zébu de 5 et 10 t ha^{-1}, les taux de charbon de bois de 0,5 et 2 t ha $^{-1}$, et une densité de boutures de manioc de 4500 ha^{-1}. Les rendements de tubercules sur les parcelles témoins à travers les trois années variaient de 1 à 1,8 t matière sèche (MS) ha^{-1} parmi les champs. Fumier n'a pas eu un effet sur les rendements dans la première année, mais a conduit à une augmentation de rendement de tubercules de 30 à 40% après trois ans dans un champ avec faible niveau de fertilité du sol et qui était cultivé continûment. Les effets de fumier ont été plus prononcés dans les plantes non infectées par le virus de mosaïque du manioc (CMV) et n'ont pas été observés dans les autres champs d'essais, ce qui peut s'expliquer en partie par les stocks de nutriments du sol suffisants associés à une demande de nutriments relativement faible par le manioc. Charbon de bois n'a pas affecté les rendements dans l'ensemble de la période d'essai. L'infection par le CMV a significativement affecté les rendements dans la plupart des cas et a conduit à une dépression du rendement de tubercules jusqu'à 30%. La densité des boutures a été réduite par 4 à 54% du total au cours des années, probablement en raison des périodes de sécheresse et d'utilisation de boutures à faible vigueur. Tandis que le fumier n'a pas systématiquement augmenté les rendements et n'a eu aucun effet sur la croissance dans la première année d'application, les quantités de nutriments appliquées avec 2,5 t ha^{-1} de fumier de bétail local serait suffisant pour remplacer les nutriments extraits par les tubercules et la biomasse de manioc au niveau de rendements actuels.

La carotte (*Daucus carota* L. var. Nantaise) et l'oignon (*Allium cepa* L. var. Red Créole) ont été cultivés dans un essai dans le village littoral d'Efoetsy pendant deux saisons sèches avec des semences obtenues d'un fournisseur de la capitale régionale de Toliara. Nous avons testé les effets de fumier du zébu local épandu à 40 t ha^{-1}, les résidus de charbon de bois appliquée à 10 t ha^{-1}, ainsi que de l'ombrage sur les rendements des légumes. Les parcelles ont été irriguées deux fois par jour à la main avec de l'eau de puits locale, avec un niveau de salinité de 7,65 mS cm^{-1}. Les rendements de carottes et oignons à travers les traitements et saisons variaient de 0,24 à 2,56 t MS ha^{-1} et de 0,30 à 4,07 t MS ha^{-1}, respectivement. Fumier et charbon n'ont pas affecté les rendements d'aucune cultures et aucune année. Ombrage a diminué le rendement de carotte par 33% dans la première année et a augmenté le rendement par 65% dans la deuxième année, tandis que les rendements de l'oignon ont été soulevées par 148% et 208% sous l'ombrage dans la première et la deuxième année, respectivement. Des expériences de germination de semences ont révélé que la salinité de l'eau d'irrigation ainsi que la qualité des semences de Toliara ont réduit de façon significative les taux de germination, conduisant à un peuplement particulièrement faible en cas des parcelles d'oignons. Sous les rendements obtenus et le système de gestion appliqué et en tenant compte des prix du marché locaux et régionaux de produits, la rémunération du travail étaient les plus élevés pour la culture de carotte sous l'ombrage de la deuxième année, mais était généralement trop faible pour permettre une production commerciale.

La rosée dans le village littoral d'Efoetsy se montait à 58 mm et a donc représenté 19% des précipitations pendant la période d'observation de 18 mois, ce qui indique que la rosée en effet contribue significativement au bilan hydrique annuel. Les quantités de rosée étaient inférieures dans le village à l'intérieur par rapport au village littoral, et étaient également considérablement plus faibles au cours des mois de la saison de pluie par rapport aux mois de la saison sèche. Les valeurs journalières maximales ont atteint 0,48 mm. L'analyse de régression avec les données météorologiques locales a révélée que les facteurs expliquant la plupart les quantités quotidiennes de rosée étaient la vitesse moyenne du vent, les valeurs maximales de différence entre la température de l'air et le point de rosée (T_{air} - T_{PR}) et la chute de température de l'air au cours de la nuit (T_{max} - T_{min}), ce qui est en cohérence avec les résultats obtenus dans d'autres études. Le dispositif de la mesure de rosée qui était employé a pu mesurer fiablement la rosée sur la plaque de condensation métallique, et les coefficients de corrélation avec plusieurs méthodes d'étalonnage ont été de l'ordre de 0,71 à 0,84. Bien que l'importance écologique de la rosée pour la végétation naturelle et les cultures reste à étudier, la rosée récoltée sur des surfaces artificielles de condensation peut être une option viable pour l'approvisionnement en eau supplémentaire dans la zone.

La discussion générale concernant les facteurs limitants les rendements de culture dans la zone d'étude suggère que le fumier actuellement disponible dans les enclos de bétail villageois peut être de trop faible qualité pour être utilisé dans les essais et par les agriculteurs sur les terrains de culture en raison de la longue période de stockage et les conditions de stockage défavorables. Les engrais utilisés dans les études présentées avaient un ratio de C:N jusqu'à 33, et les effets faible ou l'absence d'augmentation du rendement par l'épandage de fumier peuvent être dû à l'immobilisation de N après l'application. Par conséquent, de préférence du fumier fraîchement produit ou proprement stocké ou composté devraient être utilisés dans les recherches futures pour évaluer le potentiel de fertilisation du fumier local. En outre, le fumier n'est actuellement pas disponible en quantités suffisantes dans la zone d'étude pour être la seule source de fertilisation des terres cultivées en raison de la densité de bétail relativement faible par rapport aux zones cultivées. D'autres options pour la reconstitution en matière organique et en éléments nutritifs des sols sont donc discutés ainsi que la nécessité d'augmenter la disponibilité en eau, l'accès aux matériels végétaux adaptés et de haut qualité, et les facteurs socio-économiques qui sont connus à entraver l'intensification des systèmes de cultures dans le sud-ouest de Madagascar. Enfin, des recommandations sont données concernant des approches de recherche, à savoir concernant la nécessité d'une meilleure documentation des interventions en cours, la coordination entre les parties prenantes, la nécessité pour des essais en milieu paysan bien conçus qui sont de manière appropriée et en fonction des objectifs spécifiques, et la nécessité pour le renforcement des capacités à travers des méthodes participatives. En absence de conditions favorables à l'intensification des systèmes de cultures, les activités alternatives de revenus peuvent devenir de plus en plus attrayantes pour les paysans et conduire à une émigration de la population rurale agricole. Cette tendance est déjà observable dans les stratégies actuelles de diversification des revenus des ménages, y inclus la migration vers la capitale régionale de Toliara, et doit être abordée dans les interventions de développement.

Abbreviations

ACF	**A**ction **C**ontre la **F**aim
AVSF	**A**gronomes et **V**étérinaires **S**ans **F**rontières
CA	**C**onservation **A**griculture
CMV	**C**assava **M**osaic **V**irus
GIZ	**G**esellschaft für **I**nternationale **Z**usammenarbeit
GRET	**G**roupe de **R**echerche et d'**E**changes **T**echnologiques
GSDM	**G**roupement **S**emi **D**irect **M**adagascar
masl	**m**eters **a**bove **s**ea **l**evel
NGO	**N**on-**G**overnmental **O**rganisation
SSA	**S**ub-**S**aharan **A**frica
SWC	**S**oil and **W**ater **C**onservation
TAFA	**Ta**ny sy **Fa**mpandrosoana (Land and Development)
TLU	**T**ropical **L**ivestock **U**nit
WFP	**W**orld **F**ood **P**rogram
WWF	**W**orld **W**ide **F**und for Nature

1. General introduction, research objectives and hypotheses

1.1 General introduction and background

Madagascar is among the poorest countries in the world with more than 80 % of the population estimated to live on less than 1.25 $ a day in 2010 (World Bank, 2014). Within the country, the South and South-West are the economically most neglected and climatically most disadvantaged regions, leading to highest rates of household food insecurity (WFP and Unicef, 2011). Almost 85 % of the population works in agriculture and 75 % in livestock keeping, while infrastructure and access to inputs and markets are very low or absent (INSTAT et al., 2003).

Southern Madagascar has a long history of food insecurity as people have been suffering from famine on a regular basis since the documented past, due to drought, cyclones and crop destruction by locust swarms and other pests, leading to waves of outmigration and regular food aid interventions (FAO and WFP, 1997, 2009, 2013a,b; Wüstefeld, 2004). Substantial parts of the area have been affected by heavy deforestation in the last decades due to expansion of cropland and pasture as well as timber exploitation and fuel wood collection (Casse et al., 2004). Population growth coupled with the extensive agricultural practices result in increasing land use pressure and call for an intensification of cropping systems in the near future (Fauroux, 2000; Milleville and Blanc-Pamard, 2001).

The food insecurity situation has been aggravated by political instability and lack of state development capacity, especially since the political coup in 2009, which led to many development donors suspending their funding towards the country (CIA, 2014). Consequently, the semi-arid southern and south-western regions have been neglected by national and international research and development for decades in favor of regions with more development potential, and research concerning the regional cropping systems is relatively scarce and/or not well documented (Hoerner, 1991; Morlat and Castellanet, 2012).

Interest in the conservation of natural resources in south-western Madagascar has been rekindled since the end of the 20th century due to this region's high endemic biodiversity combined with the dramatic mining of forest resources. With 75 – 90 % of its flora and fauna being endemic to the region and/or to Madagascar (Fenn, 2003; Madagascar National Parks, 2014; Phillipson, 1996), it represents the highest level of plant endemism within Madagascar (Gautier and Goodman, 2003).

It has been shown that agricultural development is the primary and most effective way out of poverty in Africa as a whole and in Madagascar in particular (Diao et al., 2010;

Minten and Barrett, 2008). However, despite international relief aid and efforts by non-governmental organizations, the region has been named a “project cemetery" as implementations are hardly ever adopted after the end of project interventions (Unicef, 2011).
In view of the urgent need for more sustainable land use options and existing knowledge gaps, this research aims at strengthening the knowledge base by investigating several promising areas of cropping system improvement through literature reviews and on-farm field trials in the Mahafaly Plateau region. It is integrated in the interdisciplinary BMBF-funded research project SuLaMa (Participatory research to support sustainable land management on the Mahafaly Plateau in southwestern Madagascar, `www.sulama.de`).

The overall objectives of this research are embedded in the overall objectives of the SuLaMa project, hence they are:

1. to understand the constraints and opportunities for improved and more sustainable crop production in the research area;
2. to identify promising crop production and management systems and field test them under conditions on farmers’ fields and
3. to provide the scientific basis for recommendations to stakeholders and decision makers

1.2 Study area

The study area is situated in the northern part of the calcareous Mahafaly Plateau and the adjacent littoral zone within the spiny forest ecoregion of south-western Madagascar, with altitudes increasing from the coast inwards up to about 300 meters above sea level (masl, Figure1.1). The area includes the Tsimanampetsotse National Park which was founded in 1927 and comprises an area of 43 200 ha (Madagascar National Parks, 2014). The park contains and is named after the Tsimanampetsotse Lake, a shallow salt water body (Guyot, 2002).
High population growth and the extensive use of land and forest resources present constraints for local farmers and may increasingly cause land use conflicts as access to land for cultivation and grazing is restricted within the National Park area and buffer zone. Similar to other south-western regions, the estimated forest losses over the past four decades amount to 45 % and are projected to continue if productive cropping systems on existing arable land or alternative income sources are not available to local farmers as well as to migrants originating from further South (Brinkmann et al., 2014).

The regional capital of Toliara is historically an important destination of the local Mahafaly and Tanalana ethnicities migrating temporarily or permanently out of the region in search for paid labor (Hoerner, 1990a; Rasolofoharinoro et al., 1992; Thibaud, 2010). While the city provides major access to regional and national markets and triggers increasing demand for agricultural products, few people from the Mahafaly Plateau currently have access to it due to inadequate infrastructure and high transport costs.

1.2.1 Soils and hydrogeology

The Mahafaly Plateau is made up of tertiary limestones (du Puy and Moat, 1996) and its karstic geology leads to quick infiltration of rainwater into deeper levels (Guyot, 2002). The groundwater table is thus very deep (>70 m, de Haut de Sigy, 1965), and the only permanent sources of surface water are the Onilahy river to the North and the Linta to the South of the study area. The population on the Plateau depends on groundwater from several aquicludes in the area that are not connected to the deep groundwater level and only recharged temporarily by rainwater, leading to highly seasonal water availability (de Haut de Sigy, 1965; Guyot, 2002; Rajaobelison et al., 2003). The soils are Lithosols on slopes and rocky hilltops, Calcic Cambisols in depressions that are suitable for crop lands, and Calcaric Regosols in sedimentation areas (Hillegeist, 2011). Some villages are also situated in a corridor of Chromic Luvisol, formed by a fossil river valley filled with quaternary cristalline and calcareous sediments (de Haut de Sigy, 1965; Guyot, 2002).

The adjacent littoral zone to the west is made up of quaternary dunes with calcareous and sandstone sediments of a sandy texture where water infiltrates quickly (Guyot, 2002). The soils that prevail on crop lands are hence poorly developed Calcaric Regosols (Hillegeist, 2011), while patches with clayey texture form temporary water pools after heavy rainfalls and become an important source of water for livestock and people (Guyot, 2002). Groundwater is recharged from the calcareous Plateau and crystalline inland areas in the West and the water table is shallow and influenced by the nearby sea water level. While water is thus easily accessible to villagers throughout the year it has a relatively high salinity level due to sea water intrusion (Guyot, 2002; Rajaobelison et al., 2003).

1.2.2 Climate

In the Littoral the climate can be characterized as Sahelian (Badejo, 1998), or hot desert climate with a dry winter season (BWhw) according to the Köppen climate classification, with annual precipitation of 200-500 mm. In the Plateau zone, the climate is slightly wetter classified as hot steppe climate (BShw), comparable to the Sudano-Sahelian zone

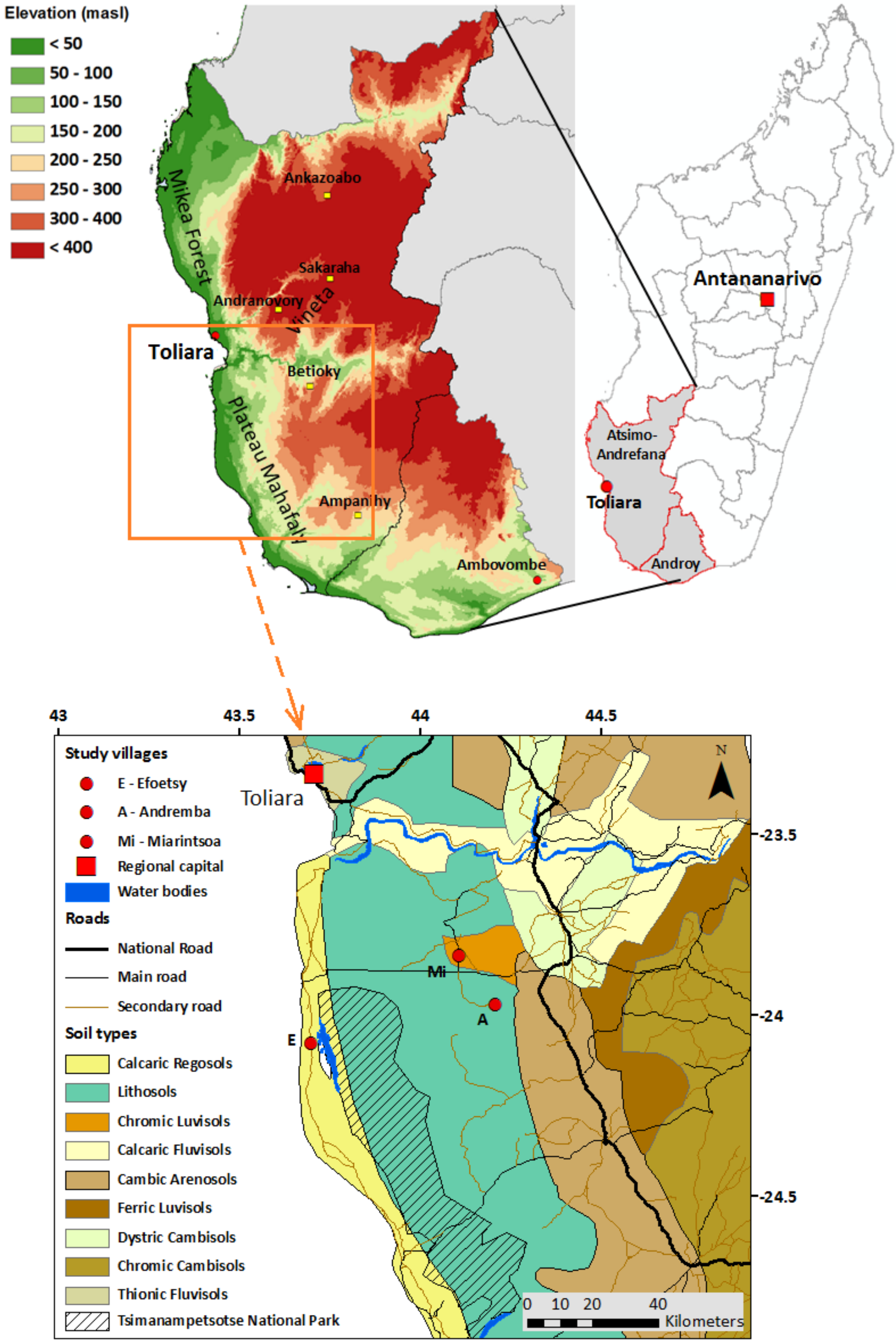

Figure 1.1. Overview of the southern administrative regions Atsimo-Andrefana ("South-West") and Androy, with elevation data, prominent landscapes and towns referred to in the thesis (top). Map of the project area with location of study villages and predominant soil types (bottom). Source data: CGIAR-CSI (2014), FTM (Institut géographique et hydrographique de Madagascar) (2014a), FTM (Institut géographique et hydrographique de Madagascar) (2014b), Hillegeist (2014), DIVA-GIS (2014).

with 500 – 800 mm annual precipitation (Badejo, 1998; CNA, 2014; Sourdat, 1969; WFP and Unicef, 2011). Rain falls unimodally during the rainy season months from December until May, while some rainfall events can occasionally occur during the dry season months. However, annual rainfall amounts are highly variable between years. For example, the Littoral received between less than 200 up to 700 mm in the 1950's (Battistini, 1964), and Toliara and the town of Betioky have experienced insufficient rainfall or extreme drought in one in two years over three decades (Hoerner, 1977). According to WFP and Unicef (2011), total seasonal rainfall between 1995 and 2009 varied by 40% (coefficient of variation) in the South/ South-West, making it the region in Madagascar with the highest interannual rainfall variability. Likewise, the western coast and South are the regions with the highest occurrence of drought, based on water requirements of maize and cassava (WFP and Unicef, 2011). Furthermore, in South-West Madagascar the majority of rainfall occurs in the form of local convective storms with high rainfall amounts in a few days (Rollin and Razafintsalama, 2001). As many of the rain fed crops require specific rainfall patterns to complete their vegetation cycles, and part of the rainfall will be lost to leaching or run-off in high intensity rainfall events, this variability is complex to analyze with respect to agricultural use (Hoerner, 1977).

Apart from precipitation through rainfall, the deposition of dew has been acknowledged as an important source of moisture for native plant vegetation but possibly also for crops grown in the off-season, particularly in the coastal areas (Besairie, 1954; Guyot, 2002; Hoerner, 1977; MinAgri, 2003; Rasolofoharinoro et al., 1992). Annual dew deposition has been estimated to be less than 30 mm per year in the littoral zone of the Mahafaly Plateau, hence only representing 10 – 30% of annual rainfall (Hoerner, 1977). However, further studies to quantify the dew deposition and evaluate its importance for crops are lacking.

Average monthly temperatures ranged from 19°C in July to 29°C in January across the region and study period (SuLaMa weather station data). Another important climatic factor in the research area is strong wind and the occasional passage of cyclones. Wind and water erosion is thus of particular concern on the Plateau, as well as damage to crops and soil drying effects.

1.2.3 Agricultural and livelihood system

The local Mahafaly and Tanalana ethnicities are traditionally livestock keepers (Kaufmann and Tsirahamba, 2006; Poupon, 1957; Rakotomalala, 2008; Rasolofoharinoro et al., 1992), and their agricultural cropping systems are very extensive and considered rudimentary (Vautravers and Ravelomandeha, 2012). In the past people practiced slash-and-burn for cultivation of maize, sorghum or millet. Labor constraints have been considered more important than constraints due to land availability (Rollin, 1997). However, access to fertile land is becoming scarce due to prohibition of slash-and-burn by the national park, as well as population growth and growing insecurity in recent years, resulting in a transition towards continuous cultivation. People have been more and more forced to cultivate fields closer to the village for longer periods of time or with shorter fallow periods.

Part of the following data were obtained by a household survey of a representative sample of 10% of households across villages in the SuLaMa study area, conducted in 2011 (Neudert et al., 2014; Sulama WP 6 Socioeconomics, 2014). Currently, three main field types are usually distinguished (Sulama WP 6 Socioeconomics, 2014): slash-and-burn fields (*teteke* or *hatsake*) that are planted for a few years and often not fenced, as well as continuously cropped and fenced new and old fields (*baiboho*). The percentage of farmers practicing slash-and-burn tends to be difficult to assess due to fear over sanctions by conservation and natural park authorities (Coral Guerra, 2014). Field sizes range from 0.2 to 8 ha with a mean of 2.1 ha, while households own on average 5.3 fields of different types. The vast majority of fields (>96%) is owned under traditional rights without a formal land title. While extensions of existing fields, including the burning of existing fence hedges, are a common way to increase cropping area and soil fertility (SuLaMa, 2011), only 4% of households have reported to have done so in recent years (Neudert et al., 2014; Sulama WP 6 Socioeconomics, 2014).

Among the village population, 97% report to be engaged in farming. The main staple crops are cassava (*Manihot esculenta* Crantz, cultivated by 99% of farmers), maize (*Zea mays* L., 86%), at least one of six common legume species (*Vigna unguiculata*, *Vigna radiata*, *Vigna umbellata*, *Lablab purpureus*, *Vigna subterranea*, *Phaseolus lunatus*, 84%), sweet potato (*Ipomoea batatas*, 62%), cucurbitaceae (45%), peanut (*Arachis hypogea*, 54%), and pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*, 8%). Due to the lack of surface water, rice (*Oryza sativa*), a main staple in Madagascar, is not grown in the region. Sorghum, which was traditionally more important than maize until the beginning of the 20th century, was replaced by the latter due to the necessary labor to scare predator birds off the sorghum crop (Vautravers and Ravelomandeha, 2012), as well as less demand on the market for sorghum (Rakotomalala, 2008; Rakotondramanana, 2005) and changed dietary habits of the population (Rakotondramanana, 2005; Ratovoheriniaina et al., 2005).

The majority of planting material is bought on local markets or saved up from the previous harvest, and is often of low quality (McGuire and Sperling, 2013; Randrianatsimbazafy, 2012). Additional shortage in planting material results from the regular failure of crops which makes it often necessary to resow several times a year (Rollin and Razafintsalama, 2001). Numerous crops are typically mixed in fields, which is rather attributed to labor shortage for land preparation and weeding, lack of land of a certain quality, diversification and filling of empty patches during the season, than to the consideration by the farmer of specific advantages of intercropping to crops or soil characteristics (de Haut de Sigy, 1965; Fauroux, 2000; Rakotomalala, 2008). In slash-and-burn systems, monoculture of maize or millet prevails (Ratovoheriniaina et al., 2005). The cropping densities are generally very low, presumably determined by water availability (Rollin, 1997). Some authors state a lack of crop rotations (Bayala et al., 1998; Dostie et al., 1999; Rollin, 1997), while others say farmers use rotations (Ratsirarson, 2003). In general, if some farmers seem to rotate crops, it can be assumed to be out of considerations other than soil fertility or pest management.

Regarding animal husbandry, 39% of households were found to own no livestock (poor households), 47% to own an average of 6 zebu and 13 small ruminant units (average household), and 14% to have mean herd sizes of 42 zebu and 57 small ruminants (wealthy households) (Neudert et al., 2014). Furthermore, current average livestock numbers (zebu, goat, sheep and poultry) were reported to be less than half of those 10 years ago, while those accounts may be subject to a strong bias (Sulama WP 6 Socioeconomics, 2014). Livestock is kept in corrals in or near villages overnight, where zebu and goat manure is accumulating, often over decades.

However, the majority of farmers in the South-West do not use livestock manure for field fertilization (Bayala et al., 1998; Coral Guerra, 2014). The reasons given by farmers are the perceived sufficient fertility of the soil, the high labor demands for manure application, increased disease pressure, “burning" of plants and lack of knowledge for its use (Bayala et al., 1998). Farmers prefer to shift crop fields to new land if yields are declining, instead of investing in labor-intensive fertility management (Rollin, 1997). On the other hand, Hänke and Barkmann (2012) found that among 400 households from 11 villages of the littoral zone, transport and cost of manure were not considered a constraint. Furthermore, local taboos concerning manure use are sometimes pointed out (Bayala et al., 1998; Dagnon and Beauval, 1993; Rollin, 1997) while others found that this is not the case (Jenny, 1975). In our study villages, we found that taboos regarding manure use are very individual, easily overcome or non-existent, as confirmed by Hänke and Barkmann (2012). Misconceptions about this fact combined with the difficulty to change cultural predispositions seem to have contributed to the lack of studies to investigate the potential of manure use in field trials (M. Baehrel, regional coordinator of Agronomes et Vétérinaires sans Frontières, personal communication 29.05.2014).

The majority of farmers use simple hoes to work the soil and only a few people in some villages have access to ox-drawn ploughs (Coral Guerra, 2014). Use of the plough has been reported by on average 7% of households in the study communities, but regular soil tillage is presumably much lower as ploughs are predominantly used for breaking up the soil of newly established fields (Sulama WP 6 Socioeconomics, 2014). Generally, apart from ox-carts (*charrette*), which are owned by about a third of households and are the main form of transport in the area (Sulama WP 6 Socioeconomics, 2014), the link between agriculture and animal husbandry is considered very weak (Andrianasolo and Razafintsalama, 2013).

Use of off-farm inputs is also extremely low: mineral fertilizer is used by less than 3%

of households (Sulama WP 6 Socioeconomics, 2014), and use of insecticides has been reported by 1% of surveyed households (Hänke and Barkmann, 2012).

Many authors consider climatic factors to be the main constraint to rain-fed agriculture in the region (Battistini, 1964; de Haut de Sigy, 1965; Dostie et al., 1999; Rasolofoharinoro et al., 1992; Rollin, 1997; Thibaud, 2010). Likewise, households across wealth categories report the lack of rain as the main constraint to the improvement of their livelihood, before lack of money, tools and knowledge or people's health (Neudert et al., 2014). Consequently, instead of intensification of cropping systems, the locals' risk management and coping strategies are rather based on diversification of income sources due to high risk of failure of farming activities (Neudert et al., 2014). The majority of households report that their own crop production is never enough for food subsistence (54%), or only sufficient in years with lots of rain (41%), while only 5% reported harvested crops to be sufficient to feed all household members (Neudert et al., 2014). Similarly, Coral Guerra (2014) found that only 33% of surveyed farmers reported that farming and animal husbandry provided 75-100% of their income, while for 17% it made up only 0-25%.
Collection of timber and non-timber forest products for food, medicine, construction material and charcoal production is thus practiced by 98% of surveyed households. Fishing presents alternative food and income to 13% of households, mostly to those living in the littoral zone. Off-farm activities contribute to households income in 71% of cases. These include off-farm paid labor, temporary migration, trade and crafts (Neudert et al., 2014). Overall households thus rely on six sources of income on average, derived from farming, livestock keeping, use of natural resources and off-farm activities (Neudert et al., 2014). Nonetheless, and despite the reported inability of crop production to provide for household needs, 75% of households still consider farming the most important source of income, before livestock keeping (Sulama WP 6 Socioeconomics, 2014).
Regarding migration, vast amounts of farming population have been migrating temporarily or permanently out of Madagascar's southern zones, including the Mahafaly Plateau, into forest zones in the North with low population density for slash-and-burn agriculture (see chapter 1.3 below), especially following drought periods such as those of 1985 - 1986 and 1991 - 1992 (Bayala et al., 1998; Dagnon and Beauval, 1993; Fauroux, 2000; Thibaud, 2010). Therefore, the perception among (migrating) farmers is that sufficient fertile forest land is still available, thus preventing incentives to invest in productivity improvements of existing arable land.

1.3 Literature review: Agricultural research and development in south-western Madagascar

Agronomic research on cropping systems in south-western Madagascar is very scarce or difficult to access, includes few publications, and is otherwise mostly limited to university theses, project reports, and other grey literature. Quantitative research is particularly scarce. Furthermore, where results are accessible there has been little incentive to implement them in practice (Morlat and Castellanet, 2012; Razanaka et al., 2001). State programs and activities of the agricultural research center FOFIFA has been quasi absent and dysfunctional whereas the private sector has been more interested in fast economic returns than development of sustainable agricultural methods (Dagnon and Beauval, 1993; Razanaka et al., 2001). FOFIFA in Toliara is currently focusing their limited resources on the maintenance of germplasm of rice, cassava, maize, cotton (*Gossypium hirsutum*), lima bean (*Phaseolus lunatus*), sorghum and legume shrubs (FOFIFA, 2014, A. Randrianasolo, director of FOFIFA Toliara, personal communication, 09.05.2014).
The history of crop plants cultivated in the South as well as cropping systems, as documented by Perrier de la Bathie (1931) and Le Thomas (1946), give an overview about the changing importance of various crop species in the past. Since the second half of the 20th century, extensive agricultural development in south-western Madagascar has been spurred by several periods of cash crop production encouraged by governmental policies and world market prices. During a period of high demand for lima bean on the world market in the 1940's, its cultivation was wide spread in the South-West and of interest for agricultural research, but farmers' production methods remained rudimentary (Hoerner, 1981; Le Thomas, 1946). From the 1960's until the 1980's peanut (*Arachis hypogaea*) cultivation was promoted by the state and the FAO oil plant program and reflected in the establishment of an oil-processing plant in Toliara (Dagnon and Beauval, 1993). During this period, trials were also conducted with sunflower (*Helianthus annuus*). The economic importance of peanut, however, diminished with the increase of large scale palm oil (*Elaeis guineensis*), sunflower and soy (*Glycine max*) production in Latin America and the US (Dagnon and Beauval, 1993). Land clearing for cotton in the South-West increased more than fourfold from 7000 to 31700 ha in four years during the 1980's (Hoerner, 1990b). The "cotton boom" quickly subsided due to yield declines (from 1.3 to less than 0.5 t ha^{-1}), insufficient rainfall, insufficient pest control, lack of paid labor for weeding of the vast privately owned fields, and land use conflicts between "new-comer" farmers and local pastoralists (Hoerner, 1990b; Rasolofoharinoro et al., 1992). Since the end of the 1980's large areas of forest were cleared for extensive maize production due to a high demand of livestock fodder from Réunion island (Faroux, 2000). Area for maize cropping has thus increased fourfold in two decades since the 1980's (Blanc-Pamard et al., 2005), and Casse et al. (2004) concluded that maize

production is the most important driver of deforestation in the South-West.
The extensions in cropping area within the South-West were most dramatic in the Mikea forest, the Vineta Plateau and the Sakaraha region (Fauroux, 2000, Figure 1.1). Consequently, most of the agronomic research as well as documentation of deforestation dynamics have been concentrated in these areas, as well as in the Androy region in the far South (Figure 1.1). Milleville and Blanc-Pamard (2001) investigated the development of maize yield with age of slash-and-burn fields and found that yields declined from 2 t ha^{-1} in the first two years to less than 0.5 t ha^{-1} after five years. Weed biomass increased at the same time to up to 1 t ha^{-1}, whereas after 9 years maize yield was quasi zero. Similarly, Grouzis and Razanaka (2001) found that weed pressure in extensive maize systems increased over the course of 9 years and resulted in 70 % ground cover and 1-2 t ha^{-1} weed biomass yield. Studies with mineral N-P-K fertilization revealed that yields of 6-7 year old fields could be increased to the same level as in the 2nd year (Milleville et al., 2001), but due to the high risk associated with climatic conditions mineral fertilizer use is considered to be not economically attractive to farmers (Randrianarivelo, 2000). Slash-and-burn thus continues to be the preferred cropping system compared to more intensified cultivation due to less labor and input expenses, but also due to the prevailing traditional land rights system, in which a person who first cultivates a piece of land, becomes the owner (Blanc-Pamard et al., 2005; Fauroux, 2000). The observed crop land expansions were subsequently criticized as highly speculative and without regulation and regard to sustainable soil fertility management (Dagnon and Beauval, 1993; Hoerner, 1981).
In the Mahafaly region, farming practices were less influenced by these developments due to lower potential (Hoerner, 1988), and local farmers rather migrated temporarily or permanently to the regions with better growing conditions mentioned above. Nonetheless, the observed deforestation dynamics in the Mahafaly Plateau region are similarly attributed to non-sedentary agricultural activities, partly by farmers immigrating into the forest zone from other regions hit by drought (Brinkmann et al., 2014). The slash-and-burn maize cropping systems practiced on the Mahafaly Plateau are probably comparable in yield and weed pressure dynamics to those investigated in the Mikea and Vineta regions.

Various other descriptive or quantitative agronomic studies conducted in the past include the following: Le Thomas (1946) documented cassava experiments with two local varieties and “improved" management over six years in Ambovombe. De Haut de Sigy (1965) pointed out the potential for the intensified cultivation of peanuts in the zone of Luvisols of our study area (including villages Miarintsoa and Andremba, Figure 1.1), but he emphasized at the same time that the main constraint to intensification are rainfall conditions, while intensified cropping practices might quickly erode fertile soil, and might be in competition to grazing and livestock keeping as peoples’ primary cultural and economic activity. Jenny (1975) conducted fertilization and variety experiments with maize, sorghum and peanut in Andranovory (South-West) and Ambovombe (Androy). Arraudeau (1977) reports of fertilizer and crop management trials and variety selection of sorghum conducted in the 1960's in the South. ALT (Andrew Lees Trust) (2011) promoted the cultivation of sorghum in the Androy region through distribution of certified seed, demonstration trials and farmer training. Charfi (1981) documents the successes and failures of wind-breaker hedges in Androy and gives recommendations for suitable tree and shrub species, management options and research topics. Maille (1991) investigated the effect of *Tamarindus indica* leave mulch on maize performance in Beza Mahafaly. Bernard and Rakotoarimanana (1991) conducted variety trials with cotton. Vegetable production systems in the South-West as well as the supply and demand in the capital Toliara are covered by Daou (2008); Gildas Dosy (2007); Rakotomalala (2008) and Rijarimamy (2011). Fisher (2009) investigated the problems regarding adoption of *Bracharia* spp. cultivation for livestock fodder after its promotion in the Mahafaly area since 2003. Ranomenjanahary et al. (2005) surveyed the incidence of whiteflies, Cassava Mosaic Virus (CMV) and Sweetpotato Virus Disease in four regions of Madagascar, including the south-western coast in the Toliara region. Since 1994 the NGO TAFA together with "Groupement Semi Direct Madagascar" (GSDM) have been testing conservation agriculture techniques at three sites in the South-West (Ankazoabo, Andranovory, Sakaraha, Figure 1.1, Langevin and Razafintsalama, 2000; Naudin et al., 2003; Serpantié, 2009). In Androy, the french NGO GRET has been working on the selection and field-testing of species and varieties adapted to the zone, such as maize, sorghum, and millet and various legume species, as well as on conservation agriculture techniques, particularly intercropping with leguminous cover crops and fodder shrubs (GRET, 2014).

Overall, among the reviewed literature, the recommendations or promoted interventions for cropping intensification and land use system improvements in the South-West can be summarized as follows (see Appendix A for a detailed list and references):

- use of the plough and other ox-drawn equipment
- mechanical soil tillage
- conservation agriculture (including crop rotations, intercropping, mulching)
- agroforestry and wind-breaker hedges
- use of livestock manure
- use of mineral fertilizer
- crop diversification including vegetables; selection and introduction of drought and pest/disease resistant varieties
- testing of different planting densities, depths and seeding techniques

- enhancement of fodder availability
- improvement of harvest processing and storage
- rainwater harvesting
- improvement of market access, farmer organization and education
- necessity of long-term investment
- promotion of alternative income sources besides crop production

The agronomic studies and crop cultivation experiences conducted in the Southwest and South of Madagascar in the past decades can only partly be extrapolated to the zone of the Mahafaly Plateau, as they consistently focused on regions with better infrastructure (Dagnon and Beauval, 1993; GEREM, 1996; Randrianaivo et al., 1993; Ratovoheriniaina et al., 2005), as well as systems that have been subsidized by state-controlled cooperatives to provide inputs otherwise not available to farmers, particularly mineral fertilizers and pesticides. In fact, the Mahafaly region is often simply classified as not suitable for agriculture and as having very limited or non-existing opportunities for intensification (Battistini, 1964; Bourgeat et al., 1995; de Haut de Sigy, 1965; Langevin and Razafintsalama, 2000; ORSTOM, 1980). This is attributed to the facts that rainfall in the littoral zone is the lowest as well as the most variable of all of Madagascar (Hoerner, 1977; MinAgri, 2003; WFP and Unicef, 2011), surface water for irrigation is quasi absent and access to groundwater limited (de Haut de Sigy, 1965), and infrastructure and education levels among the lowest of the country (INSTAT, 2006; MinAgri, 2003). As livelihoods of the local population are nonetheless highly dependent on agriculture, improvement of cropping productivity on the Mahafaly Plateau is gaining more attention.

1.4 Research Objectives

In view of the above identified knowledge gaps, combined with the repeatedly emphasized need to close nutrient cycles by the use of livestock manure, the application of manure was identified as one major opportunity for cropping system intensification that merits investigation, as manure is readily available to most farmers and soil fertility known to decline quickly on continuously cropped land. Particularly, no studies are available that have examined the potential of cassava yield increases with locally available manure in the research area. Cassava constitutes the main staple crop grown by the majority of farmers for subsistence and income, while it is adapted most to rainfall constraints and unaffected by locust swarms.

Furthermore, irrigated vegetable production during the dry season is a potential risk management and diversification strategy in the littoral zone, where groundwater is available throughout the year. Additionally, the current focus on the promotion of vegetable

cultivation by several locally active development projects demands a quantification of production potential and constraints.
Finally, due to the observed substantial dew deposition in the region and references about its importance in the literature, quantification of dew and the evaluation of its contribution in the water balance and for plant growth presented another research focus.

The specific objectives of the following chapters were thus to investigate:

1. the potential of the use of local manure as well as charcoal to increase productivity of cassava;
2. the potential of irrigated vegetable production with manure and charcoal amendments in the littoral zone of the study area; and
3. the amount of dew deposition and its possible significance in the annual water balance.

Beyond these research questions tackled in chapters 2 to 4, the aim of this research was also to critically review further options for cropping system intensification to give recommendations to stakeholders, which is presented in chapter 5.

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2. Cassava yield enhancement on the Mahafaly Plateau in south-western Madagascar – effects of local zebu manure and charcoal in a multi-stress environment

2.1 Abstract

Cassava (*Manihot esculenta* Crantz) is the main staple of smallholder farmers of the Mahafaly Plateau in south-western Madagascar, but recurrent droughts and low access to inputs regularly result in drastic reduction of crop yields. We examined the potential for cassava yield increases through the use of local zebu manure, which is readily available to farmers due to the traditional importance of livestock keeping, but is currently not used in field fertilization of the traditionally extensive cropping systems. Manure was applied annually at 5 and 10 t ha^{-1} over three years and on three fields differing in soil type and soil fertility status. The results showed that across fields manure did not affect cassava tuber yields in the first year of application, but led to tuber yield increases of 30 – 40% after three years in a single continuously cropped field with low soil fertility. Fertilization effects were more pronounced in healthy plants and were not observed in the other fields, which may be partly explained by sufficient soil nutrient stocks combined with relatively low demands of cassava. A similar application of charcoal at 0.5 and 2 t ha^{-1} neither affected cassava yields, but infection with cassava mosaic virus resulted in tuber yield depressions of up to 30%. Furthermore, low and heterogeneous plant establishment at the beginning of the crop season led to plant stand reductions of up to 38%. Due to the high labor demand for manure application compared with the traditional extensive cropping system, farmers may be reluctant to use manure, and dissemination of healthy, virus tolerant cassava cultivars may be more effective measures to enhance yields and cropping system resilience. At the current tuber yields of 1 – 1.8 t DM ha^{-1} local manure at the rate of 2.5 t ha^{-1} would be sufficient to replace nutrients exported through total biomass. However, if other constraints to yield enhancement are alleviated, deficiency of soil P may become yield limiting.

2.2 Introduction

Traditional cropping systems of the Mahafaly Plateau area in south-western Madagascar are based on cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.), various legumes and sweet potato (*Ipomea batatas*) grown extensively without external inputs (INSTAT, 2004; Neudert et al., 2014; WFP and Unicef, 2011). In this region cassava is cultivated by 99% of the farming population (Neudert et al., 2014), and is also the most important trade product (Coral Guerra, 2014). Cassava makes up a quarter of the caloric intake, and is the main food source in the lean season (Dostie et al., 1999). This is crucial considering that south-western Madagascar has the highest levels of food insecurity in the country affecting up to 70% of households (WFP, 2005; WFP and Unicef, 2011). The importance of cassava may be explained by the particularly harsh agro-ecological conditions in this semi-arid area with low fertility soils in which other crops often fail (Udoh and Kormawa, 2007). In this regard, it has been suggested that with increasing frequencies of drought and higher temperatures due to climate change, the importance of cassava may increase compared to cereals due to higher stress tolerance of this crop (El-Sharkawy, 2012; Jarvis et al., 2012; Schlenker and Lobell, 2010; Vololona et al., 2013). Furthermore, cassava has the ability to yield even on soils where most other crops would fail (Howeler and Cadavid, 1990). At the same time, the general increase in cassava production in Africa is also attributed to its ability to survive locust attacks (Hillocks et al., 2002), which are a recurring ecological problem in Madagascar (FAO and WFP, 1997, 2013; Wüstefeld, 2004).

Yet, in the south-western zone of this country production levels barely keep up with people's subsistence needs, and have been reported to decrease by up to 60 – 70% in drought years (WFP and Unicef, 2011). Coupled with the lack of infrastructure for appropriate storage of tubers (Dostie et al., 1999; Thouillot and Maharetse, 2010), this leaves little room for escape from poverty and results in dependence on regular external food aid. Moreover, given political turmoil and neglect, national agricultural research or assistance to farmers to improve cassava cropping systems in south-western Madagascar have been virtually absent for decades (Dagnon and Beauval, 1993; McGuire and Sperling, 2013). Nevertheless, a shift to more productive and intensive cultivation systems is necessary in the near future due to increasing pressure on cropping land, aggravated by population growth and the creation of natural conservation areas in the surrounding spiny forest.

Cassava is predominantly cultivated without inputs for many years on low fertility soils leading to ever declining yields (Hillocks et al., 2002). On the other hand, manure is a locally available soil amendment on the Mahafaly Plateau, where animal husbandry, particularly zebu and goat herding, is an important socio-cultural and economic activity

of local farmers. Typically, livestock is kept in corrals overnight in and around the villages, where manure has been accumulating for years and even decades, but so far is neither being used for fertilizing field crops nor for other purposes.
Furthermore, in recent years charcoal applied to soil as powder and/or pieces has been shown in numerous studies to have beneficial effects on soil properties, especially of marginal acid soils, such as increased water holding capacity, reduced nutrient leaching and gaseous emissions and higher cation exchange capacity, while increases of crop production were also reported (Glaser et al., 2002; Verheijen et al., 2010). However, little is known about biochar effects on arid alkaline soils.

Hence the objectives of this study were to (i) evaluate the effects of zebu and goat manure on vegetative performance and tuber yield of cassava over three seasons, (ii) determine the effect of a one-time application of charcoal alone or in combination with manure on cassava yields, and (iii) investigate the potential interactions of treatment effects on yields with other yield determining factors in the study area, particularly infection with Cassava Mosaic Virus (CMV).

2.3 Materials and Methods

2.3.1 Study sites and plot installations

Three trial fields were installed in 2011 in two villages of the Mahafaly Plateau area representing slightly different geological and soil type units. The local climate is semi-arid with 500-700 mm annual rainfall and soils are loamy sands classified as Calcic Cambisols or Chromic Luvisols (Hillegeist, 2011). One trial field was situated in the village of Miarintsoa (Mi; 23°50’33” S, 46°06’50” E, 170 masl) and two in Andremba (An1, An2; 23°58’ S, 44°12’30” E, 260 masl). Prior to treatment application soil samples of the 0-15 cm layer of the control plots were taken and analyzed for basic properties at the FOFIFA (National Agricultural Research Center) laboratory in Antananarivo (Table 2.1). All trial sites had been cultivated in the past. An1 and Mi were cultivated with cassava and cowpea (*Vigna unguiculata* L.) while An2 was in fallow for several years before the establishment of the trial, presumably explaining higher organic matter and nutrient levels. Each trial field consisted of a two factorial design (3x3) including one control treatment (Table 2.2), with four replicates laid out in a completely randomized design. Plots were 4*5 m^2 in size, with one meter distance between plots.
Manure for the soil applications was collected from local goat (on field Mi in 2011) and zebu enclosures (on all other fields and years) and mixed thoroughly before application without any further treatment. Charcoal for application was taken from the nearby village Antanantsoa where locally produced charcoal, mainly from *Tamarindus indica*,

Table 2.1. Soil characteristics of the three trial sites on the Mahafaly Plateau in south-western Madagascar (average of control plot composite samples per field, 0-15 cm layer).

	Andremba1	Andremba2	Miarintsoa
Sand (%)	78	64	84
Silt (%)	12	26	6
Clay (%)	10	10	14
pH (KCl)	7.23	7.12	6.19
C_{org} (%)	0.90	2.31	1.01
N (%)	0.09	0.20	0.08
C:N	10.1	11.4	12.0
P (BrayII) (ppm)	55.8	46.4	35.9
CEC (meq 100 g^{-1})	8.2	20.7	7.8
K (%)	0.031	0.097	0.035
Ca (%)	0.183	0.409	0.108
Na (%)	0.022	0.049	0.019
Mg (%)	0.007	0.020	0.007
Soil type (FAO)	Calcic Cambisol		Chromic Luvisol

Table 2.2. Treatments in each of the three trial fields on the Mahafaly Plateau in south-western Madagascar (n=4).

Treatment	Application rate (t ha^{-1} fresh matter)	
	Manure	Charcoal
Control	-	-
Manure rate 1	5	-
Manure rate 2	10	-
Charcoal rate 1	-	0.5
Charcoal rate 2	-	2
Manure 1 * Biochar 1	5	0.5
Manure 1 * Biochar 2	5	2
Manure 2 * Biochar 1	10	0.5
Manure 2 * Biochar 2	10	2

Table 2.3. Properties of cattle/ goat manure and charcoal used for treatments on the Mahafaly Plateau in south-western Madagascar.

		pH (KCl)	C (%)	N (%)	C:N	P (%)	K (%)
Cattle manure	Miarintsoa (2012, 2013)	7.4	35.1	1.36	25.8	0.21	1.28
	Andremba (all years)	7.5	27.8	1.82	15.3	0.27	1.73
Goat manure	Miarintsoa (2011)	7.9	23.8	2.77	8.4	0.27	3.18
Charcoal		7.2	66.8	1.42	47.0	0.07	0.70

is sold for fuel on a large scale. Its powder and small pieces up to ca. 2 cm size were collected from sites where charcoal rests have been accumulating on the ground and normally remain unused. Charcoal was applied only once in November 2011, while manure was applied every year before the rainy season (Nov. 2011, Nov. 2012, Oct. 2013). Treatments were applied broadcast in the first year, while manure was applied locally to manioc planting mounts in the following years, and applications were hand-hoed to 15 cm soil depth each time. In the first year manure and charcoal samples were extracted at the time of application for DM determination and nutrient analysis (Table 2.3).

Nutrient amendment rates with manure at 5 t ha^{-1} were 80 kg N ha^{-1}, 12 kg P ha^{-1} and 76 kg K ha^{-1} in Andremba each year, 124 kg N ha^{-1}, 12 kg P ha^{-1} and 138 kg K ha^{-1} in Miarintsoa in 2011 and 63 kg N ha^{-1}, 10 kg P ha^{-1} and 60 kg K ha^{-1} in Miarintsoa in 2012 and 2013.

Plots were planted with the local cassava variety “Amerikani” (a bitter variety) from field owners’ planting stock according to farmers’ practice immediately after the onset of the first major rainfall (typically amounts above 35 mm falling over the course of one to two days). Following local practice each plot comprised nine planting holes, amounting to a plant density of 4500 plants ha^{-1}. Weeding was done according to farmers practice in regular intervals, normally three times per season.

2.3.2 Measurements

Cassava shoot height was measured three times during the cropping period, at 3 months after planting (MAP), 5 MAP and 7 MAP in each year. Since plants were partly attacked by CMV, at each measurement cycle, the degree of visible CMV incidence for each plant was visually classified on a seven-step-scale (0 – no visible signs of infection, 7 – severely affected with stunted growth and all leaves chlorotic and distorted).

Cassava plants are usually harvested after 8 – 20 months depending on individual plant status and rainfall conditions. Whether a plant was harvested was entirely decided by the field owner at the time of harvest. Plants ready for harvest were uprooted and replaced at the beginning of the following rainy season while plants remaining in the soil were cut to the base for re-sprouting in the next season.

At harvest, tuber biomass as well as leaf and stalk biomass were weighed, in 2012 at the plot level and in 2013 and 2014 at the plant level, and samples taken for dry matter determination at 65°C. Furthermore, tubers were counted and grouped into three size categories (<20 cm, 20-30 cm, >30 cm). Composite soil samples from three cassava mounts of each plot were extracted after harvest in the third year (2014) and analyzed to detect effects of amendments on soil properties. Rainfall data was recorded for all three years in the village of Andremba. Next to total rainy-season-rainfall (Dec.-May), the following rainfall distribution characteristics were calculated: the number of dry spells classified as above 7 days without rain, above 14 days without rain and above 21 days without rain (Gönster, 2013), the number of rainy days (≥1 mm) and the length of the rainy season from first to last day of rainfall.

2.3.3 Data analysis

Plant stands and plot-averaged harvest data (tuber and above ground biomass, tuber numbers) as well as soil parameters of 2014 were analyzed with a factorial two-way ANOVA with manure and charcoal rates as fixed factors for each year and field, as well as for mean harvest across years. Tuber and biomass harvest data was analyzed on a per plant basis instead of per surface unit on the following grounds: the high heterogeneity in plant establishment was unaffected by treatments (see 2.4.3) and hence is rather due to other factors, presumably differences in the quality and vigor of planting material. If harvest data is summarized per plot without taking into account plant numbers, treatment effects on individual plant growth are confounded with other experimental factors that remained uncontrolled in the trials. Nevertheless, plant data on control plots was also extrapolated to total harvest per hectare each year, based on yield per plant and number of harvested plants, in order to be able to compare overall yield trends between years and with values in the literature.

Tuber and biomass yield data of 2013 and 2014, which were recorded at the individual plant level, were correlated with virus infection scores of 2013 and 2014 with a non-parametric Spearman's rho test (one-tailed) across fields and treatments to detect the degree of the yield depressing effect of virus infection. Due to the ordinal scale of virus scores, we further re-classified the plants into uninfected (virus score zero) and infected plants (virus score >0) for a t-test of virus effect on yield. The effects of manure and charcoal treatments were subsequently analyzed for the two virus infection classes separately with a two-way ANOVA. In these analyses, plants were taken as replicates instead of plots after the following considerations: planting distances were rather high and treatments were applied to the planting hole after the first year, hence spatial correlation of soil fertility is assumed to be low, and factors such as planting material quality and the virus infection state are not spatially correlated (Fauquet and Fargette, 1990). Information on the influence of virus infection on plant parameters is thus lost if these are averaged per plot. Furthermore, harvest data of 2013 and 2014 were totaled in order to average out the effects of staggered harvests.

Residuals of all tests were examined for normality and homogeneity of variance with the Kolmogorov-Smirnov and Levene tests, respectively. On the plot level, residuals were not normally distributed in a few cases. On the plant level, residuals were often not normally distributed and variance not homogeneous. This was taken into account in the interpretation of ANOVA outputs for these cases, and Tukey-tests were performed for post-hoc analyses.

Linear multiple regression analysis was performed to identify some of the yield determining factors across years and fields, with plot level tuber and biomass yields as dependent variables. Regarding tuber yield data, we differentiated between including plots with zero harvest and excluding them from the analysis, as we assumed that zero harvest was not only influenced by external factors but by individual farmer's decision which is also influenced by other factors. Predictor variables were considered according to their expected effect on yield and according to results of above analyses, i.e. rainfall parameters (mm, number of rainy days, length of the rainy season, number of dry spells), plant survival rate, virus infection rates (plot average), initial soil parameters (soil type, pH, C, N, P, K) and manure rates. After correlation analysis (Spearman), number of dry spells $>$14d was removed due to strong correlation with other rainfall parameters, and regarding soil characteristics only soil C and soil P were retained as they correlated strongly with other soil parameters but had no correlation between themselves. As it was not clear which of the variables would most explain yields, we tested a stepwise approach to identify significant predictors, and sequentially improved the model by looking at plausibility of predictor coefficients, sufficient independence of residuals (Durbin-Watson value), and in order to identify a parsimonious model that explains most of the variation with the least number of predictors (Miles and Shelvin, 2001). Validity of the obtained model was subsequently checked by Q-Q-Plot and a scatter plot of predicted values and residuals.

The percentage yield loss per field due to virus infection state was estimated with the formula

$$\text{Yield loss}(\%) = \frac{1 - \text{Observed yield per ha}}{\text{mean yield of} P_{v0} * \sum P} \cdot 100$$

where P_{v0} = plant with zero virus infection rate

$\sum P$ = number of all harvested plants

For 2013 and 2014, the fact whether a plant was harvested or not in a specific year was compared to the height measurement data before harvest with a t-test and harvest (yes/no) as factor as an estimate of field owner's decision and to validate that the choice to harvest a specific plant was determined by plant height. All statistical analysis was performed with SPSS 17.0 software and the significance level for all analyses was set at $\alpha = 0.05$.

2.4 Results

2.4.1 Rainfall patterns

Rainfall during the rainy season (Dec. - May) amounted to 534 mm (2011-2012), 391 mm (2012-2013) and 414 mm (2103-2014) in the village Andremba. This as well as well as the other rainfall distribution parameters were not directly reflected in annual yields (Table 2.4).

2.4.2 Overall yields

Average tuber yields on control plots across years ranged from 1 – 1.8 t ha^{-1} and were substantially higher in An1 compared to the other fields, which were not harvested every year (Figure 2.1a). Average above ground biomass (leaves and stems) ranged from 0.6 – 1.2 t ha^{-1} and reflected the same trends as tuber yields (Figure 2.1b).

Table 2.4. Total rainfall, occurrence of dry spells, length of the rainy season (first to last day of rain) and number of rainy days (≥1mm) over the course of the rainy season (Dec.-May) during the trial period in the village Andremba on the Mahafaly Plateau in south-western Madagascar.

		2011/2012	2012/2013	2013/2014
Total rainfall		534	391	414
Dry spells	>7 d	4		2
	>14 d		3	
	>21 d		1	2
Length of rainy season (d)		118	134	116
Number of rainy days (≥1 mm)		38	24	27

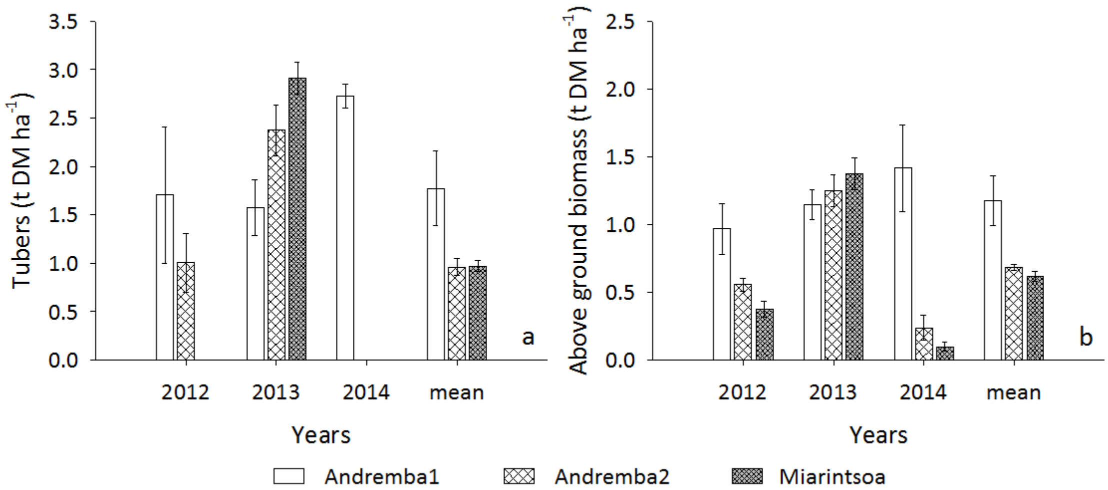

Figure 2.1. Annual and average tuber (a) and biomass yields (b) of control plots at three trial fields on the Mahafaly Plateau in south-western Madagascar. Vertical bars represent ± one standard error of the mean (n= 4).

2.4.3 Treatment effects

Neither the number of established nor the percentage of harvested plants per plot per year were significantly affected by treatments (data not shown). This allowed to assess treatment effects on a yield per plant basis rather than per area (plot).

Over the three study years, there was a tendency of increased tuber yields on An1, but not on An2 and Mi (Figure 2.2). Moreover, manure effects tended to increase over the years in An1, the only field in which tubers were harvested each year. Above ground biomass yields showed the same trends as tuber yields and tended to increase with manure application on An1 and Mi. Neither effect was significant at the 0.05 level (An1: P = 0.090 – 0.698; An2: P = 0.216 – 0.839; Mi: P = 0.202 – 0.888 across tuber and biomass yield parameters and years). ANOVA revealed that also charcoal effects were not significant, and that there were no interactions between manure and charcoal treatments, with no conclusive trends across fields and years for tuber and biomass yields (data not shown). Tuber number per plant and tuber size classes were not significantly affected by manure or charcoal treatments (data not shown).

Correlation analyses (Spearman's rho) indicated that tuber yields tended to decline with increasing virus infection score of 2013 across fields, while the effects on biomass yields were not as pronounced (Table 2.5). Virus infection scores of 2013 explained 18% of tuber yield variation and 5% of biomass yield variation, but virus infection of 2014 did not significantly affect yields. Similarly, with plants reclassified into healthy (Virus class 0) and infected (Virus class 1) plants, total tuber and biomass yields differed significantly between virus infection classes of 2013 (Table 2.6).

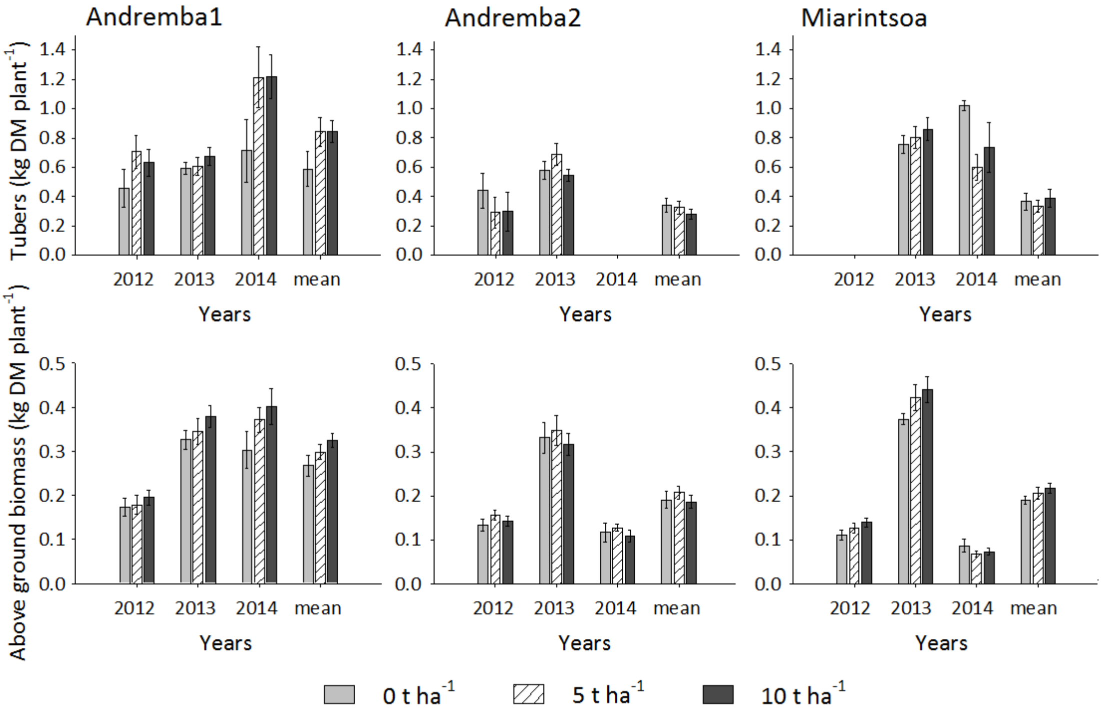

Figure 2.2. Effects of manure rates on above ground biomass and tuber yields across years at three trial fields on the Mahafaly Plateau in south-western Madagascar. Vertical bars represent ± one standard error of the mean at the plot level (n=12).

Table 2.5. Results of Spearman's rho correlation analyses between total yields (tuber and biomass, 2013+2014) and mosaic virus infection rates on the Mahafaly Plateau in south-western Madagascar (2013 and 2014).

		Virus 2013	Virus 2014
Tuber yield	Correlation coefficient	-0.422	0.071
	Sign. (1-tailed)	<0.001	0.054
	N	781	521
Biomass yield	Correlation coefficient	-0.213	0.061
	Sign. (1-tailed)	<0.001	0.065
	N	835	623

When treatment effects were analyzed for virus infection classes separately and with individual plants as replicates, only healthy plants (Virus class 0) in An1 showed a significant effect of manure on tuber and biomass yields, which increased by 30 – 40% and 20 – 30%, respectively (Figure 2.3, Table 2.7). In the field Mi, tuber yields tended to increase with manure by 11 – 14% in healthy plants and biomass yields by 14 – 23% in infected plants, but effects were not significant. Furthermore, while effects of charcoal were significant in some cases (Table 2.7), there was no conclusive trend of yield increasing or depressing effects of charcoal amendment (data not shown).

Table 2.6. T-test results of mosaic virus infection classes of 2013 (0 = uninfected, 1 = infected) in total cassava yield at three trial fields on the Mahafaly Plateau in south-western Madagascar.

Field	Virus class (2013)	Tuber yield (kg DM plant^{-1})			Biomass yield (kg DM plant^{-1})		
		N	mean	Sign.	N	mean	Sign.
Andremba1	0	148	1.08	<0.001	158	0.72	0.001
	1	118	0.65		122	0.59	
Andremba3	0	101	0.89	<0.001	121	0.45	0.001
	1	155	0.45		158	0.35	
Miarintsoa	0	120	1.04	<0.001	130	0.45	0.048
	1	139	0.73		146	0.40	

Table 2.7. Results of ANOVA (P-values) for treatment effects on total tuber and biomass yields of cassava at three trial fields on the Mahafaly Plateau in south-western Madagascar over two years (2013+2014), analyzed separately by mosaic virus infection classes (0 = uninfected, 1 = infected).

Virus class	Factor	Andremba1		Andremba2		Miarintsoa	
		Tuber yield	Biomass yield	Tuber yield	Biomass yield	Tuber yield	Biomass yield
0	Manure	0.014	0.014	0.170	0.738	0.200	0.468
	Charcoal	0.114	0.001	0.783	0.881	0.240	0.235
	Manure* Charcoal	0.258	0.038	0.831	0.236	0.148	0.363
1	Manure	0.425	0.462	0.347	0.368	0.928	0.049
	Charcoal	0.049	0.025	0.037	0.001	0.096	0.091
	Manure* Charcoal	0.545	0.840	0.038	<0.001	0.128	0.521

2.4.4 Multiple Regression Analysis

The coefficients of regression analysis across fields and years were not plausible for a number of parameters, in that soil C, total rainfall and number of rainy days had negative coefficients, while number of dry spells(>14d and >21d) had positive coefficients. Similarly, for tuber yields the factor soil P had a negative coefficient. Furthermore, their explanatory effects (change in R^2 by inclusion in the model and significance of the coefficient) were very low (data not shown). We presume that the influence of these parameters was overlaid by other factors, were thus by themselves not good predictors and were thus excluded in the model. Virus infection also had a non-significant explanatory effect across the whole dataset. Consequently, the factors plant survival, number of dry spells (>7d) and soil P best described observed biomass yields (Table 2.8), while for tuber yield, plant survival and number of dry spells (>7d) were the best predictors

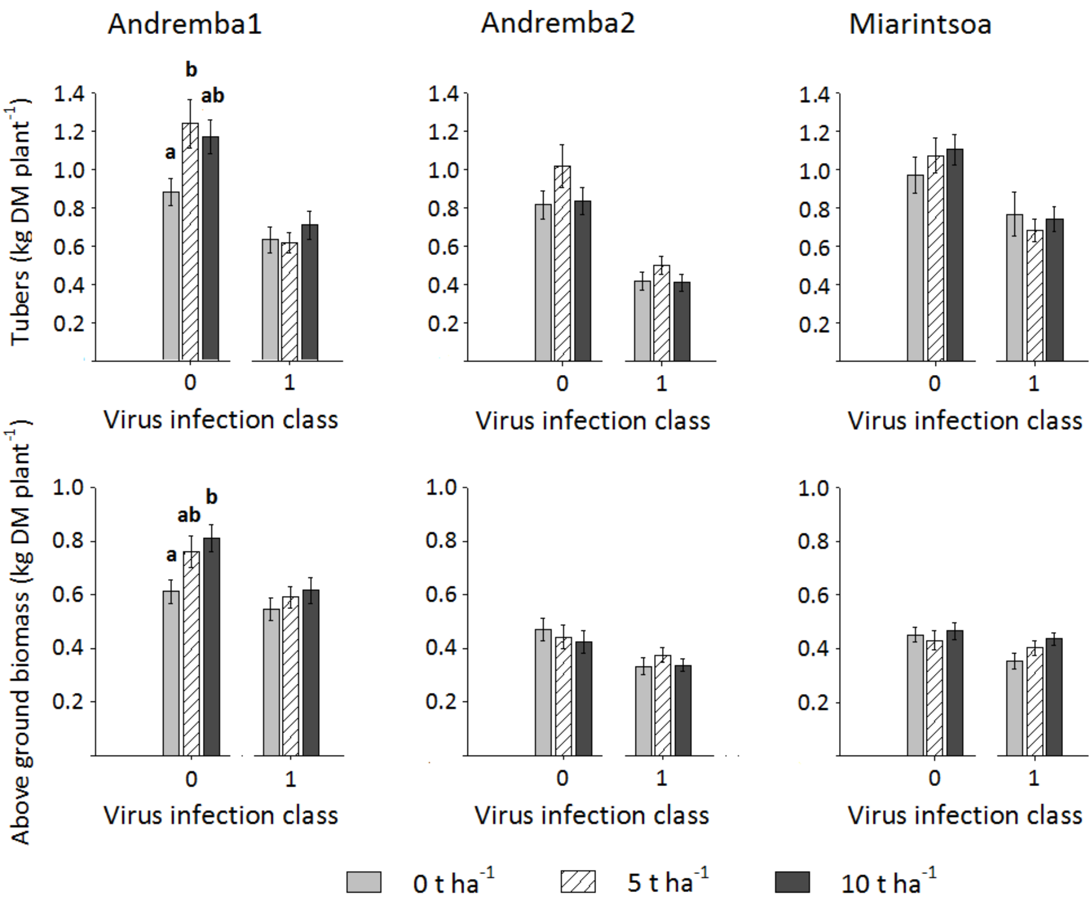

Figure 2.3. Effects of manure treatments on tuber and biomass yields of cassava at three trial fields on the Mahafaly Plateau in south-western Madagascar (2013+2014) according to mosaic virus infection class (0 = uninfected, 1 = infected). Vertical bars represent ± one standard error of the mean (plant level data). Different letters above bars indicate significant differences between manure treatments within virus infection categories (α = 0.05).

Table 2.8. Results of a multiple regression analysis for biomass yield of cassava on the Mahafaly Plateau in south-western Madagascar.

	B coefficient	B s.e.	β (standardized B)	Sig.	R^2 change
Constant	-0.372	0.119		0.002	
Dry spells (>7 d)	-0.219	0.012	-0.603	<0.001	0.360
Plant survival	0.015	0.001	0.601	<0.001	0.281
Soil	0.010	0.002	0.142	<0.001	0.019

Model Summary: R^2 =0.66, Durbin-Watson = 1.075; ANOVA: p<0.001, RMSE=0.349

(Tables 2.9, 2.10). The resulting models described 66, 28 and 53% of biomass and tuber yield variation (zero-harvest plots excluded and included), respectively. Our data analysis also revealed that variances of residuals were not homogenous across the data but were increasing with predicted yields, especially in the case of tuber yields that included zero-harvest-plots. Hence the models, while describing the dataset fairly well, have limited value to be generalized beyond the sample (Field, 2009).

Table 2.9. Results of multiple regression for tuber yield (excluding zero-harvest-plots) of cassava on the Mahafaly Plateau in south-western Madagascar.

	B coefficient	B s.e.	β (standardized B)	Sig.	R^2 change
Constant	0.140	0.360		0.968	
Dry spells (>7 d)	-0.317	0.042	-0.488	<0.001	0.124
Plant survival	0.028	0.004	0.418	<0.001	0.157

Model Summary: R^2 =0.281, Durbin-Watson = 1.132; ANOVA: p<0.001, RMSE=0.910

Table 2.10. Results of multiple regression for tuber yield (including zero-harvest-plots) of cassava on the Mahafaly Plateau in south-western Madagascar.

	B coefficient	B s.e.	β (standardized B)	Sig.	R^2 change
Constant	0.153	0.173		0.376	
Dry spells (>7 d)	-0.498	0.030	-0.642	<0.001	0.311
Plant survival	0.026	0.002	0.474	<0.001	0.218

Model Summary: R^2 =0.529, Durbin-Watson = 0.981; ANOVA: p<0.001, RMSE=0.873

2.4.5 Estimated yield loss due to CMV infection and irregular plant stands

The estimated tuber and biomass yield losses due to virus infection state per field ranged between 10 – 30% and 10 – 15% respectively (Table 2.11) in 2013, while effects of 2014 virus scores on yield were inconclusive.

Plant stands across treatments and fields decreased from 92 to 62% of those planted over the course of three years. Furthermore the percentage of harvested plants among established plants changed from 16 to 90 to 17% during the three years (Table 2.12).

In 2013 and 2014, mean plant height differed significantly (P <0.001) between harvested plants and those left in the ground for the following year (Table 2.13). There was nevertheless a large overlap between these groups in terms of minimum and maximum heights.

Table 2.11. Estimated tuber and biomass yield losses due to cassava mosaic virus infection at three trial fields on the Mahafaly Plateau in south-western Madagascar.

	2013		2014	
Field	Tuber yield loss (%)	Biomass yield loss (%)	Tuber yield loss (%)	Biomass yield loss (%)
Andremba1	- 9.6	-	- 15	-
Andremba2	- 30.8	- 15.2	-	-
Miarintsoa	- 20.3	- 9.7	-	-

Table 2.12. Cassava plant survival rate (%) and percentage of harvested plants across treatments at three trial fields on the Mahafaly Plateau in south-western Madagascar.

	Plant stand (% of full stand)			Harvested plants (% of plant stand)		
Field	2012	2013	2014	2012	2013	2014
Andremba1	94	82	86	36	71	36
Andremba2	96	85	46	12	100	0
Miarintsoa	86	79	53	0	100	14
Mean	92	82	62	16	90	17

Table 2.13. T-test results of height differences between harvested and non-harvested plants in cassava on the Mahafaly Plateau in south-western Madagascar (2013 and 2014).

	2013		2014	
Harvested	yes	no	yes	no
n	724	121	102	181
Mean height (cm)	134.2	83.8	144.80	88.2
Min height (cm)	14	20	32	44
Max height (cm)	177	201	210	136
p	<0.001		<0.001	

2.4.6 Correlations between plant height and yield data

Height correlated significantly with yield and above ground biomass across all years and fields (Table 2.14). As residuals of parametric regression were not normally distributed in all occasions, only Spearman's rho is given as the correlation coefficient.

Table 2.14. Correlation coefficients (Speraman's ρ) and significance levels for plant height, tuber yield per plant and above ground biomass of cassava in 2013 and 2014 and across all fields on the Mahafaly Plateau in south-western Madagascar.

		Height	Tuber yield	Biomass yield
Height	ρ	1	0.61	0.75
	P		<0.001	<0.001
	N	1485	799	1209
Tuber yield	ρ	0.61	1	0.83
	P			<0.001
	N			802
Biomass yield	ρ			1
	P			
	N			1215

2.4.7 Effects of amendments on soil parameters

Manure tended to increase all tested soil parameters except pH and C/N ratios after three years of application, but only soil C, N, Mg, K and Na concentrations were significantly affected. Similarly, one-time charcoal applications lead to higher levels of all tested soil parameters, but none of these effects was significant (Table 2.15), while there were no manure*charcoal interactions (data not shown).

2.5 Discussion

2.5.1 Cassava yields

While maximum cassava yields of 27 t ha^{-1} DM have been reported at near optimum growing conditions on-station (El-Sharkawy, 2012), the yields observed here are comparable to values reported from semi-arid areas: in Colombia at 555 mm annual rainfall cassava yields amounted to 0.4 – 3.3 t DM ha^{-1} (de Tafur et al., 1997a), and in Nigeria with 600 – 700 mm rainfall, dry matter yields ranged between 1.36 and 1.87 t ha^{-1}

Table 2.15. Effects of manure and charcoal amendments on soil parameters after three years of annual application (manure) and initial one-time application (biochar) (n = 4) on the Mahafaly Plateau in south-western Madagascar. Letters behind values indicate significant differences between manure treatments.

Treatment means		pH (KCl)	C (%)	N (%)	C/N	P Bray II (ppm)	Ca (%)	Mg (%)	K (%)	Na (%)	CEC (meq $100g^{-1}$)
Manure (annually)	0 t ha^{-1}	7.62	1.18 a	0.099 a	12.08	37.74	0.117	0.009 a	0.031 a	0.024 a	8.72
	5 t ha^{-1}	7.84	1.60 ab	0.135 ab	11.99	46.36	0.146	0.016 b	0.045 ab	0.029 ab	10.22
	10 t ha^{-1}	7.82	1.85 b	0.149 b	12.63	48.77	0.164	0.023 c	0.057 b	0.033 b	10.84
	p	0.061	0.013	0.027	0.674	0.260	0.182	<0.001	0.003	0.057	0.225
Charcoal (one time)	0 t ha^{-1}	7.70	1.38	0.120	11.76	42.04	0.117	0.015	0.037	0.027	9.09
	0.5 t ha^{-1}	7.76	1.50	0.129	11.75	42.77	0.138	0.015	0.045	0.028	9.87
	2 t ha^{-1}	7.81	1.75	0.133	13.20	48.07	0.171	0.018	0.051	0.030	10.81
	p	0.540	0.226	0.773	0.117	0.639	0.114	0.267	0.116	0.672	0.390

(Okogbenin et al., 1999). Planting distance for these comparisons as well as the observed irregular plant stands have to be taken into account, as plant density in our study area was 4,500 plants ha^{-1} while Okogbenin et al. (1999) used more than 10,000 plants ha^{-1}. In south-western Madagascar, farmers' yields are known to vary between 1 - 5 t ha^{-1} of fresh tubers and above ground biomass yields of 1 t ha^{-1} have been reported previously (Bayala et al., 1998). One study on cassava yields in southern Madagascar reported obtained yields of above 10 t ha^{-1} fresh tubers with "improved" management compared to average yields in farmer' fields of 2.5 t ha^{-1} (Le Thomas, 1946), dry matter content of tubers is about 40%), but the applied management techniques are unclear.
While the observed yield trends over the years do not reflect rainfall amounts, they illustrate the common practice of local farmers to harvest cassava only after two seasons. The partial harvest of a field every year can be considered a risk aversion strategy, as plants already in the ground have a higher chance to survive and grow in the following season than newly planted stems if rainfall conditions are unfavorable. In this regard, while plant heights were significantly higher in harvested plants, there was a large overlap of plant heights between harvested and non-harvested plants (Table 2.13), indicating that the decision to harvest a plant depends on numerous factors besides plant status, which are presumably related to immediate food security considerations and estimation of risk.
In our study area cassava is often grown continuously in the same field for many years, and in Thailand yields have been found to decrease to 60 – 70% of initial yields after 20 – 25 years of continuous cropping (Howeler, 1991). Since yield levels are generally low and variable and detailed field history information absent or unreliable, the yield decline due to continuous cropping on the Mahafaly Plateau, while generally reported

by farmers, is difficult to quantify.

2.5.2 Soil fertility and fertilizer responses

Tuber yields in our study showed a significant response to annual fertilization with local manure after three years in one field and with healthy plants, indicating that in the other cases either soil nutrient stocks were sufficient for the tested cassava varieties, cropping systems and yield levels, that manure did not provide sufficient amounts of yield limiting nutrients, or that other factors are more or at least as limiting to yield enhancement as nutrient availability.

El-Sharkawy (2012) points out that cassava is very tolerant to low soil fertility compared to other crops while it is also considered to respond poorly to fertilizers (Tittonell and Giller, 2013). According to Howeler and Cadavid (1990), critical soil nutrient levels for cassava are 5 ppm for available P and 0.18 meq 100g^{-1} (=0.007%) for K, which are much lower than those for other crops such as maize (*Zea mays* L.). On the Mahafaly Plateau, soil organic C, N, available P and K concentrations have been found to be lower on crop lands compared to fallow and grazing land (Fricke, 2014). Likewise, soil K and organic matter levels of the field which lay fallow before the trial (An2) were substantially higher than on the other two fields, which reflects the soil fertility declines with continuous cropping. Nonetheless, the nutrient concentrations found in soils of our study sites are far above the critical levels, even apparently after many years of cultivation. De Ridder et al. (2004) point out that under continuous cultivation on low fertility soils, detectable decline in soil parameters are only found after several decades due to the exponentially decreasing rate of soil organic matter decomposition. According to (Howeler and Cadavid, 1990), a build-up of soil K beyond 0.20 meg may actually even result in a yield decrease due to induced deficiencies of calcium (Ca) and/or magnesium (Mg). While this potential yield-decreasing effect is probably not the case in our study due to the relatively high soil Ca and Mg levels, the sufficient K stock in the soil probably partly explains the absence of a tuber yield increase especially in An2. On the other hand, cassava is known to extract K with harvested tubers, which becomes the most limiting nutrient after several years of cultivation (Howeler and Cadavid, 1990). According to (Howeler, 2012b), K was found to be the most limiting element for cassava production in Madagascar, but this presumably applies to the highland region where agronomic research has been more prevalent and agro-ecological conditions are very different from the South. Overall, where yields are at 10-15 t ha^{-1}, they can be sustained for a long time with minimal removal of K and hence without K fertilization (Aye, 2012).

The second most limiting nutrient in continuous cassava cultivation is P (Howeler, 1991). At the same time, cassava is tolerant to low soil P levels due to a highly effective symbiosis with vascular arbuscular mycorrhiza (VAM) compared to other tropical crops, and the plant depends more on the mycorrhiza population and strain in the soil than on soil P levels for efficient P uptake (Hillocks et al., 2002). Studies on the status of mycorrhiza in cassava fields in our study area are lacking, but may reveal important insights about yield variation between fields of different soil types and cropping history. The relatively low yields, despite high soil fertility, of the field which lay fallow before the trial (An2, Figure 2.2) may thus be partly explained by a low symbiotic mycorrhiza population. Furthermore, compared to acid soils found elsewhere in Sub-Saharan Africa, soils in our study area may not be considered as critically low in available P due to the neutral pH of calcareous parent material and the prevalence of young and weakly developed soils in depressions that have not yet been exposed to strong chemical weathering in the current climate (Bourgeat et al., 1995). On the other hand, on crop lands across several villages on the Mahafaly Plateau, P levels were found to be in the order of 5 – 6 ppm and in some villages only 2-3 ppm on typical crop fields (Fricke, 2014), which are much lower than levels observed on our study sites, and which are near or below the threshold level for cassava. Phosphorus supply may therefore remain a possible yield limiting factor on continuously cropped land in the study area which needs to be further investigated.

Pellet and El-Sharkawy (1993) studied the responses of different cassava varieties to P fertilization and their different partitioning between sinks (roots, fruits, leaves) and found that aerial biomass was more responsive to P application than roots, and that response of aerial biomass to fertilizer was not always correlated with increases in root yield. Generally, the partitioning of assimilates into tubers and aerial plant parts, i.e. the harvest index, is a variety characteristic (El-Sharkawy, 2012) and should be taken into account when screening for varieties that are more adapted and appropriate for the environment and cropping system in our study area. Likewise, a high variability of yield among cultivars grown under the same conditions is often observed (de Tafur et al., 1997b; Okogbenin et al., 1999), and nutrient demands are found to be highly variable between cassava varieties. For example, Pellet and El-Sharkawy (1993) showed that among tested varieties, one did not respond significantly to P fertilization up to 100 kg ha^{-1}, and only in the second year an increase in above ground biomass was observable. Overall, cassava yield responses to N, P and K fertilization vary substantially across agro-ecological conditions and variety characteristics (Howeler, 2012b).

Manure of smallholder farmers is often found to be of low quality (Harris, 2002; Lupwayi et al., 2000), especially under open-air storage conditions (Predotova et al., 2010). Nutrient concentrations of N, P and K of manure used in our study were comparable and partly above those found in African smallholder fields (Bationo and Mokwunye, 1991; Lekasi et al., 2003; Lupwayi et al., 2000) while Ca and Mg concentrations were relatively high, presumably due to the influence of the calcareous soil parent material, partly deposited as dust. Manure quality, particularly C and N concentrations and the resulting C/N ratio, which in turn determine N availability, are affected among others by the quality of fodder (Powell et al., 2006) and animal type (Azeez and Van Averbeke, 2010). Goat manure used in our trials had a lower C/N ratio and higher N and K contents than zebu manure, which is in line with findings reported in the literature as small ruminant manure tends to be of better quality than cattle manure (Azeez and Van Averbeke, 2010; Williams and Powell, 1995).

Considering nutrient concentrations of cassava biomass and tubers reported in the literature (Howeler, 1991, 2012a) and under the yield levels observed in our studies, annual nutrient exports across fields and years amount to about 27 kg N ha^{-1}, 3 kg P ha^{-1} and 30 kg K ha^{-1} if all biomass is exported from the field. Hence, under the current yield levels, application of local manure at 2.5 t ha^{-1} would supply sufficient amounts to replace exported nutrients. Availability of those nutrients may, however, not coincide with plant needs, especially in the first years of manure application on a poor fertility soil (Fatondji et al., 2009).

Overall, under the extensive low-yielding cropping systems currently found in our study area combined with the high soil nutrient stocks relative to cassava demands, cassava cultivation may so far not be limited by soil nutrient supply, except in some older fields with low soil fertility. On the other hand, manure effects on soil and nutrient availability to plants may be low in the first years of application and increase over years. Nonetheless, soil nutrient concentrations after manure and charcoal amendments tended to increase for all parameters, even if effects were not significant in all cases.

At the same time, nutrient losses through the erosion of top soil are another pathway besides the extraction through harvested products. Under the observed low plant density, and the slow initial growth rate at the beginning of the rainy season, topsoil erosion is indeed problematic for soil fertility in cassava cultivation (Howeler, 1991), even if at our sites soil is not tilled in the traditional system. Soil erosion, which is a considerable problem in south-western Madagascar in general (Harimanitra, 2006; Service des Eaux et Forêts, 1961; Sourdat, 1972), may be alleviated in cassava fields by intercropping with soil covering legumes and Cucurbitaceae, as it is sometimes practiced by farmers in the study area. However, Service des Eaux et Forêts (1961) found no differences in amounts of rainwater run-off and eroded soil between cassava monocrop systems and soil covering legume and grass systems in southern Madagascar. Furthermore, competition for nutrients and particularly for water has to be investigated in order to give specific recommendations for intercropping in cassava systems. In this regard, mulching may be effective in suppressing weeds, and it has also been shown to double cassava yields in Colombia (Cadavid et al., 1998). On the other hand, in semi-arid areas and in south-western Madagascar in particular, the availability of mulching material is a constraint for the adoption of this system due to low biomass production and competing uses of crop residues for livestock fodder (Rollin, 1997; Serpantié, 2009).

2.5.3 Charcoal effect

Islami et al. (2011) obtained a cassava tuber yield increasing effect by about 30% with 15 t ha^{-1} charcoal application in the second year after application in a humid environment. The lack of any charcoal response in our study may be due to the low application rate of charcoal, and the fact that charcoal was applied broadcast in the first year, therefore diluting the amount of charcoal per cassava plant due to the low plant density. Furthermore, charcoal effects on crop yields vary substantially across soil types, and have been found to be negative or much lower on Calcarosols compared to loamy or acid soil types presumably due to the positive liming effect from charcoal (Verheijen et al., 2010).

2.5.4 Impact of CMV and plant stands on yield

In southern Madagascar infection rates of CMV were estimated at 40% (McGuire and Sperling, 2013), and yield losses of 30 – 40% in infected plants have been reported for Africa (Nweke et al., 2002), which are similar though slightly higher compared to estimates in our study. Overall, the use of cuttings that are already infected and have low vigor, together with other poor cultural practices may contribute to yield losses of 50% (Hillocks et al., 2002). An additional detrimental effect of virus infection is posed by the fact that infected plants may respond less to fertilization than healthy plants (Fermont et al., 2009), as our results suggest (Figure 2.3).

Virus infection of the year 2013 had a stronger influence on harvests than of the year 2014. This is difficult to attribute to specific factors, but the relatively low number of rainfall events in that year, as well as the passage of a cyclone, may play a role as stressed plants are more susceptible to infection (Ranomenjanahary et al., 2005; Tahiny, 2006; Vololona et al., 2013). The relatively weak correlation between virus infection scores and tuber and biomass yields observed in this study may be partly attributed to the fact that plants with mild infection rates can outperform healthy plants, as was observed elsewhere (Thresh et al., 1994).

Nweke (1994) and Andrianasolo and Razafintsalama (2013) recommend the selection of healthy stems, uprooting and burning of infected plants, and use of resistant varieties to combat the high prevalence of CMV in Africa and on the Mahafaly Plateau, respectively. However, in Africa farmers often do not have sufficient knowledge to be able to select healthy planting material and are reluctant to eliminate plants that will otherwise produce some yield (Hillocks et al., 2002). Another constraint in dry areas is the limited availability of planting material due to low biomass production, as well as the necessity to replant several times during the season, which forces farmers to use all stems that are available and may encourage the disuse of varieties that have a relatively low biomass production (Hillocks et al., 2002; Nweke et al., 2002). In south-western Madagascar, a drought in the 1990's may thus have contributed to the rise in virus infection rates of the

region, as farmers used any planting material regardless of its quality, and more infected material was thus introduced into the system (Dagnon and Beauval, 1993).
The breeding and diffusion of resistant varieties as well as the establishment of a supply market for healthy cuttings is therefore a priority (Hillocks et al., 2002). While in East Africa pest and disease pressure were found to be the least and soil fertility the most important yield limiting factor, this has been attributed to the fact that resistant genotypes are commonly used in this region (Fermont et al., 2009), which is, however, not the case in our study area. Selection for CMV resistance in southern Madagascar has been absent or slow (McGuire and Sperling, 2013). Furthermore, environmental and management conditions on the Mahafaly Plateau already differ considerably from those at the regional agricultural research site, and cyanogenic acid contents tend to change quickly with agro-ecological conditions, calling for location-specific selection (Githunguri et al., 2007). A variety selected at the research site has thus been found to be too bitter to be used for human or livestock consumption when grown in slightly drier conditions in southern Madagascar (F. Manjary, personal communication, February 2014).
Fermont et al. (2009) conclude that the "dissemination of improved genotypes will form the back-bone of any new technology package, because the introduction of new genotypes presents the ideal entry point for the promotion of alternative crop management options." On the other hand, there are no cultivars that are completely resistant to infection and if the use of tolerant cultivars is not accompanied by sanitary measures, infection and considerable yield losses can nonetheless occur (Fauquet and Fargette, 1990). A study in Madagascar found that use of infected cuttings was with 86% of observations the much more prominent source of infection compared to transmission by the whitefly vector after planting (Ranomenjanahary et al., 2005). Additionally, virus tolerance may be difficult to evaluate by itself, as there are trade-offs between virus resistance and other characteristics important to farmers (Fauquet and Fargette, 1990). Sweet varieties were found to be more popular among African farmers in drought prone areas, as these can be consumed without lengthy pre-treatment (Nweke et al., 2002). Similarly, farmers in the Mahafaly Plateau, especially in the extremely dry littoral zone, prefer to plant a considerable part of the field with sweet varieties of cassava (Andriamparany, 2014), which are lower in cyanogenic acid content and can be freshly eaten throughout the year, but which tend to be more susceptible to virus infection. With the introduction of improved varieties that are higher yielding, the importance of soil nutrient depletion due to higher exports with harvested products would increase and call for adaptation of traditional cropping methods (Fermont et al., 2007).
The observed incomplete plant stands and frequent replanting necessary during the rainy season as observed in our study are probably due to the desiccation of stems after longer dry spells (Okogbenin et al., 1999), but also to use of already infected stems that tend to take root and grow more slowly than healthy stems (Fauquet and Fargette,

1990). The lack of an effect of manure treatments on plant stands is in contrast to results obtained by Buerkert and Stern (1995), where phosphorus application resulted in higher and more vigorous millet crops stands in Niger (542-603 mm rainfall). On the other hand, one field owner in our trial remarked that plants amended with manure established poorly and tended to dry out at the beginning of the rainy season, possibly due to some hydrophobic property of the very dry manure and differences in wetting patterns compared to the soil.

Nonetheless, selection of vigorous planting material but also other management practices are likely to improve the establishment of plants at the beginning of the season. Planting in furrows has thus been found in Nigeria (813 mm rainfall) to lead to higher plant stand compared to planting in ridges (Okogbenin et al., 1999). Also longer stems (>20 cm) and a deeper planting depth tend to increase survival rate of planted stakes especially in sandy soils in a dry climate (Aye, 2012). Regarding planting material, the selection of vigorous stakes from the middle portion of the basal branches of fertilized mother plants has been found to result in higher yields (Moreno, 1992). It is unclear to what degree farmers on the Mahafaly Plateau make conscious decisions when selecting stakes and are constrained by low availability of planting material.

2.5.5 Water availability

Cassava responds better to fertilization under optimal water availability. For example, yield increases after N, P and K fertilization have been found to be in the order of 50% under water stressed conditions whereas 100 – 200% yield increases have been reached in watered plots across several cultivars (de Tafur et al., 1997b). This indicates the trend that, with increasing water stress, response to fertilizer diminishes, even across cultivars, and may add to the absence of a systematic fertilizer effect across fields and years under the low rainfall conditions in our study area. The distribution of water availability during the cassava vegetation cycle is of importance especially in the first six months of the crop season, and water stress after the 4th month after planting has been found to not depress yields significantly (de Tafur et al., 1997b; El-Sharkawy, 2012; Fermont et al., 2009). On the other hand, it has also been observed that cassava can recover and compensate for yield loss after a period of water stress, and even produce higher yields with water stress at the beginning of the crop cycle (El-Sharkawy and Cadavid, 2002). However, this would not be expected in our study area, as there is usually no rainfall during the dry season which would help plants to recover.

While the rainfall amounts over the 4-5 month rainy season during our field trials did not explain annual yields, in regression analysis, dry spells >7d and plant establishment explained most of the tuber and biomass variation in our dataset. However, due to the small size of the dataset it is difficult to assign any causation to this relationship and to separate yearly rainfall effects from other factors changing between years, particularly staggered harvests. Plant establishment percentage did not correlate strongly with any of the rainfall parameters, which indicates that either plant establishment is more related to other (e.g. management related) factors, or the calculated rainfall parameters did not represent the most crucial determinants of plant establishment. For example, the occurrence of dry spells in the beginning of the season is probably more important than total number of dry spells during the season.

2.5.6 Further research recommendations

In south-western Madagascar several yield depressing factors act together, such as recurring droughts, disease pressure, soil erosion and declining fertility as well as restricted access to improved germplasm, inputs and cultivation technology. Fermont et al. (2009) point out that in a multi-stress environment removing one stress will increase production less than in an environment facing only one or two stresses. Hence it is evident that various other constraints have to be tackled as well for the use of local manure or even mineral fertilizer to be economically practical in the long term. Management of cassava can have a strong impact on yield, and proper agronomic practices can substantially improve the response to fertilizers (Fermont et al., 2009). Weeding is reported to be the most limiting and also the most labor intensive factor in cassava cultivation (Melifonwu, 1994), and timing of weeding is especially important in the first two months after planting (Aye, 2012). Differences in weeding management may thus also partly contribute to the observed differences in overall yield between trial fields, regardless of soil nutrient status. Soil tillage by ox-plough may be one possibility to improve yields, as soils have a hard crust and cassava mounts are prepared manually by hoe to relatively shallow soil depths and with considerable investment of labor. On the other hand, Moreno (1992) concludes from literature reviews that tillage is more effective for weed management than for increasing root bulking, while obtained results are very site specific. Use of the plough may thus help to alleviate several of these labor constraints. The majority of farmers on the Mahafaly Plateau have, however, little access to ploughs or draught power, and the promotion of soil tillage has been the subject of controversy among stakeholders (Dagnon and Beauval, 1993; Rollin, 1997; SuLaMa, 2011). A method similar to the *Zaï* technique, which included addition of biomass in 1*1 m^2 holes and planting in micro-catchments, has been promoted by several organizations working on the Mahafaly Plateau and been found to lead to an average ten-fold increase in tuber yield (F. Babarezoto, personal communication, 30.09.2013), but controlled studies are as yet lacking and should be pursued, also taking into account labor inputs, performance of different cassava varieties and possible constraints due to biomass availability.

Potential for yield improvements lies also in intercropping with cover crops, where effects on cassava yield, fertilization potential with legumes, reduction of soil erosion and weed suppression are of interest. In this regard, fertilization with local manure may be more effective if applied to more demanding intercrops rather than cassava plants, which can still have indirect positive effects on cassava growth. Intercropping may also contribute to cropping system resilience due to crop diversification. According to Nweke et al. (2002), local agronomic research is needed to determine optimal cassava and intercrop plant densities as they depend on many factors and are hence highly location specific. The same applies for the screening of improved cassava strains that are virus tolerant while adapted to the local ecological and management conditions. The use of wind breaks such as elephant grass and perennial shrubs has been studied in southern Madagascar in the past, and the positive effect on cassava plants has been recognized (Le Thomas, 1946), presumably due to the strong prevailing winds and their drying effects.

According to CIAT (1992), cassava field trials differ from trials with cereal plants such as maize in that planting distances are large, resulting in relatively low numbers of individuals and high variation in a trial plot. They point out that, although a minimum of 25 plants per plot and 6 replicates per treatment are recommended, this is often not practical due to cost and surface area constraints. In our on-farm trials, the need for homogeneous soil conditions and a field size that would be manageable by field owners restricted the plot size per treatment and led to a high variation within treatments. Buerkert et al. (1995) point out that micro-variability in soil physical and chemical characteristics in the Sahel can inhibit the detection of soil amendment effects on millet yield. Accordingly, Buerkert and Stern (1995) conclude from amendment trials in Niger, that plot sizes should be relatively large if the interest is in average treatment effects across a range of soil properties, or plots should correspond to patches of differing soil characteristics if the consistency of treatment effects across varying soil conditions is the focus. The first case can be considered to concern a more applied research question appropriate for on-farm trials (amendment effects on yields in farmers' fields), whereas the second case concerns a more basic research question to understand underlying processes. Hence plot sizes should be chosen according to the research question. Overall, a high number of treatments do not seem to be practical in on-farm trials in our study area, where there are numerous factors influencing crop performance that are difficult to control. Plot sizes should preferably be larger at the expense of number of treatments. Buerkert and Stern (1995) also point out that germplasm from farmers stock can increase observed variation within plots, and our results suggest that controlling for cassava plant vigor (here equivalent to virus infection status) helps to better understand the effects of treatments on plant growth.

Furthermore, in the Mahafaly region, where cassava plants are often harvested after two seasons and climatic conditions are very unreliable every year, longer experiments would be necessary in order to cover a wider range of situations, while the focus should be on improving the long-term resilience of the existing cropping system instead of annual yields alone.

Overall, to determine the yield influencing factors, and accordingly identify entry points for improved cassava cropping systems in the study area, a broader observational study across farmers and villages (and ideally years) may be appropriate, as it would enable the establishment of a more reliable regression model of yield determination with local rainfall patterns, management factors and introduced practices such as manure application.

Finally, farmers' investment in intensification measures will also only take place with improved market access and producer friendly pricing policies (Place et al., 2003). These factors remain a major bottleneck for intensification on the Mahafaly Plateau (Bayala et al., 1998; Groupe de Travail de Développement Rural 2, 2001; Hoerner, 1981), as farmers lack the social and economic capital to intensify crop management on their own (Fermont et al., 2009).

2.6 Conlusions

This study showed that among three field sites differing in soil types, initial soil fertility and field history, livestock manure application up to levels of 10 t ha^{-1} affected tuber yields in only one field and in healthy plants, with yield increases in the order of 30-40% compared to control after three years of annual application under the current cropping system. On the other hand, yield loss estimates due to infection with CMV amounted to 9 – 30%. Furthermore, considerable losses can be associated with low plant survival at the beginning of the season, which was reduced by 8 – 38% across fields and years. Hence, while some yield increases with manure were observed on a continuously cropped field, the labor necessary for its application, which may also only be accessible to wealthier households, is likely to restrain farmers from this management system. Yield enhancements are constrained by many other factors, particularly water availability and quality of planting material, some of which are currently more difficult to control by the farmer. On the other hand, at the current yield levels, application of local manure at a minimum level of 2.5 t ha^{-1} would be sufficient to replace extracted amounts of N, P and K. Local manure increased soil organic matter and nutrient concentrations after three years of application, but the role of soil erosion in soil fertility decline may be considerable and should be investigated. Furthermore, if any of the other constraints are alleviated, soil fertility management can be expected to be of paramount importance.

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3. Feasibility of carrot (*Daucus carota*) and onion (*Allium cepa*) production under semi-arid salinity conditions in south-western Madagascar

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3.1 Abstract

On the Mahafaly Plateau in south-western Madagascar traditional rain-fed cropping systems are vulnerable to recurring droughts, leading to often drastic yield decline and dependence on food aid, while the region shows the highest levels of malnutrition in the country. Vegetable production may have potential to improve household nutrition and diversify income sources during the dry season. Hence we tested the feasibility of irrigated vegetable production with cattle manure (40 t ha^{-1}) and charcoal (10 t ha^{-1}) amendments as well as shading for two dry seasons in 2013 and 2014. Carrot and onion yields across treatments and seasons ranged from 0.24 to 2.56 t DM ha^{-1} and from 0.30 to 4.07 t DM ha^{-1}, respectively. Manure and charcoal amendments did not affect yields of both crops, but manure lowered the alkaline soil pH and enhanced Corg, N and P concentrations. Shading decreased carrot yields by 33% in 2013 and enhanced yields by 65% in 2014, while onion yields were raised by 148% and 208% under shading in 2013 and 2014, respectively. Onion plant stands in 2013 under sun and shade only reached 8% and 12% of the initial density, whereas in 2014 they amounted to 5% and 20% under sun and shade, respectively. Germination experiments revealed that the salinity of irrigation water (EC=7.03 mS cm^{-1}) as well as quality of locally available carrot and onion seeds hampered germination rate and vigor. Return to labor under the current management was highest for carrot cultivation under shade in 2014, but was generally too low to allow commercial production. Improvement of seed quality and identification of better adapted cultivars are prerequisites to improving the feasibility of vegetable production in the study area.

Key words: salinity; *Daucus carota*; *Allium cepa*; south-western Madagascar

3.2 Introduction

On the Mahafaly Plateau in south-western Madagascar traditional cropping systems are based on rain-fed production of cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.), sweet potato (*Ipomea batatas* L. Lam.) and leguminous crops (Battistini, 1964; Neudert et al., 2014; Rakotomalala, 2008). Droughts in this region are a recurrent phenomenon, leading to sometimes drastic reduction in crop production, regular famine and food aid interventions (WFP and Unicef, 2011; Wüstefeld, 2004). Hence local households in this region are among the most food insecure and malnourished of Madagascar, with diets primarily based on cassava and a low consumption of vegetables (WFP and Unicef, 2011).

It is well recognized that increased vegetable and fruit consumption can lead to enhanced health and reduction of chronic diseases in Africa (Ganry, 2009). Furthermore, in areas with ready market access, vegetable production can help to diversify income sources and reduce risks due to crop failures. At the same time, for poor farmers with little access to (urban) markets, household vegetable production may be the only way to access vegetable produce for consumption (Ruel et al., 2005).

In the littoral zone of the Mahafaly Plateau, cultivation of high-value and nutritious vegetable crops in the dry season can thus be an important strategy for the diversification of diets as well as provide income for small-scale farmers, as there is year-round access to groundwater for irrigation and cattle manure is available in villages without being traditionally used for field crops. Furthermore, charcoal has been shown to improve soil characteristics of sandy soils (Glaser et al., 2002b) and is readily available to farmers from residues of charcoal production practiced in the area.

Simultaneously, opportunities for marketing produce are developing due to tourism as well as access and relative proximity to the regional capital Toliara. This expanding city receives the majority of vegetables from nearby regions and the Malagasy highlands (Daou, 2008), while urban and peri-urban agriculture are still very poorly developed. Therefore, vegetable cultivation is increasingly being promoted by non-governmental and UN organizations' interventions as a diversification strategy for poor small-holder farmers in southern Madagascar (McGuire and Sperling, 2013), but little is known about the productivity of these systems and their fit to the agro-ecological and socio-economic conditions of the region.

Carrot (*Daucus carota* L.) and onion (*Allium cepa* L.) are important vegetable crops that are often also cultivated in arid and hot areas of sub-Saharan Africa (Grubben and Denton, 2004). They are also promising vegetable crop species in the study area because of high demand coupled with low supply in the city of Toliara (Daou, 2008; Gildas Dosy, 2007; Rijarimamy, 2011). Furthermore, locals are already familiar with the consumption of onions, which are sold on village markets, and the crops are less perishable and easier to store and transport than leafy or fleshy vegetables. Growing conditions for carrots and onions have been found to be relatively favorable compared to the effects of high pest and disease pressure in tomatoes (*Solanum lycopersicum* L.) and potato (*Solanum tuberosum* L.).

Yet, many potential constraints to local vegetable production exist in the study area and are little understood. These include access to quality seeds, extreme weather conditions including heat, wind and intensive rainfall events and salinity of irrigation water, especially since onions and carrots are known to be sensitive to salinity (Shannon and Grieve, 1998).

Hence the objectives of this study were to (i) assess the effects of manure and charcoal application on carrot and onion yields in a field trial in a coastal village over two cropping seasons, and (ii) identify the major constraints for vegetable production and test options to overcome them.

3.3 Materials and Methods

3.3.1 Study site

A trial field was installed in the village Efoetsy (24°4.3' S, 43°42' E) in March 2013. The soil at the plot was a poorly developed calcaric Regosol (Hillegeist, 2011) with a sandy texture (92% sand, 4% silt, 4% clay) and a pH (KCl) of 8.3, 0.94% C_{org}, 0.08% N, 15.63 mg kg^{-1} P (Bray II) and 0.014% K. The local climate is semi-arid with an average annual rainfall of 360 mm (CNA, 2014) mainly falling in the rainy season from December to April, and a mean monthly temperature ranging from 20 to 28°C. Cultivation of carrots and onions in this area is most suitable in the dry season from April to September due to lower air and soil temperatures and the often high rainfall intensity during the rainy season. The field was situated near a local well from which water was brought every day by ox-cart to the plots for irrigation. The water had a relatively high salinity during the dry season (July) of 7.65 mS cm^{-1}, a pH of 7.74, and Na, K and P contents of 118, 7 and 0.6 ppm, respectively.

3.3.2 Plot installation

Plots of 2*3 m size were arranged in a completely randomized design, with 1 m distance between plots. Treatments consisted of a control without any inputs, manure at the rate of 40 t ha^{-1} fresh matter, charcoal at the rate of 10 t ha^{-1}, and manure and charcoal mixed. Resulting nutrient amounts with manure application were in the order of 450 kg N ha^{-1}, 67 kg P ha^{-1} and 230 kg K ha^{-1} in 2013 and 415 kg N ha^{-1}, 62 kg P ha^{-1} and 380

kg K ha^{-1} in 2014, while manures had C:N ratios of 19 (2013) and 28 (2014). The manure was obtained from a local zebu cattle corral and applied without any pretreatment, while charcoal in the form of particles $\leq$2 cm size were obtained from a village selling large quantities of locally produced charcoal as fuel, predominantly produced from tamarind (*Tamarindus indica*) with traditional methods. In 2013 each treatment had four replications, and amendments were added to the soil in March and manually incorporated to 15 cm depth. In the 2014 season, each treatment was repeated seven times. Due to soil compaction at ca 15 cm depth observed after the first season's harvest, plots were prepared in December 2013 with the 10 cm topsoil layer removed, amendments incorporated to 20 cm depth and mixed with the topsoil. In both years, the southern half of each plot was covered with a shading structure of traditionally used reed thatch at 50 cm height, resulting in a split plot design.
Carrot and onion seeds were obtained at the regional capital of Toliara, where only carrots of the variety "Nantaise" and onions of the variety "Red Creole" are available, originating from seed suppliers in the 900 km distant capital Antananarivo. Each crop was sown in March each year in one half of each plot, resulting in 3 m^2 area per crop, of which 1.5 m^2 was under sun and 1.5 m^2 under shade. Sub-plot allotments to carrot and onion were rotated between years. Carrots were thinned to a distance of 20 cm between rows and 10 cm within rows, resulting in a planting density of 42 plants m^{-2}. Plots were irrigated manually every morning and every evening at the rate of 13.3 l m^{-2} day^{-1}, that is 400 mm per month. Soil water potential was thus kept below a level of 40 kPa throughout the cropping season as measured by WatchDog watermark soil moisture sensors (Spectrum Technologies, Plainfield, IL, USA) which were installed in four plots in June and July 2013 at a depth of 10-15 cm.

3.3.3 Measurements

In June and July 2013 temperature and relative air humidity sensors were installed in one carrot subplot under full sun and under shade. Harvest of carrot took place in July 2013 and August 2014, while onion was harvested in October 2013 and September 2014. At harvest, fresh biomass of carrots, onions and respective leaf biomass of each subplot were weighed and samples taken for dry matter determination. Harvested onion bulb numbers per sub-plot were recorded in both seasons due to poor plant stand, while in 2014 bulbs were also classified in size classes of $<$5 cm, 5-10 cm and $>$10 cm.
After the first season, composite soil samples were taken from each (shade-)subplot, as well as from an adjacent site which was not irrigated, and air dried for analysis of pH (KCl), C_{org}, N, P, K, CEC and conductivity (EC).

3.3.4 Seed germination trials

Following irregular and slow germination and plant establishment during the first season of the trial period, particularly in onion, we tested the factors seed origin, water quality and hydropriming on seed germination and vigor in two germination tests differing in substrate and temperature conditions (Table 3.1).

Table 3.1. Setup of germination trials with onion and carrot seed in south-western Madagascar.

	Factors	Substrate	Temperature range	Irrigation regime
Experiment I	Seed origin (SO) * water quality (WQ) (2 x 2)	Sand	22.1 – 40.1°C (field conditions under shade)	100 ml in the morning, 100 ml in the evening per pot of 50 seeds
Experiment II	Seed origin (SO) * water quality (WQ) * priming (2 x 2 x 2)	Paper towels	22.1 – 24.3°C (room temperature conditions)	Daily moisture adjustment with spraying can

Carrot seeds of the variety “Nantaise" and onion seeds of the variety “Red Créole" were obtained from a German seed supplier (seed lot “GE") as well as from the same local seed store as for the vegetable trial (seed lot “Tul"). The two different water types used for irrigation/moistening and priming were well water of the village Efoetsy (EC = 7.03 mS cm^{-1} and Na concentration of 118 ppm) used for irrigation of the vegetable trial and tap water of the city Toliara (EC = 0.68 mS cm^{-1}). Sand as germination substrate was obtained from the site of the vegetable trial plot and had a pH (KCl) of 8.3 and nutrient contents of Corg = 0.9%, N = 0.08%, P (Bray II) = 15.6 ppm, K = 0.014%, CEC = 5.1 meq 100 g^{-1} and conductivity of 0.49 mS cm^{-1}.

The first experiment was conducted at the site of the vegetable field trial in plastic containers of 12 cm diameter which were buried to the soil surface level and shaded. In each container 50 seeds were planted, with each treatment being replicated four times and all units arranged in a completely randomized design. Starting at the second day after sowing (DAS), germinated seeds with cotyledons appearing above the sand substrate were counted every day until 21 DAS.

The second experiment included the above treatments as well as hydro-priming of seeds, i.e. the submergence of seeds for a specific time in a solution before planting (Brocklehurst et al., 1984; Cantliffe and Elballa, 1994; Caseiro et al., 2004; Harris et al., 1999;

Tajbakhsh et al., 2004). To this end, seeds were submerged in tap water or saline water (see above) for 48 h and then dried for 6 h before the beginning of the trial. An onion seed lot from the nearby town Tanymeva (seed lot "TM") was included in the trial to broaden the scope of our study. One hundred seeds per replicate were placed on paper towels in plastic containers with a lid and moistened daily with tap or saline water. From the second DAS, germinated seeds with at least 0.5 cm radicule protrusion were counted every day until 21 DAS.

3.3.5 Data analysis

Manure, charcoal and shading effects on harvest parameters and soil characteristics over time were analyzed as a split plot design with the repeated measures procedure in SPSS 17.0 (IBM Corp., Armonk, NY, USA), with manure and charcoal as between-subjects effects and shading as within-subjects effect. Effect of irrigation between soil of control plots of the field trial and non-irrigated soil was tested with a t-test. Regarding germination trials, the percentage of germination at the end of the trials as well as the germination index (GI) were analyzed for treatment effects with ANOVA. The GI is an indicator of seed vigor and was calculated according to Gupta (1977) as

$$\text{GI} = \sum(n/d)$$

where n = number of seedlings emerging on day "d"
d = day after planting

A seed lot having greater germination index is considered to be more vigorous. Normality and homogeneity of variance were tested with Shapiro-Wilk and Levene tests for all data groups. Assumptions were not met in a few cases in carrot and onion harvest parameters, which was taken into account when interpreting parametric test results. The significance level for all analyses was set at α = 0.05.

3.3.6 Economic feasibility

To draw conclusions about the economic feasibility, returns to labor from carrot and onion cultivation were estimated assuming the following cost and price information (Table 3.2): Market prices of onions at local village markets ranged between 500 – 2000 MGA (Malagasy Ariary, 1 €= 3000 MGA) kg^{-1} depending on the season (personal observation). Carrots are currently not sold on village markets, while prices in Toliara vary between 800 – 1500 MGA kg^{-1}. Local costs of shading material (reed) amounted to about 500 MGA m^{-2}, and were included in the calculation of revenue as shading had a significant effect on yields. Fresh marketable yields obtained from field trials were normalized to a surface area of 10m^{2}, assuming that this is the surface area manageable by one person. For estimation of daily returns to labor, cropping period lengths of 150 days for carrots and 210 days for onions were assumed. Labor throughout the season, which has to be covered by revenue, thus includes preparation of the plot and shading structure, sowing and thinning, daily watering, occasional weeding and harvest, as well as storage in the case of maximum revenue.

Table 3.2. Calcution of total revenue of onion and carrot cultivation in south-western Madagascar, including deduction of costs for shading material, based on a 10 m^2 area.

		Carrot	Onion
Under sun	Minimum revenue	Yield (kg 10 m^{-2}) * 800	Yield (kg 10 m^{-2}) * 500
	Maximum revenue	Yield (kg 10 m^{-2}) * 1500	Yield (kg 10 m^{-2}) * 2000
Under shade	Minimum revenue	(Yield (kg 10 m^{-2}) * 800) - 5000	(Yield (kg 10 m^{-2}) * 500) - 5000
	Maximum revenue	(Yield (kg 10 m^{-2}) * 1500) - 5000	(Yield (kg 10 m^{-2}) * 2000) - 5000

3.4 Results

3.4.1 Treatment effects on yields

Average carrot yields ranged between 0.24 and 2.56 t DM ha^{-1} across treatments and seasons, with yields in the 2014 being substantially higher than in the first season. Manure and charcoal treatments did not have an effect on carrot yields nor root-shoot-ratio in both seasons (Figure 3.1, Table 3.3). Shading significantly affected carrot root yield and root-shoot-ratio, but with contrasting effects between years. There were no significant interactions between factors (data not shown). Onion yields ranged between 0.30 and 4.07 t DM ha^{-1} across treatments and seasons. In 2014 plant establishment and overall yield was substantially higher than in the first experimental year. Manure only had a significant effect on above ground biomass per plant in 2013 while other parameters were not affected by manure and charcoal application in either year (Figure 3.2, Table 3.4). Shade affected bulb yield in both years and above ground biomass yield and plant stand (total bulb numbers and number of bulbs in size classes) in 2014. Repartitioning of bulb numbers into size classes of $<$5 cm, 5-10 cm and $>$10 cm were 45%, 48% and 6% under sun, respectively, and 53%, 32% and 15% under shade, respectively. Across manure and

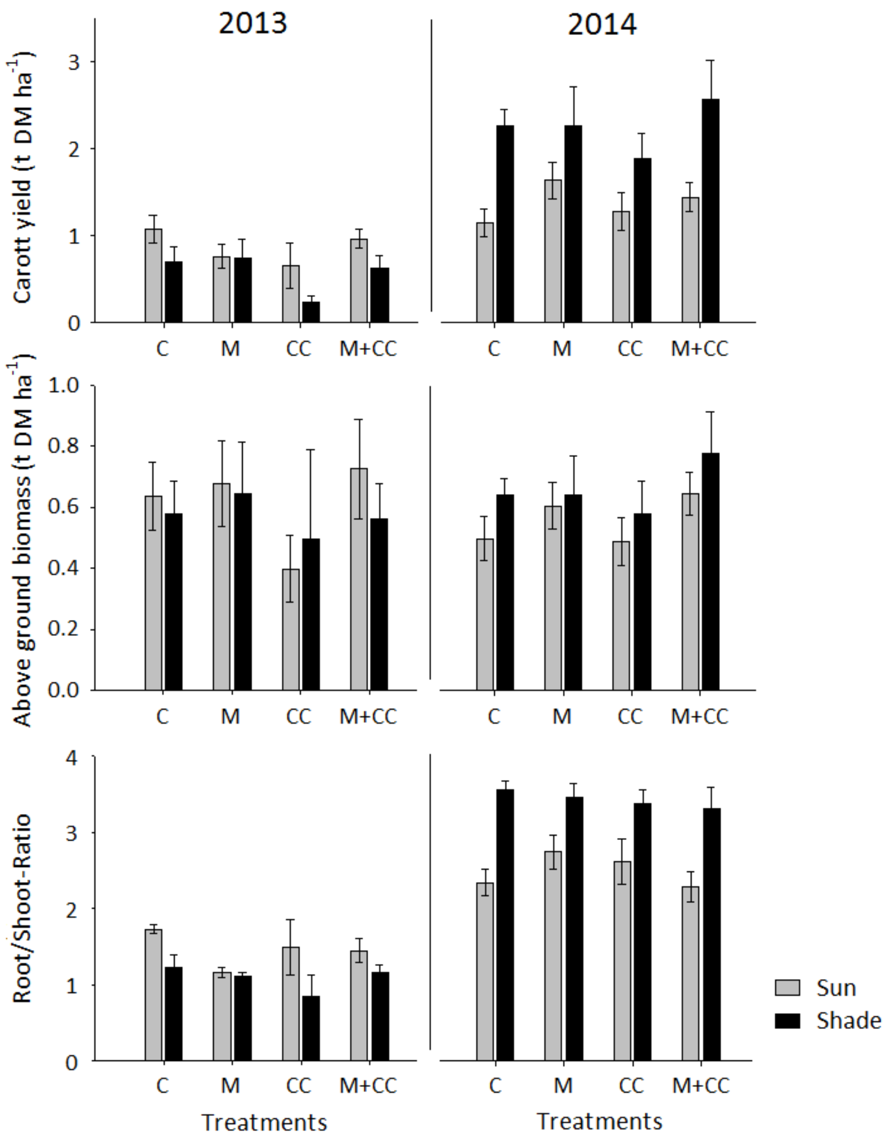

Figure 3.1. Carrot yield data of the 2013 and 2014 seasons in an irrigation experiment in south-western Madagascar. C = control, M = manure, CC = charcoal. Error bars represent ± one standard error of the mean (2013: n=4; 2014: n=7).

charcoal treatments, plant stands in 2013 under sun and shade only reached 8% and 12% of initial sowing density, respectively, whereas in 2014 they amounted to 5% and 20% under sun and shade, respectively. Temperature at the soil surface in June and July 2013 differed only slightly between shade and full sun sub-plots, with maxima of 43.4 and 43.9°C, minima of 9.4 and 9.6°C and averages of 21.5 and 21.0°C, respectively. Similarly, relative air humidity was comparable between shade and full sun sub-plots with maxima of 100% in both sub-plots, minima of 12.5 and 13.3% and averages of 76.1 and 79.9%, respectively.

Table 3.3. Probabilities of treatment effects on carrot root and above ground biomass yields as well as root-shoot ratios in an irrigation experiment in south-western Madagascar (2013: n=4; 2014: n=7; no significant interactions, data not shown).

Effects		2013			2014		
		Root yield	Above ground biomass	Root/ shoot ratio	Root yield	Above ground biomass	Root/ shoot ratio
Within-Subjects	Shade	0.003	0.601	0.004	<0.001	0.107	<0.001
Between-Subjects	Manure	0.484	0.403	0.512	0.104	0.073	0.670
	Charcoal	0.210	0.550	0.661	0.762	0.954	0.573

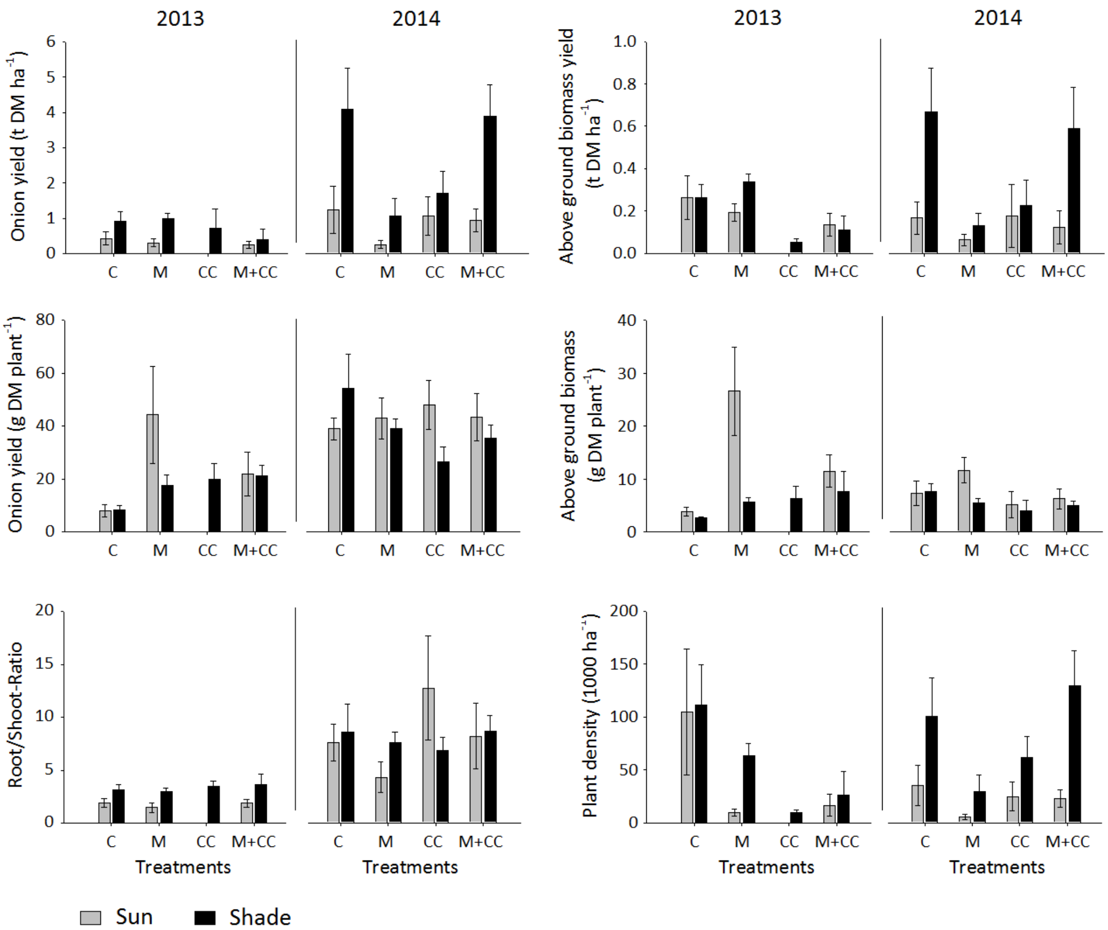

Figure 3.2. Onion yield data of the 2013 and 2014 seasons in an irrigation experiment in south-western Madagascar. C = control, M = manure, CC = charcoal. Error bars represent ± one standard error of the mean (2013: n=4; 2014: n=7).

Table 3.4. Probabilities of treatment effects on onion bulb and above ground biomass yields, number of bulbs per plot as well as root-shoot ratios in an irrigation experiment in south-western Madagascar (2013: n=4; 2014: n=7; no significant interactions in 2013, data not shown).

Effects		Bulb yield ha^{-1}	Bulb yield $plant^{-1}$	Above ground biomass yield ha^{-1}	Above ground biomass yield $plant^{-1}$	∑bulbs	<5 cm	5-10 cm	>10 cm	Root/ shoot ratio
2013										
Within-Subjects	Shade	0.013	0.447	0.447	0.217	0.556				0.076
Between-Subjects	Manure	0.941	0.056	0.978	0.025	0.064				0.422
	Charcoal	0.749	0.495	0.468	0.286	0.968				0.438
2014										
Within-Subjects	Shade	0.002	0.626	0.016	0.079	0.002	0.005	0.010	0.017	0.686
Between-Subjects	Manure	0.289	0.525	0.259	0.190	0.528	0.456	0.772	0.827	0.238
	Charcoal	0.601	0.281	0.680	0.011	0.231	0.309	0.253	0.586	0.146
	Manure * Charcoal	0.002	0.286	0.013	0.906	0.006	0.051	0.001	0.236	0.915

3.4.2 Treatment effects on soil properties

Soil pH, C, N, P and K concentrations and C/N ratio were significantly increased with manure application, while charcoal did not affect soil parameters (Table 3.5). Irrigation significantly increased soil pH, and decreased available P and CEC.

Table 3.5. Means of soil parameters and effects of manure, charcoal, shade and irrigation after the first season (2013, n=4) in an irrigation experiment in south-western Madagascar. Effect of irrigation was tested by comparing control plot values with values of soil immediately adjacent to the trial field (n=4).

Effects			pH(KCl)	C_{org} (%)	N (%)	C/N	P (ppm)	K (%)	CEC (méq $100g^{-1}$)	EC (mS cm^{-1})
Within-Subjects	Shade	no	8.78	1.37	0.111	11.97	12.34	0.015	5.12	0.69
		yes	8.79	1.27	0.104	11.99	13.37	0.017	5.28	0.58
		p	0.512	0.240	0.215	0.950	0.169	0.156	0.566	0.305
Between-Subjects	Manure	no	8.97	0.87	0.078	11.15	10.59	0.017	4.53	0.60
		yes	8.60	1.76	0.137	12.81	15.11	0.015	5.88	0.67
		p	<0.001	<0.001	<0.001	0.010	<0.001	0.221	0.57	0.433
	Charcoal	no	8.80	1.25	0.104	11.79	12.85	0.015	5.36	0.62
		yes	8.76	1.37	0.111	12.17	12.84	0.017	5.04	0.65
		p	0.363	0.336	0.415	0.490	0.979	0.407	0.634	0.705
Irrigation		no	8.30	0.94	0.082	11.80	15.63	0.014	5.12	0.49
		yes	9.01	0.78	0.070	11.11	9.99	0.016	4.30	0.58
		p	<0.001	0.379	0.261	0.571	<0.001	0.394	0.029	0.306

3.4.3 Germination trials

With the sand substrate under shade in field conditions, the water quality but not seed origin significantly affected germination rate as well as GI of carrot seeds. In onion the seed origin affected both total germination and GI while water quality only affected the GI (Figure 3.3, Table 3.6). Onion seeds from Toliara had extremely low germination rates. There was an interaction between seed origin and water quality, in that seeds from Toliara tended to be less affected by saline water than seeds from Germany.

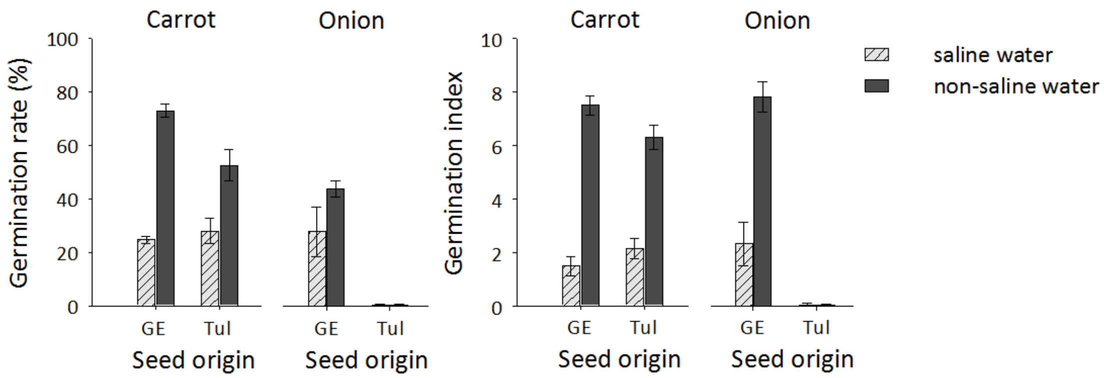

Figure 3.3. Germination rates and germination indices of carrot and onion seed lots treated with saline and non-saline water and germinated in sand substrate under shaded field conditions in an irrigation experiment in south-western Madagascar. GE = seed lot from Germany, Tul = seed lot from Toliara. Error bars represent ± one standard error of the mean (n=4).

Table 3.6. Probabilities of the effects of seed origin, water quality and interactions on germination rate and germination index of carrot and onion seed lots germinated in sand substrate under shaded field conditions in an irrigation experiment in south-western Madagascar (n = 4).

Factors	Carrot		Onion	
	Germination rate (%)	Germination index	Germination rate (%)	Germination Index
Seed Origin (SO)	0.201	0.499	<0.001	<0.001
Water quality (WQ)	<0.001	<0.001	0.173	<0.001
SO * WQ	0.009	0.036	0.173	<0.001

In the second germination experiment with seed priming, germination rate differed significantly between seed lots of different origin, in the order GE>Tul>TM (onions) and GE>Tul (carrots). The locally produced onion seed lot (TM) had an extremely low seed germination rate and index (Figures 3.4 and 3.5). While priming and non-saline water tended to accelerate germination at the beginning of the trial, they significantly reduced overall germination in most cases (Figure 3.4, Table 3.7). Germination indices differed

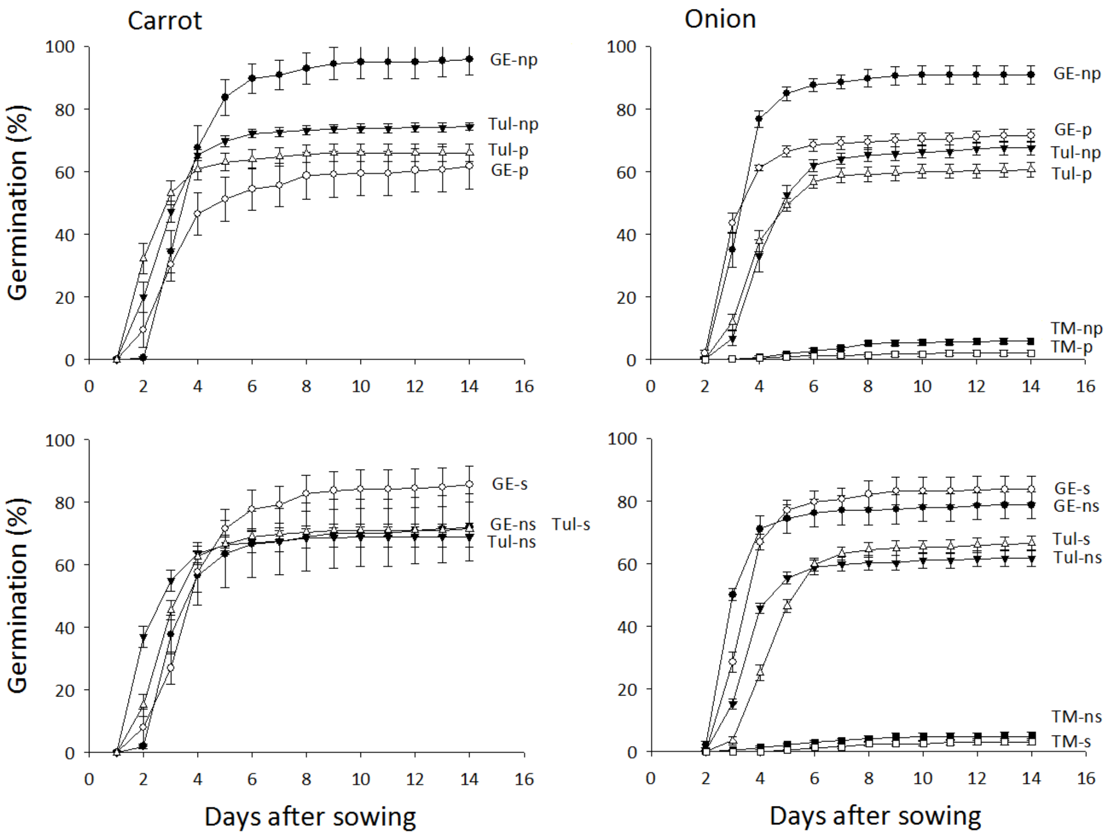

Figure 3.4. Cumulative germination of three carrot and onion seed lots grouped according to priming treatment and water treatment in a seed germination experiment in southwestern Madagascar. GE = seed lot from Germany, Tul = Seed lot from Toliara, TM = seed lot from Tanymeva, np = non-primed, p = primed, s = saline water, ns = non-saline water. Error bars represent ± one standard error of the mean (n= 8).

significantly between seed lots in the order GE>Tul>TM (onion) and Tul>GE (carrot). Seeds from Germany tended to be more negatively affected by priming with saline water than seed lots from Toliara, as there was a tendency for priming to enhance germination index in the Tul seed lots treated with saline water.

Germination rates and indices were higher in the second germination experiment compared to the first one across all treatments, presumably due to controlled conditions and a more favorable temperature range.

3.4.4 Economic feasibility

The total (fresh matter) yields of our field trials normalized to a surface area of $10m^2$ and depending on shading ranged between 4.8 and 10.5 kg for carrots and between 0.4 and 4.3 kg for onions (Table 3.8). Daily returns to labor attained at most 71 MGA for carrot cultivation under shade in 2014, and were even lower or negative for onion cultivation.

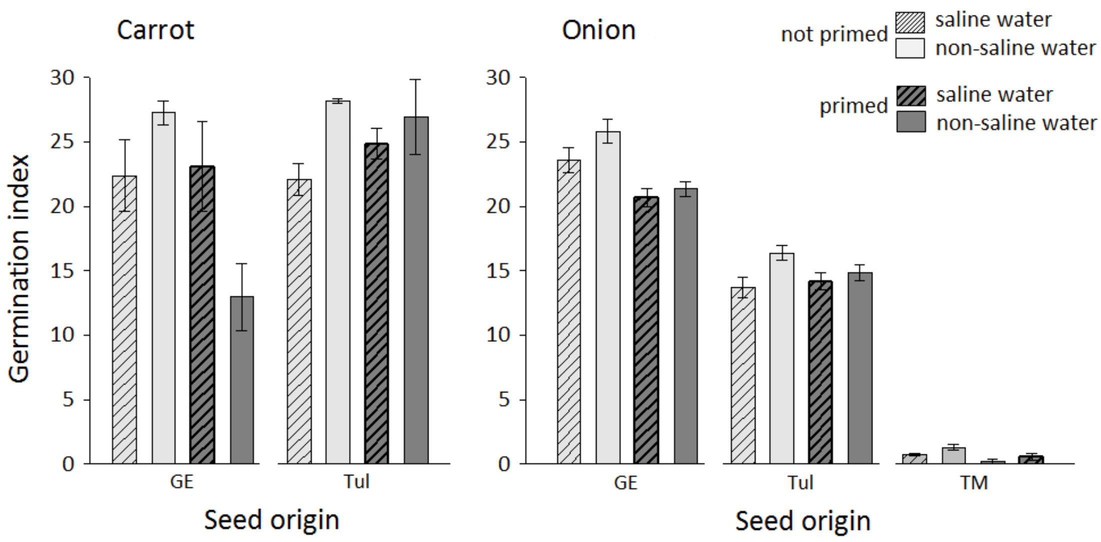

Figure 3.5. Germination indices of carrot and onion seeds with priming and water quality factors in a seed germination experiment in south-western Madagascar. GE = seed lot from Germany, Tul = seed lot from Toliara, TM = seed lot from Tanymeva. Error bars represent ± one standard error of the mean (n = 4).

Table 3.7. Probabilities of the effects of seed origin, priming, water quality and interactions on germination rate and germination index of carrot and onion seed in a seed germination experiment in south-western Madagascar (n = 4).

	Carrot		Onion	
Factors	Germination rate (%)	Germination index	Germination rate (%)	Germination index
Seed Origin (SO)	0.034	0.015	<0.001	<0.001
Priming	<0.001	0.064	<0.001	<0.001
Water quality (WQ)	0.045	0.640	0.067	0.002
SO * Priming	0.003	0.023	<0.001	0.001
SO * WQ	0.156	0.041	0.162	0.342
Priming * WQ	0.011	0.005	0.358	0.080
SO * Priming * WQ	0.076	0.090	0.590	0.563

3.5 Discussion

3.5.1 Effect of manure, charcoal and shading treatments

The applied manure rates and respective applied nutrient amounts were relatively high in our study, yet contrary to our hypothesis they did not significantly affect vegetable yields in any year.

Lacking manure effects may be explained by low manure quality (C:N ratios up to 28) and asynchrony between nutrient availability and uptake by plants, particularly since germination and growth rates of seedlings were very slow. Furthermore, since manure

Table 3.8. Returns to labor from carrot and onion cultivation in 2013 and 2014 based on a 10 m^2 area (after expenses for shade).

	Carrot					Onion				
	Yield (kg)	Min. revenue (MGA)		Max. revenue (MGA)		Yield (kg)	Min. revenue (MGA)		Max. revenue (MGA)	
		Total	Per day	Total	Per day		Total	Per day	Total	Per day
2013										
Under sun	6.9	5000	37	10312	69	0.4	183	1	733	3
Under shade	4.8	-1138	-41	2241	15	0.9	-4532	-45	-3129	-15
2014										
Under sun	6.3	5058	34	9483	63	1.4	690	3	2762	13
Under shade	10.5	3370	22	10693	71	4.3	-2869	-37	3524	17

is stored in village corrals for many years, remaining organic matter may be in stable form which may further decrease decomposition rates and availability of nutrients.

Reports of charcoal effects on yields are very variable, and addition to Calcarosols has been shown to have much lower or even negative effects compared to those on acid soils, partly due to the pH increasing effect of charcoal (Van Zwieten et al., 2010; Verheijen et al., 2010). Also charcoal effects on yield may need time to develop (Glaser et al., 2002a; Major et al., 2010). Lacking charcoal effects on yields are in line with recent results from Oman where activated charcoal added to manure did not increase yields of maize or radish (Ingold et al., 2015). According to a study by Andriamparany et al. (2013), charcoal trial plots at our trial field treated with a rate of 5 t ha^{-1} had a decreased feeding activity of soil fauna compared to plots without charcoal amendments, indicating that organic matter decomposition and hence nutrient availability were lowered. On the other hand, in a pot experiment (Jordan et al., 2011) found charcoal mixed with compost to increase yields of radish (*Raphanus sativus* L.) and root-shoot ratios compared with sole compost or mineral fertilizer.

Yields of fresh carrots were reported to average 21 t ha^{-1} worldwide and 8-12 t ha^{-1} in Africa (Grubben and Denton, 2004). At dry matter contents of 11% (Grubben and Denton, 2004) to 20% (our study), obtained yields from our study are in the order of African average yields and largely reflect low germination rates and final stand densities. In Oman carrot yields were found to be between 0.7 – 1.5 t DM ha^{-1} with substantially lower N and K amendment rates than in our study and comparable soil N and K concentrations (Siegfried et al., 2013). Soil P and P amendment rates with manure in our study were, however, relatively low compared to values reported from Oman. Yield differences between the two seasons may be partly due to less soil compaction in the second season, as carrots in the first season were observed to be slightly stunted presumably due to soil compaction below 15 cm depth.

Shading was beneficial for seed germination leading to higher seedling stands and yields obtained in onion under shade in both seasons (Figure 3.2). However, for carrot in 2013, yields of shaded plots may have been hampered by delayed germination and comparatively enhanced plant growth in full sun later in the season. Average daily solar radiation as measured by a nearby weather station amounted to 250 W m^{-2} in March and declined to 170 W m^{-2} in July of both years, whereas average daily air temperatures declined from 27 to 20°C in these months. Consequently, temperatures on the soil surface under shade and in full sun in 2013 were comparable due to the shading effect of carrot shoot growth, which was unaffected by shading (Figure 3.1). However, the different effects of shading on root yield and root-shoot ratio of carrots between years remains to be explained and the benefit of shading for vegetable cropping in the study zone will thus have to be further investigated by comparing several management options throughout the season, particularly sowing dates and the timing of shading within the crop growth cycle.

Under the management system applied in our study, that is the currently practiced manual watering twice daily and daily use of ox carts to haul water from the local well, the return to labor is too low for commercial production of carrot and onion vegetables, considering that salaries of wage labor in the region are commonly about 1000-2000 MGA per day (SuLaMa, 2011). On the other hand, opportunity costs for women in the dry season may be relatively low, and vegetable production may still be a viable activity for household consumption. At a small scale, labor requirements may also be greatly reduced if household waste water is used for watering.

3.5.2 Salinity

Salinity slows down germination rate, growth and maturity rate in many vegetable species, including onions and carrots (Benincasa et al., 2013; Shannon and Grieve, 1998). There are, however, major differences between species, cultivars and stages in a crop's cycle regarding tolerance to salinity. In onions tolerance to salinity is reported to be high at the germination stage, but very low during seedling growth (Shannon and Grieve, 1998), and Pasternak et al. (1984) found seedlings to be most sensitive to salinity at the emergence state. Bagayoko (2012) reported complete germination inhibition of onion var. Red Créole seeds at soil salinity levels of 16 mS cm^{-1}. On the other hand, Wannamaker and Pike (1987) reported onion germination to not be affected by salinity levels up to 20 mS cm^{-1} across five cultivars. Similarly, we found saline water to reduce speed of germination in onion in the first DAS resulting in significantly lower germination indices, but final germination percentage was not affected. Salinity has been found to decrease onion yields by up to 72% after irrigation with brackish water (EC = 4.4

mS cm^{-1}) in Israel, while yield reduction was completely prevented if plants were germinated and irrigated with fresh water for the first 45 days after planting (Pasternak et al., 1984). Similarly, Al-Harbi et al. (2002) tested the yield response to saline irrigation of ten onion cultivars grown in Saudi Arabia, including Red Créole. Water with a salinity level of 8 mS cm^{-1} reduced yields by 70-80% with no differences between cultivars and reduced bulb sizes by 50%. Chauhan et al. (2007) also found onion yield declines of 67% at salinity levels of 8 mS cm^{-1}.

Carrot yield reduction due to salinity has been estimated at 14% for every unit increase in salinity of 1 mS cm^{-1} (Shannon and Grieve, 1998), while De Pascale and Barbieri (2000) reported carrot yield decreases of 28% per unit increase in soil salinity. The drastic yield reducing effect of saline water thus presents a major drawback in onion and carrot cultivation in our study zone, especially for commercial purposes.

Continuous irrigation with saline water may be problematic in the long term due to build-up of soil salinity. In our study salinity was increased after one cropping season, though not significantly (Table 3.4). Soil pH was also increased, presumably due to the input of ions with the irrigation water, which may be partly responsible for decreased P availability. However, the sandy nature of the soils in the research zone and the typical occurrence of several intense rainfall events during the rainy season may allow that salts accumulated in the dry season cropping period are effectively drained during the following rainy season. Soil salinity should thus be monitored if continuous irrigated cultivation is promoted. Generally, soils salinity levels in our study area were found to be very low compared to those found in semi-arid areas prone to salinity, such as in Oman (5 up to 45 mS cm^{-1} Al-Busaidi et al., 2014) and Mali (1.6 – 1.9 mS cm^{-1} Bagayoko, 2012).

3.5.3 Priming effects

Poor crop stand in vegetable cultivation has been previously reported for many regions (Arin et al., 2011; Cantliffe and Elballa, 1994; Miyamoto et al., 1985; Schmidhalter and Oertli, 1991). Through seed priming and use of non- saline water, germination speed at the beginning of planting could be enhanced, but to the detriment of overall germination rate. The value of priming treatment is thus questionable in this context.

Caseiro et al. (2004) found that hydro-priming improved germination speed in six different onion seed lots, while less vigorous seeds did not respond well to priming. On the other hand, Brocklehurst and Dearman (1983) found that seed lots with slowest emergence responded most to priming in polyethylene glycol solution. We similarly found that the less vigorous seed lots of carrot and onion (Tul) responded better to priming than the more vigorous seed lot (GE). There may be potential to test different priming parameters such as length of the priming and drying period and different priming solutions. Cantliffe and Elballa (1994) reported that 96 h of hydro-priming accelerated carrot germination speed more than a 48 h imbibition. These authors concluded that high quality seed responds more positively to priming than low quality seed. Farmers in our study area may be able to use rainwater as priming solution before irrigating with saline water. Use of solutions with controlled osmotic potential or addition of plant hormones, which are sometimes successfully used in priming studies (Arin et al., 2011; Cantliffe and Elballa, 1994; Pereira et al., 2008) is, however, not a viable option for local farmers in south-western Madagascar.

3.5.4 Quality of seeds and variety and species considerations

Currently, farmers of the Mahafaly Plateau have virtually no access to certified vegetable seeds. Certification for vegetable seeds is not mandatory in Madagascar, and in 2002 only one seed company in Madagascar was reported to produce exportable vegetable (Randrianatsimbazafy, 2012).

Our results suggest that the quality of the seed lot is the most important factor constraining the overall low germination rate of onions observed in the field. The quasi-zero and relatively low germination of the seed lot from Toliara in the first and second germination trial, respectively, as well as very sparse onion plant stands in both seasons seem alarming.

Generally, onion seed is known to deteriorate quickly in tropical conditions if not sufficiently sealed (Grubben and Denton, 2004). The quality of seed lots originating from the capital may thus be decreasing during transport and storage or be inherently low, which needs to be further investigated. Furthermore, it can be questioned whether the varieties of introduced vegetable species available to farmers in south-western Madagascar are best adapted to the environmental conditions of that region, as they are produced in the capital Antananarivo where climate is considerably cooler and farmers have more access to inputs. Regarding carrot, the cultivar “Nantes" (Nantaise) is considered a temperate zone type while cultivars adapted to subtropical conditions such as “Kuroda" and “Tropical Nantes" may be preferable for cultivation in south-western Madagascar (Rubatzky et al., 1999). Al-Harbi et al. (2002) tested ten onion cultivars grown in Saudi Arabia, including Red Créole, and found that this cultivar had medium yields compared to the other tested varieties, indicating that it is suitable for semi-arid conditions. While we found onion seeds that are locally produced in a village of the South-West to be of even lower vigor than store-bought seeds, training of farmers for on-farm multiplication of (open pollinated) seeds that are adapted to the local agro-ecological conditions may be the best option to overcome problems of seed quality. An alternative may be the purchase of imported seeds of controlled quality such as practiced widely in urban agriculture throughout Africa.

A survey conducted during the time of the vegetable trials indicated that local farmers were most interested in leafy vegetables, notably *kimalao* (*Acmella oleracea* L.) and brassicaceae, followed by tomato, carrot and onion (Hänke and Barkmann, 2012). Brassicaceae are considered moderately salt sensitive with relatively higher salt tolerance levels and lower yield decline compared to onion and carrot, depending on the variety (Shannon and Grieve, 1998), but management practices to cope with regularly observed damage by pests in brassicaceae will need to be identified and tested.

3.6 Conclusions

In our study manure and charcoal did not enhance vegetable yields, while shading had positive effects on carrot yields in 2014 and on onion yields in both years. Shading may thus be a viable practice to increase yields. However, considering obtained marketable yields, market prices, and costs for shading material, returns to labor are often negative and too low for cultivation of onions or carrots to be economically feasible. The main constraints to vegetable production in the study area of south-western Madagascar are the quality of commercially available seed and salinity of irrigation water. Monitoring of seed quality when promoting vegetable production in the study area, as well as identification and testing of vegetable species tolerant to salinity are thus necessary to improve feasibility of vegetable cultivation in the study area.

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4. Dewfall and its ecological significance in semi-arid coastal south-western Madagascar

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4.1 Abstract

Dew deposition is an ecologically important phenomenon in many coastal drylands, but its measurement remains difficult. We report on the construction and field-testing of a sturdy device to digitally determine dew deposition during night and early morning hours. Balance readings were compared with dew deposition measurements taken by alternative methods: a plastic sheet of 2*3 m^2 laid out on sandy ground, a plastic sheet of 1*2 m^2 laid out at 1 m height on a wooden surface, and a plastic sheet of 1*2 m^2 laid out at 1 m height on a metallic surface. Daily dew deposition rates on our device ranged from 0.055 to 0.192 mm between months with maxima reaching 0.479 mm. Dewfall amounted to 58.4 mm and represented 19% of annual rainfall after the whole observation period of 18 months. Correlation coefficients between the different measuring methods amounted to $r = 0.71$ (balance – plastic sheet on the ground), $r = 0.84$ (balance – 1 m high plastic sheet on wooden surface), $r = 0.82$ (balance – 1m high plastic sheet on metal surface) and $r = 0.99$ (1 m high plastic sheet on wooden surface - 1m high plastic sheet on metal surface). Our results suggest that in coastal south-western Madagascar dewfall may play a role in the annual water balance even if its ecological significance remains to be investigated.

Key words: Automated dew recording; Dew formation; Total precipitation in drylands

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4.2 Introduction

In many coastal drylands dew and fog formation is a recurrent meteorological phenomenon with sometimes important ecological implications. Perhaps most well known are the ancient fog harvesting systems of the Atacama desert in Chile and Peru of which water has been used for irrigation of field crops (Fessehaye et al., 2014), and natural dew collection in desert ecosystems in the Negev of Israel (Kidron et al., 2002). Similarly impressive are the Indian Summer Monsoon-dependent *Anogeissus dhofarica* (Combretaceae) forests in Dhofar province of southern Oman and Yemen (El-Sheikh, 2013; Hildebrandt and Eltahir, 2006; Kürschner et al., 2004). Dew may also play a role in maintaining plant water status through foliar uptake of moisture, which has been documented for several species in arid and humid environments (Goldsmith et al., 2013; Munné-Bosch and Alegre, 1999), as well as in the reduction of transpiration rates in early morning hours (Ben-Asher et al., 2010; Raman et al., 1973; Richards, 2004). However, the significance of these mechanisms relative to water uptake in roots are controversial, especially for crop plants (Goldsmith et al., 2013). The quantification of dew deposition amount and duration is often of concern for plant disease management (Jacobs et al., 1994; Pedro and Gillespie, 1981; Raman et al., 1973) or for estimating potential dew water harvesting yields (Beysens et al., 2007; Clus et al., 2008; Muselli et al., 2009; Sharan et al., 2007).

Little is known about the contribution of dew in the water balance of the Mahafaly Plateau region in south-western Madagascar dominated by a spiny dry forest of *Didierea madagascariensis*, *Alluaudia* spp., *Euphorbia* spp. and *Adansonia* spp. Several accounts in the literature ascribe an important role to dew deposition for natural vegetation (Battistini, 1964; Guyot, 2002), off-season crops (Hoerner, 1977) as well as traditional dew harvesting techniques in the dry season (Besairie, 1954; Le Thomas, 1946). Hoerner (1977) estimated annual dew formation in this area to be less than 30 mm year^{-1} which would amount to 10 % of average rainfall. However, solid data on dewfall for semi-arid areas are scarce and virtually missing for south-western Madagascar as measuring dewfall on plant and soil surfaces remains a technical challenge. There is no standard, internationally accepted method or instrument for its recording (Zangvil, 1996), while existing dew measuring devices present many drawbacks (Agam and Berliner, 2006; Zhang et al., 2011). Applied methods include optical approaches (Duvdevani, 1947), paper and cloth drosometers (Agam and Berliner, 2006; Kabela et al., 2009; Kidron, 1988), microlysimeters (Heusinkveld et al., 2006; Jacobs et al., 2000; Uclés et al., 2013), soil or air moisture sensors (Bunnenberg and Kuhn, 1980; Moro et al., 2007; Schmitz and Grant, 2009), leaf wetness sensors (Cosh et al., 2009; Kabela et al., 2009), balances that continuously weigh dew on artificial condensation plates (Beysens et al., 2005; Noffsinger, 1965; Zangvil, 1996), remote sensing with microwave radiometers (Jackson and

Moy, 1999) as well as the use of local meteorological data (Jacobs et al., 2002; Malek et al., 1999; Pedro and Gillespie, 1981). Most of these methods are either expensive, limited in their recording time and intervals, difficult to handle or the devices are prone to corrosion if used near to the sea. Furthermore, most devices use artificial materials as condensation surfaces, hence not necessarily measure dew accumulation in natural surroundings (Agam and Berliner, 2006; Zhang et al., 2011). Often records need to be digitized manually after data collection which is a time-consuming and error-prone operation.

The purposes of our study were to (i) design, field-test and calibrate a simple digital balance device that allows the direct long-term recording of dew deposition on an artificial condensation surface, (ii) assess its relative importance in comparison with rainfall throughout the year and in comparison with other regions, and (iii) determine the relationship between obtained dew measurements and local weather station data.

4.3 Materials and Methods

4.3.1 Study area

Measurements were conducted in the coastal village of Efoetsy, south-western Madagascar (43.70° E, 24.08° S, 10 m asl) about 2 km inland from the sea and at Andremba (44.21° E, 23.97° S, 260 m asl) about 60 km from the sea. The climate is semi-arid with a rainy season from December to April and a dry season from May to November. Annual rainfall averages 360 mm in the littoral and varies between 200 and 500 mm, while on the Plateau average annual rainfall reaches 660 mm (500 – 800 mm)(CNA, 2014). Potential evaporation has been estimated at 1200 mm in the littoral and 1700 mm on the Plateau (Sourdat, 1969), and monthly average temperatures range from 20°C in July to 29°C in January, with an annual mean of 24°C and slight differences between sites depending on the season. Soils are predominantly sandy and calcareous (Efoetsy) to loamy and ferralitic (Andremba) with a very low water holding capacity and measurement sites were covered with sparse grass vegetation.

4.3.2 Dew measurements

Dew was measured between April 2013 and September 2014 (Efoetsy) and April 2013 to August 2013 (Andremba). The basic measurement unit was a digital balance with an accuracy of ± 0.01g and a repeatability of 0.03g. (PCE-BT2000, PCE Instruments, Meschede, Germany). The balance was connected to a freely programmable data logger (P25911 and C20511, Avisaro AG, Hannover, Germany) that allowed to invoke a sleep-mode to reduce power-consumption and time-dependent measuring-cycles, that

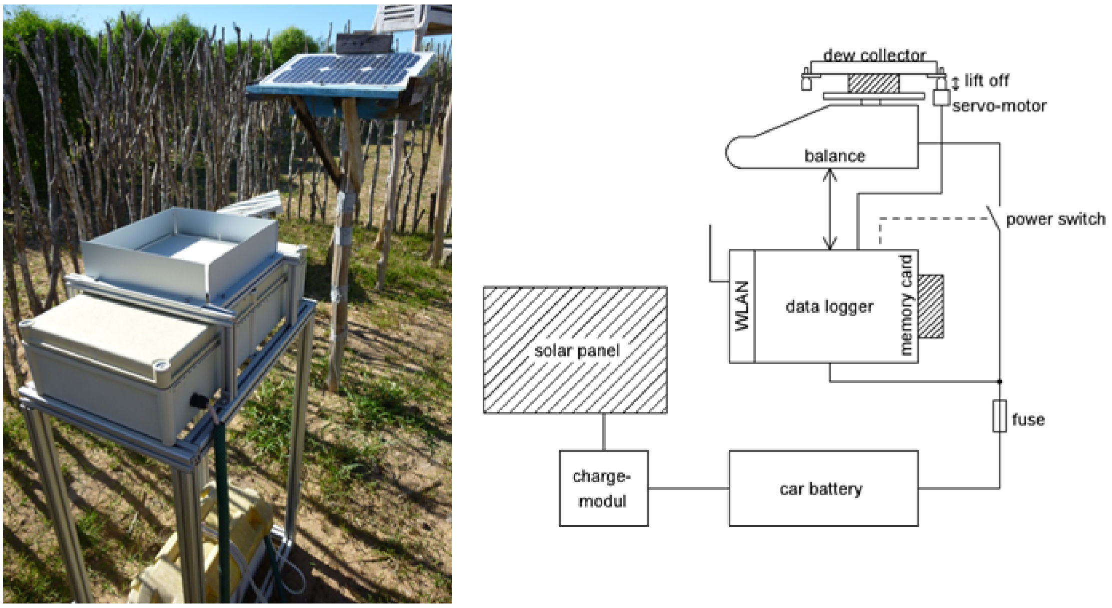

Figure 4.1. Setup of the dew balance in the village Efoetsy in south-western Madagascar. The weather station is 10 m to the left of the dew balance, the next trees are >50 m away.

were initiated every 30 minutes from 7 pm to 7 am. To estimate dew duration, the measurement cycle was extended until 12:00 pm between April and September 2014. Each cycle started with lifting up the 224 x 224 mm^2 aluminum dew collection platform by a few millimeters above the contact area to the balance by a servo-motor and switching on the balance to allow the balance to auto-calibrate the zero-point. After successful zero-calibration, the platform was lowered to settle horizontally on the balance contact area for weight measurements. The dew collection platform was laterally protected by a wind-screen which ended 50 mm above the platform to enable weight readings that are undisturbed by wind (Figure 4.1). A custom-made software allowed to limit weight readings to stable measurements that were unaffected by wind. The data logger had a built-in WiFi system that allowed to read out the data to a laptop within 250 m distance. The entire system was powered by a 12 V 60 Ah car battery continuously charged by a 60 W solar panel and mounted at 1 m above ground (Figure 4.1).

4.3.3 Dew balance evaluation

The readings of the dew balance situated in the littoral village were compared during a total of 48 nights in July/August 2013 and April/May 2014 to measurements taken by several alternative methods within 10 m of the installed balance: a plastic sheet of 2 m * 3 m laid out on the sandy ground on top of a plastic tarp to account for bare soil conditions, a plastic sheet of 1 m * 2 m laid out at 1 m height on a wooden surface, and a plastic sheet of 1 m x 2 m laid out at 1 m height on a metal surface to account for the specific heat radiation characteristics of the metallic balance plate. The transparent plastic sheets where installed at sunset and weighed every morning at 6:30 am with a digital balance with a precision of ± 5 g. Weight measurements of all methods were converted to mm dewfall and compared to device records by regression. Paired sample t-tests were used to identify significant differences of dew amounts between methods. These methods are more labor-intensive but realizable with local material and cheaper compared to the tested dew balance, and regression allows to compare and convert values between methods if these are employed in different locations. Polyethylene plastic is also considered a suitable material for dewfall collection due to its favorable hydrophilic properties (Maestre-Valero et al., 2011; Zhang et al., 2011). The larger sizes of condensation surfaces for alternative methods were chosen to account for expected higher error margins compared to more precise dew balance measurements.

4.3.4 Relationship between dew and weather data

Air temperature and humidity, wind speed and rainfall were recorded at 30 min intervals throughout the research period using a Hobo Weather Station (Onset Computer Co., Bourne, MA, USA) installed nearby the dew balance in Efoetsy. Weather data determining dew occurrence were determined by comparing nights with and without dewfall (<0.01 mm) and testing for significant differences with a non-parametric Mann-Whitney U test.

Weather data was used to fit a linear regression model for dew deposition rates at 30 min and 1 h time steps as well as to model daily maximum accumulated dew with daily averaged weather data. Included in the latter regression analysis were the mean and average differences between air and dew point temperature (T_{air}-T_{dp}), the drop in temperature during the night determined by the difference between maximum and minimum air temperature (T_{max}-T_{min}), mean and maximum wind speed and mean relative humidity.

4.4 Results and Discussion

4.4.1 Measured dew quantities and relation to the water balance

Monthly averages of measured dew per night during the months of observation ranged from 0.055 to 0.192 mm at Efoetsy and 0.086 to 0.113 mm at Andremba, with maxima reaching 0.479 mm at Efoetsy, and the frequency of dew deposition ranged from 42% of nights in February 2014 to 93% of nights in September 2013 (Table 4.1). At the coastal site total dew was 18.9 mm and thus higher than at the inland site (15.3 mm) during the same observation period of five months (April to August 2013). This resulted from a combination of more dew nights per month (71% *versus* 66% of observation days) and higher dew deposition per dew night (0.176 mm *versus* 0.154 mm), which may be partly explained by higher relative air humidity (82% - 93% *versus* 57% - 75% monthly averages).

Table 4.1. Dew measurements at Efoetsy (coastal area) and Andremba (Plateau) in south-western Madagascar from April 2013 to September 2014 at 6:30 am. n = number of observation days, Mean1 = average daily dew amount per month (all observation days), % dn = percentage of nights with dewfall (>0.01 mm) from total observation nights, Mean2 = average daily dew amount per month (only dew nights), Max = maximum daily dew amount per month.

	Efoetsy					Andremba				
	n	Mean1 (mm)	%dn	Mean2 (mm)	Max (mm)	n	Mean1 (mm)	%dn	Mean2 (mm)	Max (mm)
Apr	28	0.106	68	0.153	0.357	18	0.086	61	0.140	0.300
May	30	0.167	70	0.236	0.479	30	0.112	63	0.164	0.311
Jun	30	0.134	77	0.175	0.345	9	0.111	67	0.168	0.287
Jul	31	0.117	77	0.150	0.354	27	0.089	70	0.129	0.267
Aug	28	0.115	63	0.170	0.330	9	0.113	67	0.169	0.308
Mean[a]		**0.128**	**71**	**0.176**	**0.373**		**0.100**	**66**	**0.154**	**0.294**
Sept	30	0.192	93	0.205	0.395					
Oct	31	0.061	52	0.111	0.260					
Nov	30	0.081	53	0.147	0.443					
Dec	31	0.055	52	0.104	0.180					
Jan	12	0.095	19	0.144	0.224					
Feb	12	0.077	18	0.177	0.230					
Mar	31	0.078	71	0.111	0.201					
Apr	27	0.110	67	0.164	0.275					
May	29	0.158	79	0.200	0.336					
Jun	30	0.164	83	0.197	0.356					
Jul	31	0.132	71	0.185	0.324					
Aug	31	0.098	55	0.175	0.324					
Sept	28	0.130	71	0.182	0.310					
Mean[b]		**0.117**	**63**	**0.160**	**0.318**					

[a] a of the observation period April – August 2013 for comparison between sites.
[b] of the whole observation period in Efoetsy

Kidron and Temina (2013) found dewfall to increase between three sites in the Negev desert on a gradient with increasing altitude by 720 m, despite increasing distance from the sea, which they explain by decreasing average air temperatures by up to 6°C with altitude. In our study altitudes between sites differed by 250 m. While monthly mean air temperatures in April 2013 were lower by 5°C in the inland site, these differences were with 1°C less pronounced in the other months. Distance from the sea is thus presumably

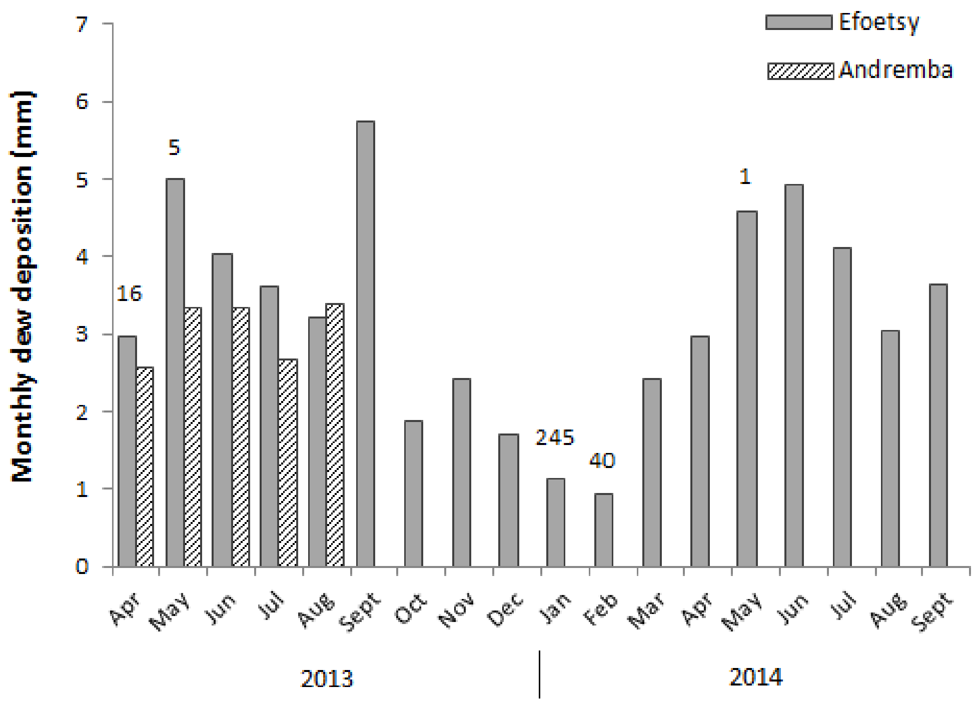

Figure 4.2. Monthly dew amounts during the observation period (2013-2014) at the sites Efoetsy (coastal) and Andremba (inland) and monthly rainfall at Efoetsy (above bars) in the study area of south-western Madagascar.

the dominating factor explaining lower relative humidity in the inland site and resulting lower dewfall amounts in our study. Dewfall was substantially lower in rainy season months compared with dry season months (Table 4.1, Figure 4.2).

During a few nights with high relative humidity and dew deposition the balance recorded erroneous data, especially at the site of Andremba, presumably due to too much obstruction of mechanical parts from dust and remaining moisture from dew which distorted weight readings. These readings could be easily identified and excluded from the measurement series. Monthly and daily dew amounts are in line with or higher than observations in the Israeli desert (Heusinkveld, 2008; Jacobs et al., 2000; Zangvil, 1996), and daily maximum values correspond to those observed in some parts of eastern India (0.45 mm, Raman et al., 1973), coastal south-western Morocco (0.50 mm, Lekouch et al., 2012) and at the Croatian Adriatic coast (0.60 mm, Muselli et al., 2009). Maximum dew amounts that can be physically expected are in the order of 0.8 mm per night (Muselli et al., 2009; Sharan et al., 2007), and dew amounts observed in crop canopies have been found to reach 0.8 mm in Iowa, USA (Kabela et al., 2009). Recorded dew represented 90% and 41% of total rainfall during the 2013 dry season observation period in the littoral and inland site, respectively (Table 4.1), while total dew amounts reached 58.4 mm corresponding to 19% of total rainfall over the whole observation period at the littoral site.

Ecologically, dew duration may play a more important role for plants than actual dew amounts (Munné-Bosch and Alegre, 1999; Sharma, 1976). We found that, across 140 observation nights during the dry season, dewfall started soon after sunset, continued until 7 am and all dew had evaporated before 10 am (Figure 4.3). Rare negative values after 10 am may be attributed to the intense heating of the metal collection plate by the sun leading to distorted weight measurements. Average dew duration of 15 h is much higher than observed by Zangvil (1996) in Israel (5-10 h night^{-1}) but comparable to estimated and observed values by Pedro and Gillespie (1981), Malek et al. (1999) and Kabela et al. (2009) in crop fields in northern American sites.

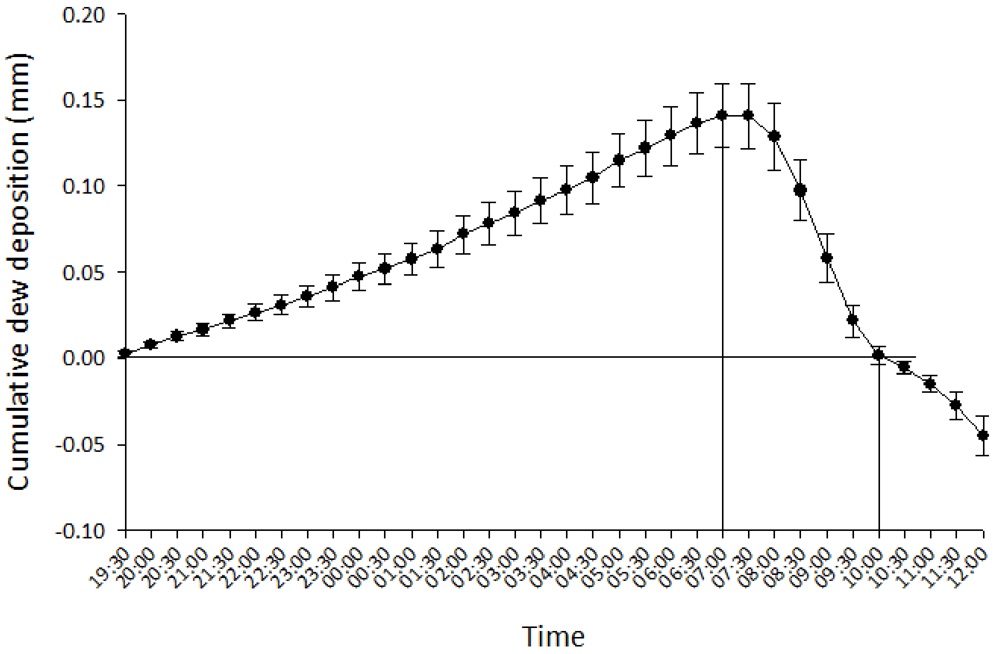

Figure 4.3. Dew accumulation and evaporation during the night and morning hours (n=140) in the study area of south-western Madagascar. Error bars represent 95% confidence intervals. Reference lines indicate that mean dew formation continues until 7:00 am and dew is evaporated by 10:00 am.

It has been suggested elsewhere that dew may play a crucial role in wild and crop plants' water balance and in overcoming periods of drought (Goldsmith et al., 2013; Malek et al., 1999; Munné-Bosch and Alegre, 1999; Went and Babu, 1978). While dew is unlikely to affect soil moisture reserves given its quick evaporation after sunrise, it may reduce transpiration during the night and thereby conserve soil water (Richards, 2004; Uclés et al., 2013), as well as enable higher photosynthesis rates in early morning hours due to increased plant water status from dew absorption through the leaves (Grammatikopoulos and Manetas, 1994; Munné-Bosch and Alegre, 1999; Munné-Bosch et al., 1999). A study in Israel showed that annual variability of dewfall was lower than of rainfall suggesting that even small amounts of dew may be a relatively reliable water source for micro-organisms such as lichen (Zangvil, 1996).

4.4.2 Relation of dew measurements and weather data

At Efoetsy nights with dewfall were characterized by significantly lower mean temperatures, higher relative humidity, higher dew point temperature, lower mean differences between air and dew point temperature (T_{air}-T_{dp}) and lower wind speed than nights without dewfall (Table 4.2). These tendencies were similar at Andremba, but not as pronounced due to a lower number of observation nights only covering dry season months (Table 4.3). In nights with highest dew deposition, mean T corresponded to mean dew point T and mean relative humidity reached 100% (Figure 4.4). The high relative humidity even in nights without detected dewfall which continued to increase through the night may be due to the generally high supply of moisture from the sea, even under low wind speed conditions.

Maximum wind speed during dew nights in Efoetsy reached 5.7 m s^{-1}, which is the same upper limit for dew formation as found by Lekouch et al. (2012) in Morocco, and similar to values obtained by Nilsson (1996) and Muselli et al. (2009). The upper limit of wind speed in our observations can be expected to be overestimated as the dew collection surface was slightly protected from the wind, according to findings by Clus et al. (2008) and Lekouch et al. (2012), which found dewfall to be higher at sites protected by wind.

Table 4.2. Weather data statistics of nights with and without dewfall and p-values of t-tests in Efoetsy, south-western Madagascar.

		Dew nights (n=343, wind speed n=192)	Nights without dew (n=56, wind speed n=32)	P-value
Mean T (°C)	Min	12.9	16.3	
	Max	27.4	26.4	
	Mean	19.4	20.7	0.001
Mean RH (%)	Min	55.5	56.8	
	Max	100.0	100.0	
	Mean	98.3	87.0	<0.001
Mean DP (°C)	Min	12.6	10.7	
	Max	27.3	26.4	
	Mean	19.1	18.5	0.258
Maximum T_{air}-T_{dp} (°C)	Min	0.12	0.14	
	Max	13.5	18.9	
	Mean	1.4	6.4	<0.001
Maximum Wind speed (m s^{-1})	Min	0	0.76	
	Max	5.7	4.6	
	Mean	1.9	3.1	<0.001

Table 4.3. Weather data statistics of nights with and without dewfall and p-values of t-tests in Andremba, south-western Madagascar.

		Dew nights (n=34)	Nights without dew (n=15)	P-value
Mean T (°C)	Min	10.7	13.2	
	Max	19.2	19.6	
	Mean	15.5	15.9	0.378
Mean RH (%)	Min	71.9	58.4	
	Max	100.0	97.5	
	Mean	89.1	76.5	<0.001
Mean DP (°C)	Min	8.5	6.0	
	Max	17.4	16.3	
	Mean	13.2	11.5	0.027
Maximum T_{air}-T_{dp} (°C)	Min	2.22	4.1	
	Max	15.3	17.4	
	Mean	8.3	8.8	0.599

In regression analysis the best fitting linear model for daily accumulated dew was obtained with mean wind speed, maximum T_{air}-T_{dp} values and air temperature drop (T_{max}-T_{min}) as predictors (Table 4.4). While the model only explains 46% of observed dew data variation, it corroborates findings that T_{air}-T_{dp}, which is strongly correlated with relative humidity, and wind speed are the main parameters influencing dew yield (Lekouch et al., 2012; Luo and Goudriaan, 2004; Muselli et al., 2009; Sharan et al., 2007). In our study dewfall was most strongly correlated with wind speed ($r=-0.576$, $p<0.001$). Cloud cover data, which is often included when modeling dewfall as it indicates night time cooling (Muselli et al., 2009), was not available in our study, but the temperature drop during the night (T_{max}-T_{min}) represents the same phenomenon, and slightly improved the model.

Weather data was not able to predict dew rates at 30 min time steps as R^2 values only reached 0.082, while at 1 h time steps R^2 only improved to 0.131. Uncertainties can be attributed to the fact that dewfall is determined by the temperature of the condensation surface for which air temperature used in our regression is just an approximation, as well as wetting conditions and heat transfer parameters of the material (Beysens et al., 2005; Clus et al., 2008; Pedro and Gillespie, 1981). These factors play a more important role in smaller time steps, hence regression with weather data alone cannot sufficiently explain observed dew rates.

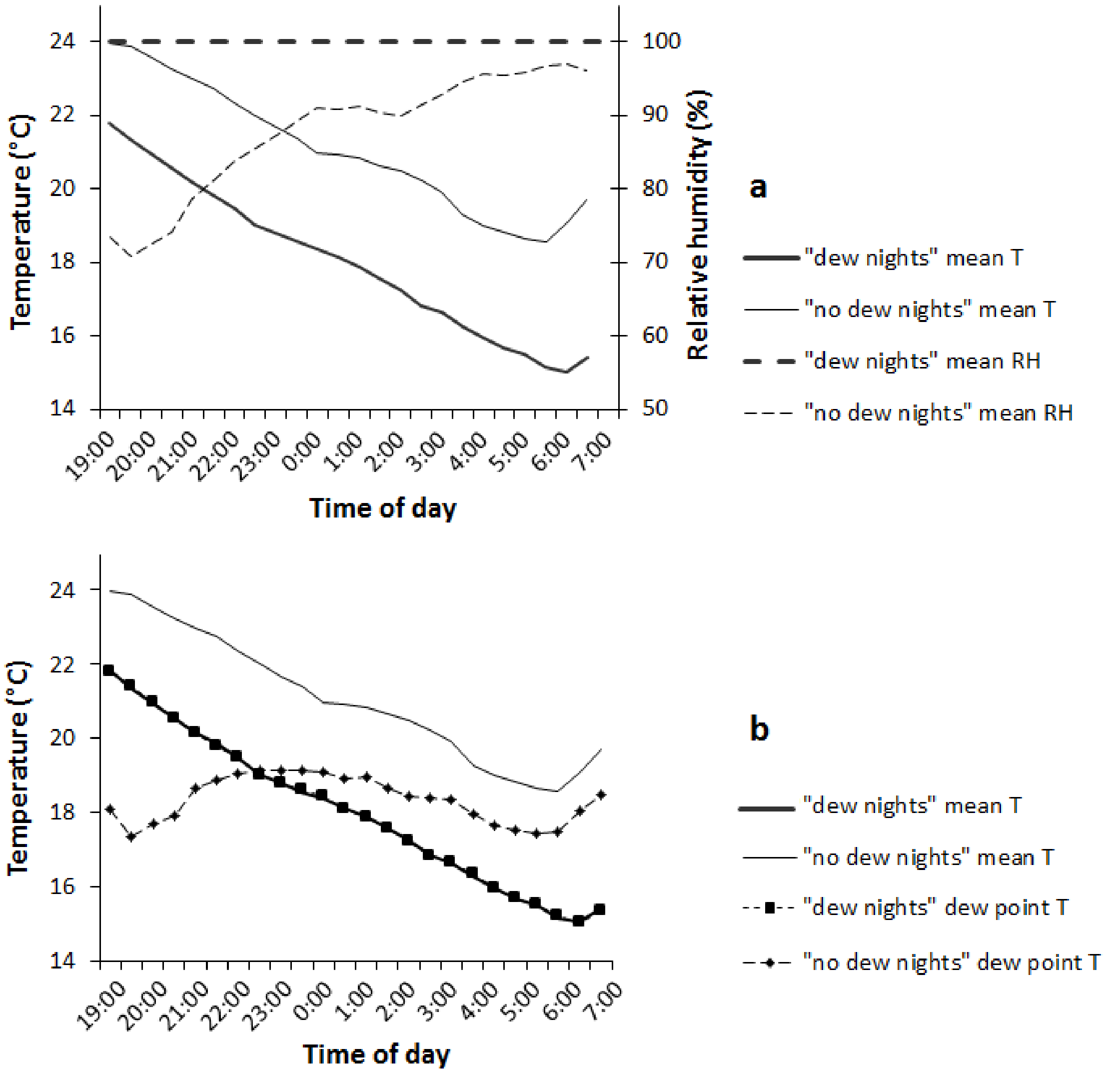

Figure 4.4. Temperature, relative humidity (a) and dew point trends (b) during nights with (n=10) and without (n=10) dew deposition in Efoetsy, south-western Madagascar. Nights with dew deposition used for calculation of means were the ten nights with highest dew deposition in the observation period (>0.35 mm), nights without dew deposition used for calculation of means were ten randomly chosen nights with dewfall <0.010 mm during the observation period.

Table 4.4. Results of multiple regression analysis for daily dew values in the study area of south-western Madagascar (n=215).

	B coefficient	B s.e.	β (standardized B)	Sig.	R^2 change
Constant	0.102	0.173		<0.001	
Mean wind speed	-0.049	0.008	-0.354	<0.001	0.331
Maximum T_{air}-T_{dp}	-0.013	0.002	-0.344	<0.001	0.062
T_{max}-T_{min}	0.019	0.004	0.263	<0.001	0.064

Model Summary: R^2 =0.458, Durbin-Watson = 1.692; ANOVA: p<0.001, RMSE=0.091

4.4.3 Balance evaluation and consequences for natural dewfall

Correlation coefficients between total dew yield during the night from the different measuring methods were 0.71 (balance – plastic sheet on the ground), 0.84 (balance – 1 m high plastic sheet on wooden surface), 0.82 (balance – 1 m high plastic sheet on metal surface) and 0.99 (1 m high plastic sheet on wooden surface - 1m high plastic sheet on metal surface; Figure 4.5). Average daily dew values in the evaluation period amounted to 0.064 mm (plastic sheet on ground), 0.136 mm (plastic sheet at 1 m height on wood), 0.123 mm (plastic sheet at 1 m height on metal) and 0.184 mm (dew balance; Table 4.5). Differences of dew amounts were significant between all methods ($P<0.001$) except between the plastic sheet on wood and on metal at 1 m height ($P = 0.878$). Hence, recorded dew values on the ground tended to be lower than the ones obtained at 1 m height with the plastic sheet method which reflects more efficient radiational cooling at height compared to the ground level (Figure 4.5).
Differences in dew deposition with height have also been reported in other studies that found dew precipitation to be increasing with height up to 100 cm above the soil (Jacobs et al., 1994; Raman et al., 1973; Subramaniam and Kesava Rao, 1983), due to missing heat flux from the soil. On the other hand Ninari and Berliner (2002) showed that water vapor adsorption adds to moisture in the soil profile as measured with micro-lysimeters. Water vapor adsorption is a different source of atmospheric water, but unlike dew not detectable on artificial condensation surfaces. Since water vapor adsorption may play a role in our study area, balance values may sometimes be lower than actual moisture deposition on the soil (Agam and Berliner, 2006; Ninari and Berliner, 2002; Uclés et al., 2013).

Table 4.5. Comparison of dew measurement methods during the calibration period at the coastal measurement site of Efoetsy in southwestern Madagascar (see Figure 4.5).

	Balance	Sheet on ground	Sheet 1 m - wood	Sheet 1 m - metal
Mean dew per night (mm)	0.184	0.064	0.136	0.123
RMSE		0.065	0.051	0.053

The specific shortcomings of the Hiltner balance, using a much smaller metal surface connected to an analog balance and a writing device for assessing dewfall, are similar to those of our method (Zhang et al., 2011). Our evaluation results suggest that measurements with the balance are indeed less appropriate for estimating dewfall on the ground itself, but offer a reasonable approximation for potential dew accumulation at the prevailing plant canopy height of 1 m. The overestimation of dew by the balance

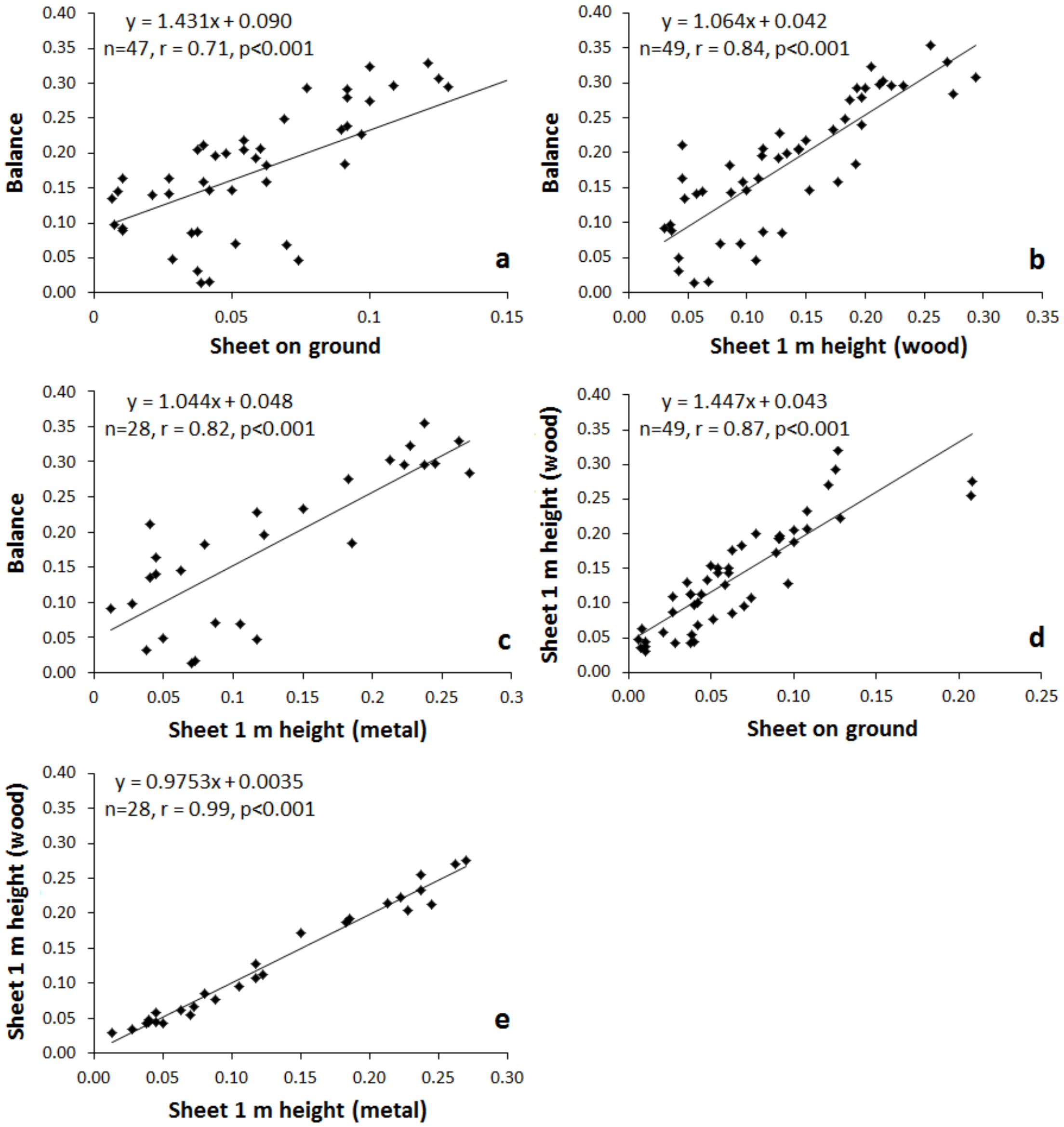

Figure 4.5. Scatter plots of measured dew values (mm) of a) balance and plastic sheet on the ground, b) balance and plastic sheet at 1 m height on wood, c) balance and plastic sheet in one meter height on metal, d) plastic sheet on the ground and plastic sheet at 1 m height on wood at Efoetsy in south-western Madagascar.

compared to the alternative methods may be explained by the different sizes and material of condensation surfaces, which lead to differing surface cooling rates during the night, as well as shielding of the condensation plate from wind (Clus et al., 2008; Lekouch et al., 2012). While Kidron (2010) found dew deposition to increase with substrate size from 2.5 x 2.5 cm^2 to 40 x 40 cm^2, this effect is presumably overlaid be the effects of difference in substrate material as well as differences in height between methods in this study.

Furthermore, small measurement values tended to be less well correlated (Figure 4.5) which probably reflects the measurement errors of both the balance and alternative methods dominating at small dew amounts. The threshold value for dew occurrence and comparison between methods may thus have to be increased from 0.01 mm as used in this study. Kidron (2000) and Kidron (2010) used threshold values of 0.03 - 0.04 mm, as proposed by Kappen et al. (1979).

Differences of artificial condensation material compared with plant and soil surfaces remain since comparison measurements were conducted with plastic sheets only. We could not improve the correlation with and decrease the difference to dew balance values by using a metal surface under the plastic sheet to partly make up for the heat radiation differences of the material, as this method was strongly correlated with the method with wood underlying the plastic sheet at 1 m height (r = 0.99, Figure 4.5e) and differences were not significant. Takenaka et al. (2003) found only a small difference in dew deposition between polytetrafluoroethylene (PTFE) and aluminum coated with PTFE. The lack of an effect of different underlying substrate on dew amounts may be due to the fact that the plastic sheet was only loosely laid on top of the wood surface and metal sheet, thus the materials were not in sufficient contact to influence the temperature of the plastic sheet. Furthermore, the measurement method may not be precise enough to detect any small differences due to underlying material. Overall, most dew measurement devices seem more suitable for dewfall comparison among sites or to estimate dew yields harvestable from similar condensation surfaces rather than to obtain absolute values of natural dewfall in an area.

4.5 Conclusions

Our newly designed dew accumulation device using an artificial condensation surface allowed reliable dew formation readings which corresponded well with comparative large scale readings at 1 m above ground. The dew amounts recorded, as a result of high percentage of dew days and high daily dew amounts, are comparable to other regions were dewfall is recognized to be an important contribution to the annual water balance. In the future, low-tech dew collection systems (Lekouch et al., 2012; Nilsson, 1996) may be a viable option for additional water supply in the coastal area. While dew deposition in natural ecosystems and mechanisms of dew use in local plant populations would need to be further investigated, results indicate that dewfall plays a role in the annual water balance and may thus be of importance for the natural vegetation in dryland ecosystems of south-western Madagascar particularly during the dry months.

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5. General discussion and conclusions

5.1 Yield gaps and agricultural intensification in sub-Saharan Africa - a short review

The outcomes of above treated field trials underline the challenge and complexity of improving cropping systems in south-western Madagascar. Combined with the reviewed experience from the past they raise more questions about the overall options of local farmers to improve their livelihoods through agricultural intensification.

Agriculture has been repeatedly shown to be at the base of poverty reduction and development in Africa, despite increasing challenges due to globalization, market liberalization and low public spending on agricultural research and development compared to the period of the first green revolution (Diao et al., 2010; Hazell et al., 2010; Minten and Barrett, 2008; Thomas and Gaspart, 2014). The importance of agricultural growth lies in the fact that it is more pro-poor than e.g. industrial growth as more poor rural people would benefit from it (Diao et al., 2010). Furthermore, many countries/regions lack alternatives to the agricultural sector for growth, and there is potential since numerous technologies and methods for agricultural intensification are known and yet not sufficiently implemented, while new technologies, such as new cultivars, continue to be developed (Hazell et al., 2010).

In this regard, poverty gaps in Africa have been shown to be closely related to yield gaps at the household level (Dzanku et al., 2015). The yield gap is the difference between yield potential and actual observed average farmers' yield in a certain region and for a certain crop and indicates the potential for agricultural growth. Yield potential is the idealized crop yield achieved without any biophysical limitations other than uncontrollable factors, such as solar radiation, air temperature and CO_2 levels (Lobell et al., 2009). Water limited yield potential is a useful reference in rainfed systems as it is also determined by water availability from rainfall. The yield gap is thus determined by management factors such as choice of cultivar, supply of all essential nutrients, plant density and protection from losses due to pests and diseases (as well as water availability in rainfed systems) (Lobell et al., 2009).

Yield potential is difficult to determine for anyone region, as it is hardly ever achieved even under controlled conditions, and as soil and climatic conditions vary even within a region and between years in order to use the same reference yield potential throughout (Lobell et al., 2009). A proxy for yield potential can be the highest attainable yield of farmers. Information of this from south-western Madagascar is hardly available or not reliable. According to Lobell et al. (2009), in extensive systems in Africa maize yields commonly reach less than 20% of yield potential. An overview of attained maize yields and gaps across Africa by Tittonell and Giller (2013) indicates yields of 0.2 - 1.6 t ha^{-1} on degraded and low fertility sites, corresponding to 3 - 26% of highest attainable yields in the region. We found in our trials that cassava yields differed substantially between trial fields. Likewise, in additional on-farm trials with maize and sorghum we found that maize yields in control plots ranged from 0 - 0.38 t ha^{-1} and sorghum yields from 0.11 - 0.70 t ha^{-1} (Hanisch et al., 2013). Attained crop yield from documented trials in southern Madagascar also vary considerably and indicate potential yields under optimum management conditions (Arraudeau, 1977; Jenny, 1975; Le Thomas, 1946). These variations indicate that there is ample room for improvement of cropping systems even within the current farmers' cropping system.

Yield gap analysis aims to identify the factors responsible for yield losses compared to attainable yield, and the degree to which these limit yield, thus indicating which interventions and policies best increase farmers' yields (Dzanku et al., 2015; Lobell et al., 2009). The main biophysical factors that determine yield gaps and are relevant to farmers in the Mahafaly Plateau area are soil nutrient deficiencies and imbalances, water stress, management factors (suboptimal planting densities and dates, weed pressure), pests and diseases and seed quality (Lobell et al., 2009).

Attaining the yield potential itself is normally not economically feasible due to high management and input costs compared to yield gains, with the result that even in intensive systems yields only attain up to 80% of potential crop yields (Lobell et al., 2009; van Ittersum et al., 2013). Furthermore, in extensively managed systems, observed highest yields are presumably far from yield potential, as even the best farmers do not apply all the optimal management measures, particularly fertilization, crop protection and use of hybrid seed, partly due to lack of access or knowledge (Lobell et al., 2009; van Ittersum et al., 2013). Hence, socio-economic factors further determine yield gaps, including profit maximization (cost-benefit-ratios), risk aversion, access to credit, and lack of time, labor and knowledge (Lobell et al., 2009).

There are often interactions between factors. For example, crop variety characteristics such as water and nutrient use efficiencies influence limitations due to water and soil nutrient availability. In the case of the Mahafaly Plateau, it can be assumed that soil fertility, water availability, crop variety characteristics and management factors all limit yield and interact closely with each other, as was concluded from cassava field trials (chapter 2). The degree to which farmers are able to invest and improve on any of these are in turn determined by socio-economic factors.

Figure 5.1 demonstrates the yield limiting effects of biophysical and socio-economic factors acting together, whereby the observed yield can be thought of as being determined by the most limiting factor, according to the concept of Liebig's law of the minimum.

The choice of a reference for yield potential is related to the discussion regarding how

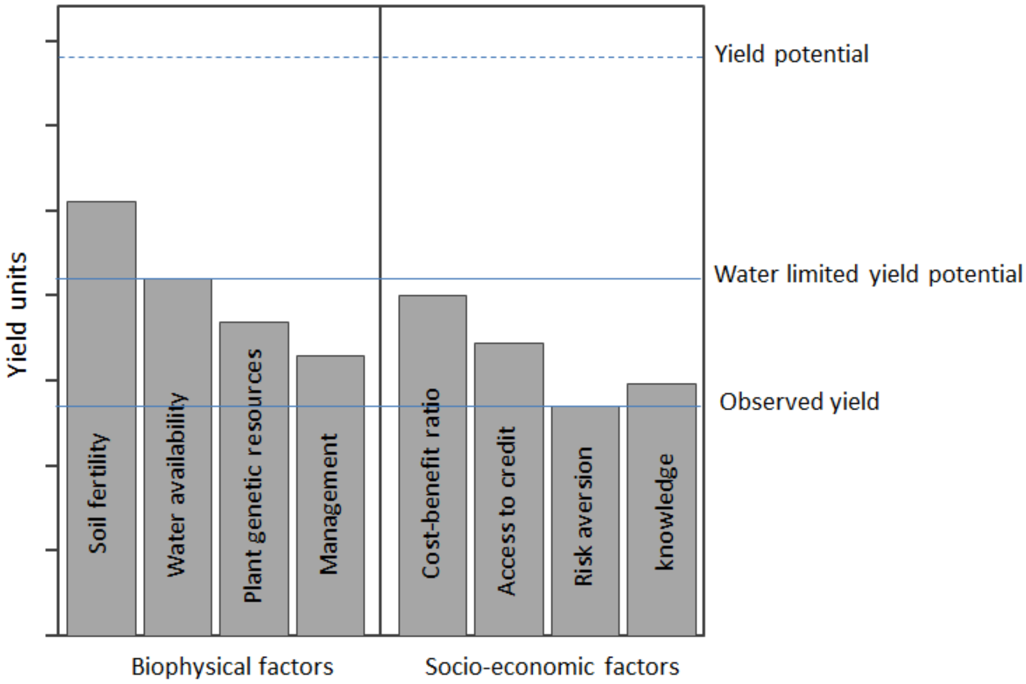

Figure 5.1. Representation of yield limiting biophysical and socio-economic factors contributing to yield gaps. Source: based on Bommarco et al. (2013); Lobell et al. (2009)

yield increases in SSA can and should be obtained. Proponents of sustainable or ecological intensification argue for systems based primarily on use of local inputs, diversification, closed nutrient cycles and agroecological methods as well as no unnecessary use of external inputs to minimize negative effects on the environment (Pretty et al., 2011). Similarly, Cassman (1999) states that in unfavorable rain-fed environments ecological intensification is achieved by crop-livestock integration, increased crop diversification and agroforestry systems providing higher economic value. Smallholder farmers depend to a large degree on regulating and supporting ecosystem services to replace external inputs such as fertilizers and pesticides in order to close the yield gap (Bommarco et al., 2013; IFAD and UNEP, 2013). Tittonell and Giller (2013) suggested that an important fraction of the yield gap may be reduced through proper agronomic management (planting dates, spacing, cultivars, early weeding, etc.) even when fertilizers are not applied. Others state that in the long term intensification is not possible without the increased use of external inputs because of insufficient quantities of organic material at the farm and village scale (de Ridder et al., 2004; Lupwayi et al., 2000; McIntire and Powell, 1995; van Keulen and Breman, 1990; Vanlauwe and Giller, 2006; Williams et al., 1995) or because of the too high labor input of many low-external input methods (Moser and Barrett, 2003). Sanchez et al. (2009) attribute the successes of recent productivity enhancement in African countries to access to improved seeds and fertilizers, partly through input subsidies.

The biophysical factors of soil fertility, water availability and availability of high quality seed of pest and disease resistant cultivars are covered in chapters 5.2.1 - 5.2.3, while socio-economic factors are discussed in chapter 5.2.4.

In view of limitations and opportunities due to these factors, chapter 5.3 addresses the potential for agricultural growth and income from on-farm activities in villagers' livelihoods on the Mahafaly Plateau in relation to increasing income diversification from off-farm activities.

5.2 Discussion of bottlenecks to sustainable intensification in the study area

5.2.1 Soil fertility

5.2.1.1 Limitations due to soil fertility decline

Declining soil fertility has been recognized as an alarming problem in sub-saharan Africa (SSA). In low-rainfall regions of Madagascar, soil N, P and K losses for the year 2000 were estimated to amount to 28-45, 4-8 and 20-28 kg ha^{-1} year^{-1}, respectively (Stoorvogel and Smaling, 1990b).

However, it has also been pointed out that due to the often inherently low soil fertility and micro-variability in fields of the Sahel it would take several decades of continuous cultivation in order to detect any declines in soil fertility (de Ridder et al., 2004). Generally, it is well recognized that in the tropics soil fertility declines quickly in the first years after clearing, while in later years decomposition rates decrease due to the relative stability of remaining organic material in the soil (de Ridder et al., 2004). Furthermore, Vanlauwe and Giller (2006) point out that nutrient stocks in soils can be sufficient for many years of cultivation and hence, even if nutrient balances are negative, soils may not need fertilization to sustain yields, depending on crops' nutrient demands. Ncube et al. (2007) also suggested that following a period of drought years, maize yields can be higher than usual due to the accumulated concentration of mineral N and other available nutrients in the soil.

Hence, estimates for soil fertility decline have been criticized for using too many biased assumptions, not taking into account spatial and temporal variation and underestimating farmers' ability to develop local strategies to deal with low inherent soil fertility or micro-variability, thus overestimating degradation (de Ridder et al., 2004; Mazzucato and Niemeijer, 2001). Nonetheless, Koning and Smaling (2005) emphasize that, despite localized examples of soil restoration and the rationality of low-external-input techniques employed by farmers in their context, continuous cropping without sufficient inputs will eventually deplete the soil even if stocks maintain yields for a long time.

Soils of arable land on the Mahafaly Plateau were found to have much lower soil fertility levels than soils of grazing land and forested zones, where fertility decline was already observed in newly cleared fields (Fricke, 2014). Similarly, Milleville et al. (2001) found in slash-and-burn maize systems of the Mikea forest (Figure 1.1) a decrease of 60% of available P, 44% of C, 55% of N and 27% of K as well as an increase in soil density, resulting in a 47% decline in permeability between the first and fifth year of cultivation. Furthermore, the erosion of top soil through wind and water are of considerable concern in Madagascar (Sourdat, 1972). Service des Eaux et Forêts (1961) determined during a rainy season (265 mm) on a 3.3 % slope that water lost through run-off amounted to 12 mm and eroded quantities of soil amounted to 880 kg ha^{-1}. Stoorvogel and Smaling (1990a) estimated soil losses of 10 t ha^{-1} $year^{-1}$ on cropland in low rainfall regions of Madagascar, and 40-90% of estimated nutrient losses of N, P and K on croplands have been attributed to erosion (Stoorvogel and Smaling, 1990b). Soil erosion from deforested areas is also responsible for accelerated sedimentation in river beds and has led to devastating floods and change of river courses in the past (Bourgeat et al., 1995; Thibaud, 2010).

It is often pointed out that addition of mineral fertilizers is necessary to supply all necessary nutrients and organic inputs alone cannot substitute for this (Vanlauwe and Giller, 2006), particularly as pasture to crop land ratios are declining with population growth (McIntire and Powell, 1995). The use of mineral fertilizer in SSA however is extremely low compared to other regions or world averages, due to costs and economic risks as well as lack of access (Mafongoya et al., 2006; Sanchez, 2002). Furthermore, reliance on mineral fertilizers alone is not sustainable as it depletes soils of organic matter and exchangeable base ions, while soils with low organic matter content respond less to mineral fertilizers, hence regular input of organic matter to the soil is a prerequisite for sustainable intensification (Bationo et al., 1995; Tittonell and Giller, 2013).

Aune and Bationo (2008) suggest a ladder approach to intensification, in which resource poor farmers first adopt technologies without any financial cost and that are based on improved use of locally-available resources, e.g. manure, local organic matter, seed priming, and water harvesting methods. Furthermore, for farmers without access to markets, low-cost intensification measures are the only feasible option (de Ridder et al., 2004).

Hence in the following discussion the focus is mainly on options for soil fertility enhancement most available to farmers in the Mahafaly area: return of livestock manure to croplands, and increased production and return of organic matter grouped under conservation agriculture and agroforestry technologies: intercropping and alley cropping, rotations and improved fallows, use of crop residues and other plant biomass as mulch.

5.2.1.2 Closing nutrient cycles through crop-livestock integration

Manure is considered the primary source of field fertilization available to farmers and the first step towards more intensified cultivation practices (Aune and Bationo, 2008; Kimani and Lekasi, 2004), hence use of manure has been repeatedly recommended to increase crop productivity in south-western Madagascar (see Appendix A).
However, while organic fertilizer use is known to be widespread in Africa (Place et al., 2003; Rufino et al., 2007), annual application rates are estimated to be quite low with 0.1-0.9 t ha^{-1} (Leeuw et al., 1995), and quasi zero on the Mahafaly Plateau. Manure amounts applied by farmers in SSA were sometimes found to be too low in N to increase yields or be economical (Materechera, 2010; Rufino et al., 2007). Materechera (2010) points to the constraints of South-African farmers that are reluctant to use animal manure on their fields. They are similar to those identified in southern Madagascar (see chapter 1.2.3), and include the lack of labor and transport, lack of sufficient information and training regarding use and management of manure, but also perceived negative effects due to encouragement of weed and insect infestation.
Our studies with manure application in cassava (5-10 t ha^{-1}) revealed relatively limited positive effects on yields after the first years of application, while in one field cassava yield increases by 30-40 % could be obtained (chapter 2.4.3). Similarly, manure at relatively high rates of 40 t ha^{-1} did not increase productivity of carrots and onions in two cropping seasons (chapter 3.4.1). Additional studies conducted in three trial fields on the Plateau with maize and sorghum amended with 30 t ha^{-1} manure resulted in yield increases in the order of 50 - 200% across crop species and fields (Hanisch et al., 2013). This is in line with a previous study in the region, which found increases of maize and sorghum yields with manure to be highest with application rates of 40 t ha^{-1}, amounting to 25% compared to control for local maize in a season with 235 mm rainfall, and 50% for sorghum in a season with 405 mm rainfall (Jenny, 1975). The same study also found no significant sorghum yield increases but rather a yield depressing effect with application rates of 10 t ha^{-1} at 339 mm annual rainfall. Smaling et al. (1992) found similarly, that farmyard manure applied at 5 t ha^{-1} showed only significant effects on maize yields in the third year of application at a site with 350-730 mm rainfall and sandy soils in Kenya, and economic returns to manure application were negative for the farmer in the first two years. Our own field trials with manure (30 t ha^{-1}) in maize and millet cropping in the littoral zone did not yield any meaningful results due to drought, while there was a trend towards a negative effect of manure on plant establishment (Hanisch et al., 2013).

Generally, the reliance of cropping systems in the region on livestock manure for sustained or increased yields depends on manure collection and corralling practices, fodder quantity and quality, livestock numbers and manure excretion rates (Fernandez-Rivera et al., 1995; Harris, 2002; Lupwayi et al., 2000; Mafongoya et al., 2006; Markewich et al., 2010; Materechera, 2010).

It is estimated that 40 - 60% (Leeuw et al., 1995; Schlecht et al., 1995) of manure is deposited during night corraling and the rest lost on grazing land. Mafongoya et al. (2006) estimate that 60% of N and 10% of P in manure are lost due to poor management in African smallholder farms, while in extensive grazing systems, 40 - 60% of N are lost for crop fertilization in the form of urine. In this regard, Williams et al. (1995) found crop yield increases after manure and urine application to be 3-4 times as high as when only manure was applied. On the other hand, the efficiency to capture urine-N is largely reduced due to quick leaching and volatilization after deposition (Rufino et al., 2006).

When manure is stored in unprotected livestock corals or composting heaps (i.e. without flooring and roofing) large parts of nutrients may be leached or lost through gaseous emissions until application (Markewich et al., 2010; Predotova et al., 2010; Rufino et al., 2006, 2007). In old manures stored for a long time, much of the remaining N is in stable forms that are only mineralised slowly, hence N availability and uptake can be low in the first season and increase in the following years (Rufino et al., 2006). This may thus partly explain a lack of or slow response to manure in our field trials. Faust et al. (2015) investigated mineralization rates in sandy alkaline soils under *Tamarindus indica* in the littoral with livestock manure and tamarind litter inputs. Presence of manure significantly increased basal respiration and N mineralization rates in incubation experiments. With 0.9% of C_{org} evolved as CO_2 and 10 μg g^{-1} net N mineralisation after 28 days, rates were, however, relatively low compared to those of other studies. At initial soil C_{org} levels comparable to soils investigated by Faust et al. (2015), Jacobs et al. (2010) found 1.4 - 2.85% of C_{org} evolved as CO_2 while Hartz et al. (2000) reported C_{org} decomposition rates of 2 - 17% of the initial after four weeks of incubation in manure-amended and unamended soils. Azeez and Van Averbeke (2010) found net N mineralization rates of 185.7 μg g^{-1} after 30 days of incubation from manure-soil mixes. Exact manure rates could not be quantified in the study of Faust et al. (2015) to be able to directly compare and draw concrete conclusions about mineralization rates of manure applications to soil in our study area. Nonetheless, quality and age of manure deposited under tree canopies during herd resting times may be comparable to the situation found in livestock corrals, and low mineralisation rates may indicate the recalcitrance of organic matter in the manure used in field trials. Alkalinity may be further responsible for low N mineralisation rates in the littoral soils with pH above 9 (Faust et al., 2015), as Pathak and Rao (1998) showed that increasing alkalinity from pH 8 to 10 decreased N mineralisation after a three-months incubation period.

Organic matter amendments, in the form of plant residue or manure, with a high C:N ratio (>23 according to Mafongoya et al. (2006); >15 according to Qian and Schoenau (2002) and Beauchamp and Paul (1989)) or with high lignin:N and polyphenol:N ratios inhibit decomposition and N mobilization in soils and thus can lead to short-term

N deficiency in crops (Delve, 2004; Mafongoya et al., 2000, 2006; Somda et al., 1995). Carbon to N ratios of manures in our studies ranged between 8 (goat manure) and 25 (zebu manure, table 2.3). Manures in the littoral had very high C:N ratios of 19-28 (vegetable trials) and up to 33 (maize and millet trial, unpublished data). Additionally, the methods used in soil and manure analysis of our samples (Walkley-Black for C, Kjeldahl for N) have been shown to underestimate C:N ratios compared to values obtained with dry combustion (Dieckow et al., 2007). Siegfried et al. (2013) found in sandy soils of Oman that manure with a C:N ratio of 25 tended to decrease yields of radish (*Raphanus sativus*), carrot (*Daucus carota*) and cauliflower (*Brassica oleracea*) compared with manures with a C:N ratio of 19, but in contrast to their hypothesis effects were not significant. On the other hand, C:N ratios of 31 manure and compost amendment types ranging between 4.5 and 15.5 were reported to be significantly negatively correlated with fescue dry weight and N uptake (Hartz et al., 2000).

Independent of the C:N ratio, presence of lignin, tannins and polyphenols in feed further limit digestibility in the rumen and degradability of manure (Cabrera et al., 2005; Rufino et al., 2006). Manure in sub-tropical regions may be relatively rich in lignin and tannin or other polyphenols due to the reliance on low-quality shrubs as fodder especially in the dry season (Rufino et al., 2006). Nonetheless, it was found that the lower the quality of the feed material, the more beneficial it is to feed it to livestock and then apply as manure, compared to direct application of the plant material to the soil, because of faster N mobilization from manure (Delve et al., 2001; Mafongoya et al., 2000; Somda et al., 1995).

Williams and Powell (1995) estimated that in semi-arid West Africa 8-11 cattle per hectare of cropland or 25-48 sheep ha^{-1} are necessary to restore soil fertility on croplands, depending on nutrient exports. These cattle/sheep in turn require an estimated 11-42 ha/ 10-40 ha of grazing land in the dry season and 4-11 / 3-10 ha in the wet season per ha of cropland, depending on grassland productivity (Williams and Powell, 1995). Similarly, McIntire and Powell (1995) estimated that pasture to cropland ratios of at least 10:1 are necessary for reliance on nutrient transfers from grazing land through manure.

According to land use and village classification data across 110 settlements in the study area generated by Brinkmann et al. (2014), mean cropland areas per village increased from 700 to 1030 ha between 2004 and 2013. Resulting livestock densities ranged from 0.1 to 0.9 tropical livestock units (TLU, = 250 kg body mass) per ha of village cropland in 2004, and decreased further to 0.1 - 0.6 in 2013 (Brinkmann et al., 2014). In combination with observed maximum herd grazing areas in two Littoral and Plateau villages estimated by Feldt and Schlecht (2015), the pasture to cropland ratios in 2013 were in the order of 7:1 and 16:1 in Littoral and Plateau villages, respectively.

A study by Schlecht et al. (1995) estimated daily faecal excretion amounts of livestock grazed extensively and corralled overnight in Mali, under similar agro-ecological and livestock management conditions as in the Mahafaly region. Organic matter excretion in the corral was found to be in the order of 0.9 kg TLU^{-1} day^{-1} during the dry season and slightly lower during the rainy season. Average reported numbers of livestock in the study zone are 16.9 zebu and 25.1 small ruminants per household (Neudert et al., 2014). Thus, when transhumance is not taken into account, on average about 5.5 t of zebu manure would be available to the average household annually. Small ruminants, which excrete about 15-20% the amounts of cattle (Fernandez-Rivera et al., 1995), would add about 1.4 t year^{-1}. Similarly, Ahlers (2014) estimated from feeding experiments with sheep in the study area that 1.3 t year^{-1} are available to the average farmer from small ruminants. The total manure availability is in line with estimates by Bayala et al. (1998) for south-western Madagascar (8 t livestock manure year^{-1} corral $^{-1}$).

Traditional transhumance patterns, whereby herds from the Littoral are moving to pasture zones of the Plateau during the rainy season, are changing due to droughts as well as rising incidences of cattle raids on the Plateau (Feldt and Schlecht, 2015; Goetter, 2014), and are therefore difficult to take into account regarding available manure (Williams and Powell, 1995). Nonetheless, even though transhumance only occurs within the study zone and there may be social ties whereby farmers would be able to use manure of transhumant herds, the manure amounts available to the farmer for fields are greatly reduced in the current extensive grazing system (Fernandez-Rivera et al., 1995). Feldt and Schlecht (2015) found daily cattle and goat grazing durations of 11-12.9 and 9.1–10.4 h day $^{-1}$ throughout the year, respectively, and some herds were found to spend nights outside the village corral over considerable periods of time.

Average field sizes in the Mahafaly region have been reported at 2.1 ha, but households own several fields of different age and type (Neudert et al., 2014; Sulama WP 6 Socioeconomics, 2014). Consequently, ruminant manure amounts available per hectar would only be a fraction of 6 t. Considering current livestock densities of 0.1-0.6 TLU ha cropland^{-1} as derived from estimates above, less than 0.5 t manure ha cropland^{-1} would be available. This is considerably lower than estimates of manure availability by Dagnon and Beauval (1993) for south-western Madagascar (6 t manure ha cropland $^{-1}$).

We found that to maintain soil N, P and K levels in cassava fields under current yield levels, annual applications of at least 2.5 t ha^{-1} of zebu manure would be necessary (see chapter 2). Regarding cultivation of more nutrient-demanding cereals (maize, millet, sorghum), necessary manure applications amount to at least about 4 t ha^{-1}, assuming yield levels of 0.5 t, nutrient contents of grain and residue according to Stoorvogel and Smaling (1990a) and complete removal of residue from the field. Additionally, nutrient losses due to quick volatilization and leaching after application, erosion and removal by termites have to be accounted for (Esse et al., 2001; Somda et al., 1995; Williams et al., 1995). Hence, even if soil fertility can be enhanced locally by manure application (Tables 2.15 and 3.5), current livestock densities and manure amounts seem to not be sufficient to rely solely on manure for long-term soil fertility management of croplands

in the study area.
A longer-term integration of livestock into the cropping system and reliance on manure as a principal source of cropland fertilization also depends on the shifting dynamics of livestock importance compared to crop production as well as productivity of grasslands and availability of livestock fodder which have to be tackled (Schlecht et al., 1995). Livestock numbers on the Mahafaly Plateau have reportedly decreased in recent years (Kaufmann and Tsirahamba, 2006; Sulama WP 6 Socioeconomics, 2014). Even if absolute numbers given by farmers and through censuses are unreliable, livestock densities will be limited due to low grassland quality and low availability of water, as well as increases in cattle raids (Feldt and Schlecht, 2015; Goetter, 2014). In Zimbabwe it was found that the carrying capacity of local grasslands allowed a livestock population that would only produce enough manure for a third of the village cropland (Zingore et al., 2011). Williams and Powell (1995) analyzed the change in livestock numbers after drought periods in West Africa and found that, as small ruminants have a higher survival rate, the ratio of small ruminants – cattle has increased between 1960's and 1991. De Ridder et al. (2004) found that in areas of Burkina Faso, where livestock densities are limited by grassland potential, farmers are shifting to soil fertility management options such as use of crop residues, composting, and use of organic matter from pasture as mulch.
There is, however, room for increasing nutrient returns to cropland independent of livestock numbers through better grazing and manure management (Leeuw et al., 1995; Rufino et al., 2006; Turner, 1995). Traditionally, livestock corrals in the Mahafaly region remain in the same place for a relatively long time, as the amount of accumulated manure relates to the size of the herd and is considered a sign of wealth, and livestock corrals have a strong cultural and spiritual meaning (personal observation). The amount of N remaining in this manure before application may thus be very low due to the long time span and ammonia volatilization in the hot dry season, and losses through nitrate leaching and denitrification in the rainy season.
The time span between manure deposition in corrals and application in the field should therefore be reduced. During storage, important improvements in manure quality may be achieved through flooring and roofing of the stalls or manure collection sites, though this requires investment of capital and labour, which are generally restricted for subsistence smallholders in Africa (Rufino et al., 2006). Use of bedding in livestock corrals can largely reduce the percentage of ammonia-N from faeces and urine lost through volatilization, while heaping manure reduces its surface area, and so decreases leaching compared with uncollected manure (Rufino et al., 2006). Rufino et al. (2007) found use of plastic covering on manure composting heaps to be a viable option to farmers to decrease N losses. In this regard, poor households that currently do not own any ruminant livestock represent about 40% of households in the SuLaMa study area (Neudert et al., 2014). To these, manure may not be available except through social relations,

and composting organic material may be an option for field fertilization. Composting of household wastes and crop residues are currently being promoted by development projects in the study area (Eliane Gomez, Mathieu Baehrel, personal communication, 29.05.2014). Different composting methods, such as in pits and heaps and with addition of plant biomass, should be tested together with farmers. On the other hand, in semi-arid areas composting practices to improve manure quality or recycle plant residues are often constrained by lack of water in the dry season, labor requirements, insufficient plant material, lack of livestock integration and lack of knowledge by farmers (Bationo and Mokwunye, 1991).

Some farmers shift corrals occasionally for various reasons after several years, and use the fertile site of the former corral for crop cultivation (SuLaMa, 2011, personal observation). This practice may be the most easily adoptable and could be promoted further, as it creates patches of fertile soil and reduces labor costs both of which are often considered crucial factors inhibiting adoption of manure use. Similarly, pegging livestock on crop lands is rarely practiced in villages of the study area, and mostly limited to draft oxen (Feldt and Schlecht, 2015). These practices would increase nutrient amounts due to lower losses of dung on grazing lands, as well as decrease labor requirements for manure application (Leeuw et al., 1995; Schlecht et al., 2004).

On the other hand, Turner (1995) pointed out that the benefits of manure (and urine) application to improving the nutrient status of croplands have to be separated into acceleration of the nutrient cycle, increasing the efficiency of the nutrient cycle or importing nutrients to the particular cropped area from elsewhere. Thus, in the long term one cannot only rely on the benefits of accelerated nutrient cycling and increased nutrient availability, e.g. through grazing of crop residues on cropland, but nutrients need to be transferred from other areas (grazing land) to the cropland. This, however, may affect long-term productivity of grazing land (Rufino et al., 2006).

Overall, it can be concluded that use of livestock manure alone is not able to replace the extensive slash-and-burn cropping systems that still prevail for demanding crops (maize, millet, sorghum) and are attractive to farmers in view of yields and low labor demands for weeding and fertilization. It is nonetheless a necessary component among other management practices that enhance or maintain fertility (Smaling et al., 1992, see chapter below).

Further studies are needed in the Mahafaly region to identify the crops as well as soil, field and management criteria, for which ruminant manure provides the highest economic return in the short, medium and long term, in order to incentivize farmers to invest labor into manure management. Our results of manure application on cassava, vegetable and cereal yields indicate that the quality, in terms of organic matter fractions and mineralization rates, of manure that is currently available in corrals needs to be better understood and consequently improved through management before widespread recommendations to farmers are given. Furthermore, in future fertilization trials, freshly produced or adequately stored manure should be used as manure stored for long time periods in corrals may be of too low quality and may also not be considered representative of long-term integration of manure in the cropping system involving regular application.

Management factors and rainfall conditions are to a large degree responsible for the variation in crop yields and effects of farmers' manure (and mineral fertilization) between farmers fields as well as between farmer and researcher managed trials (Ncube et al., 2007; Tittonell et al., 2008). When soils are very degraded after many years of cultivation without inputs, responses to organic matter or fertilizer inputs may be slow and crop yields may only recover slowly and not attain the same levels as at the beginning of cultivation (Tittonell and Giller, 2013). Furthermore, in environments with high rainfall variability, short term trials over only a few years were criticized for not being sufficient to evaluate the sustainability and feasibility of technologies based on manure application (Ncube et al., 2007). Plant yields may also only respond to manure application with a time lag due to slow decomposition and nutrient release. Similarly, as manure application may entail high opportunity costs and lead to yield depression in regions with high risk of drought (Williams et al., 1995), fertilization practices should also be coupled to simultaneous water conservation practices (see chapter 5.2.2).

5.2.1.3 Conservation Agriculture and Agroforestry

An approach that is often promoted for tackling soil fertility losses including erosion, as well as water availability constraints, is conservation agriculture (CA). It consists of minimum disturbance of soil, continuous soil cover through crop residues as mulch or cover crops, and crop rotations and associations (FAO, 2014a). According to Cassman (1999), soil and crop residue management, including conservation tillage practices that are adapted to the conditions in developing countries, are the primary way to increase yields in rain-fed agriculture where rainfall is the main constraint before soil fertility and genetic plant material.

However, it has been repeatedly pointed out that CA techniques have rarely been adopted by farmers in SSA, due to unsatisfying yield increases compared to opportunity costs, and that there is hence a need to identify the specific ecological and socio-economic conditions under which CA approaches are suitable (Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014; Giller et al., 2011, 2009). According to Rockström et al. (2002), successful CA systems in SSA are mostly confined to commercial farmers.

Rusinamhodzi et al. (2011) conducted a meta-analysis of CA effects on maize yield in semi-arid areas and under different cropping techniques. They concluded that no-tillage and mulch effects are highly variable and often negative, depending on rainfall constraints and on adequate supply of additional fertilizer, particularly N. Similarly, Brouder and Gomez-Macpherson (2014) reviewed the literature regarding CA impacts on smallholder yields, and found that yields in the short term were generally lower under no-till compared to conventional tillage. Rockström et al. (2009) point out that there is generally a time lag until CA methods result in increased yield and soil fertility.

In Madagascar CA has been studied and promoted since the 1990's (GSDM, 2014; Serpantié, 2009). However, the diffusion of CA practices is slow or reversing, mainly constrained to the agriculturally most advantaged area of the country, and incentivized by special contracts or input subsidies to participating farmers (Serpantié, 2009).

CA techniques have been subject to experimentation in the South and South-West since 2002 (Morlat and Castellanet, 2012; Ratovoheriniaina et al., 2005), but they are apparently only tested in areas where tillage of the soil by ox-plow is the traditional practice, mineral fertilizer is available and rainfall is higher than in our study area (Ratovoheriniaina et al., 2005). Furthermore, Ratovoheriniaina et al. (2005) emphasize that the use of herbicides and fungicides is obligatory in CA systems, which is currently economically difficult or impossible to farmers in the South-West due to supply and/or access constraints. The NGO GRET has been experimenting with intercropping (particularly with pigeon pea (*Cajanus cajan*)) and leguminous cover crops (*Mucuna pruriens*, *Phaseolus lunatus*) in southern Madgascar (GRET, 2014). However, documentation about yield effects, economics and farmer adoption numbers is not available.

Andrianasolo and Razafintsalama (2013) point out the constraints to the development of CA in the Mahafaly Plateau zone. They include inherently poor soils, low crop diversity, lack of fertilization means including the reluctance towards use of manure, as well as the traditionally strong emphasis of animal husbandry and its very low integration in plant production.

Agroforestry systems can be considered as an extension of CA principles, where perennials and trees are used for intercropping, alley cropping and in tree fallow rotations. Compared to some areas in the Sahel, the deliberate inclusion of trees and shrubs in croplands is not a widespread or traditional practice in southern Madagascar (Bayala et al., 1998). Agroforestry components are thus increasingly promoted in the Mahafaly Plateau area, e.g. through the distribution of fruit trees (*Mangifera indica*, *Carica papaya*, *Citrus* spp.), *Moringa oleifera*, and leguminous species (*Sesbania sesban*, *Leucaena leucocephalia*, and *Acacia auricoliformis*) (Sous-Cluster Sécurité Alimentaire et Moyens de Subsistance, 2015a). Alley cropping with (leguminous) shrubs was promoted in southern Madagascar in the past as measures against wind erosion (Charfi, 1981).

The methods of organic matter production within CA practices and their benefits for soil fertility can be grouped according to their time and place within the cropping system, and thus offer respective advantages and disadvantages regarding resource competition and use efficiencies as well as labor and land demands (Vanlauwe, 2004).

The feasibility and appropriateness of these options depend largely on systems' design and properties of crop and intercrop/fallow species regarding resource use complementarities and competition as well as quantity and quality of plant residues.

Crop residue mulching has been shown to have beneficial effects on soil properties and plant yield in the Sahelian zone of West Africa due to increased nutrient availability, decrease of wind erosion and capture of dust, and improvements in soil water availability and microclimate (Bationo and Buerkert, 2001; Bationo and Mokwunye, 1991; Buerkert et al., 2000). Furthermore, soil covering residue mulches and higher biomass production from legume intercrops were found to decrease labor requirements for weeding (Rollin and Razafintsalama, 2001; Rusinamhodzi et al., 2012).
However, biomass material may not be available in large enough amounts due to low biomass production, competing uses such as cattle feed, fuel, construction material, or due to traditional practices such as burning of residues, as well as lack of human or draught labor force for residue incorporation into the soil (Aune and Bationo, 2008; Bationo and Mokwunye, 1991; Buerkert et al., 2000), which is presumably partly responsible for the slow uptake of CA techniques in the test zones of the South-West (Rollin and Razafintsalama, 2001). Intercropping with soil covering crops may therefore be a more viable and attractive option to farmers compared to mulching (Bayala et al., 2011).
Rusinamhodzi et al. (2012) studied maize - grain legume (pigeon pea, cowpea) intercropping and fallow systems in Mozambique. Intercrops were found to be more productive than sole crops with land equivalent ratios reaching 1.9-2.4, depending on whether the intercrop was added to the maize rows or replaced maize. The system also decreased risk of crop failure as legumes were less effected by dry spells than maize. In Tanzania, promotion of integrated soil fertility management through pigeon pea - maize intercropping systems resulted in 18 000 farmers adopting the technique and maize and pigeon pea yields being raised from 1.5 to 3.5 t ha^{-1}, and from 0.4 to 1.4 t ha^{-1}, respectively (AGRA, 2014).
In south-western Madagascar, Rollin (1997) and Rollin and Razafintsalama (2001) concluded that intercropping of cereals (maize, millet, sorghum) with cowpea and other *Vigna unguiculata* spp. were promising techniques to increase biomass as well as grain production. Generally, there was, however, large variability in yields observable between demonstration sites and years (Rollin and Razafintsalama, 2001).
Well adapted and designed intercropping, alley cropping and agroforestry systems can increase system productivity by increasing exploitation of available light, water and nutrients (Ong et al., 2006). The major biophysical factors influencing the performance of mixed systems are crop and tree type, number and distribution of intercrop plants and trees, age of the tree, management of crop and tree and climate during the season (Noordwijk and Ong, 1999; Rao et al., 2007). Tree and shrub species are preferable which

have a different root distribution pattern than crops, and a leafing phenology that results in less competition for water during the cropping season (Ong et al., 2007, 2006). Management such as root and shoot pruning may alleviate competition, but this effect and the tree's ability to recover from pruning depends strongly on the species (Bayala et al., 2002; Jones et al., 1998).

Due to water shortage in semi-arid areas, it has been postulated that agroforestry and systems based on intercropping ("same place, same time") are not suitable and focus should be on tree fallows and rotations (Rao et al., 2007; Sanchez, 1995). Furthermore, crops such as maize, millet and cassava are more sensitive to shade from trees and shrubs (Rao et al., 2007). For example, Rusinamhodzi et al. (2012) found that maize grown in rotation with pigeon pea yielded eight times more than maize grown successively in the third season.

The quality of crop residues, tree and shrub litter is of importance as it can be N-immobilizing when added to soil (Bationo et al., 1995; Somda et al., 1995, see chapter 5.2.1.2 above). For example, *Sesbania*, pigeon pea and Neem (*Azadirachta indica*) litter was found to have relatively low fertilizer value despite high concentration of N due to high levels of polyphenols and/or lignin, and thus mixing with N fertilizer or high quality organic material is recommended (Delve, 2004). The timing of plant residue application to match organic matter decomposition and nutrient availability with crop plant uptake thus also plays an important role (Mafongoya et al., 2006).

A study by Maille (1991) in the Beza Mahafaly Reserve near the SuLaMa research zone investigated the effects of fresh *Tamarindus indica* and *Acacia myrmecophylla* leaves as mulch at 1 and 2 t ha^{-1} rates on maize yields. Tamarind leaves significantly decreased yields and emergence of maize plants and it was concluded that the tree is not appropriate for intercropping or agroforestry systems in maize, while *Acacia myrmecophylla* leaves did not significantly affect emergence and yield parameters. Faust et al. (2015) analyzed soil samples taken from underneath Tamarind trees in the littoral zone of our study area to determine soil ameliorating effects of tamarind litter and manure deposited under tree canopies from zebu and goat herds. It was found that soils under tamarind had improved soil chemical properties while germination of sorghum seeds was not inhibited in tamarind soils. The potential of tamarinds for agroforestry systems depends, however, on appropriate management systems that can be adopted by farmers, i.e. use of adapted and high-value crop species and regulation of tree use in grazing. The emphasis on livestock and importance of tamarind as shade tree for livestock and people, as well as use of tamarind for charcoal making may currently preclude the use of tamarinds in cropping systems. On the other hand, tamarind litter is used as input for composting of organic matter in cut and carry systems (George, 2011), and inhibiting effects of tamarind leaves on crop growth may be diminished with decomposition.

Vanlauwe and Giller (2006) caution that general promotion of leguminous species in intercropping, rotations/tree fallows or green manure with the aim to increase yields and soil fertility may be misleading. The increased yield benefits of cereals may be counteracted by increased labor input and land investment, and system adoption has been shown in Benin to decrease once subsidies and market support were withdrawn by the project (Vanlauwe and Giller, 2006). Furthermore, not all legumes fix nitrogen, and N supply amounts are often very low in smallholder systems with low soil P and water availability (Mafongoya et al., 2006). Nitrogen added to the soil also depends on the ratio of N fixed and N removed with harvested products. Green manures which add large amounts of N to the soil but without harvestable products may be less attractive to farmers, while grain legumes add low amounts of N to the soil or tend to drain soil N (Vanlauwe and Giller, 2006).

Mafongoya et al. (2006) summarized the options of soil fertility replenishment available to farmers in SSA in terms of contribution to soil fertility and their ease of adoption as ranked by farmers. Crop rotations and intercropping with legumes were found to be the most easily and agroforestry technologies the least easily adoptable. Low adoption of agroforestry options in SSA is attributed to labor shortage, availability of seed and planting material and opportunity costs of waiting for 2–5 years without benefits (Bayala et al., 2011; Mafongoya et al., 2006; Sanchez, 1995). Aune and Bationo (2008) consider agroforestry systems with inclusion of high-value cash crops to be feasible at later stages of intensification and with the existence of functioning markets.

Related to CA promotion is the controversy regarding soil tillage. While the use of ox-drawn ploughs or mechanical tillage with tractors have been recommended (see Appendix A), others stress the negative effects of tillage due to enhanced soil organic matter decomposition and soil erosion. Rollin (1997) points out the paradox regarding promotion of soil tillage by ox-drawn plough by some stakeholders, while others proclaim reduced tillage within CA packages. He finds in the context of south-western Madagascar, where soil tillage is not practiced by default, that the use of the plough constitutes nonetheless the best solution for intensification when transitioning from slash-and-burn without soil tillage to CA in permanent fields. Furthermore, Serpantié (2009) stressed that CA should be less strictly defined and instead of the focus on no-till, should include tillage with organic matter incorporation on land protected against soil erosion. He criticized that CA techniques are often compared to unsustainable cultural methods instead of to sustainable alternatives that include soil tillage.

Rockström et al. (2009) found that CA in dry environments primarily increased yields of maize and tef (*Eragrostis tef*) through increased water productivity, when subsoilers and rippers where used instead of inversion tillage. Yield increases were also found to be highest with decreasing rainfall. The use of ploughs is constrained by the lack of draught power for the majority of households (Schlecht et al., 2006; Sulama WP 6 Socioeconomics, 2014), but on the other hand use of soil scarifying and ridging appliances was found to be less labor demanding than using the plough (Rockström et al., 2009).

Furthermore, Rockström et al. (2009) found that in African semi-arid environments non-inversion-tillage is more adapted than non-tillage and use of mulch, particularly as the latter was not used in their experiments due to biomass constraints.
While animal power increases labor productivity and should thus be encouraged, the focus should be less on using the plough but other appliances that are able to loosen the soil and increase infiltration without the negative effects of inversion tillage on soil organic matter.

Overall, there are numerous agro-ecological options available to farmers, but Mafongoya et al. (2006) found that agricultural technologies that most contributed to soil fertility were also the ones that are most difficult to adopt by farmers. Rusinamhodzi et al. (2012) also stress that matching technological performance to farmers' preferences is critical for widespread adoption as farmers prefer technologies that fit within their resources such as labor, capital and management demands, as well as crop preferences and market prices of harvestable products.
These issues have to be studied and documented during promotion of CA and agro-forestry based systems. In this regard, Brouder and Gomez-Macpherson (2014) find that CA experiments are so far not sufficiently well designed and documented to be able to systematically review their effects across a range of situations, as well as to discern effects due to separate system components.

5.2.2 Water availability and other climatic factors

5.2.2.1 Limitations due to water availability

Water availability is another major constraint next to soil fertility in semi-arid Africa (Badejo, 1998; Barry et al., 2008). The perceived risk of crop failure due to weather conditions is also an important factor that determines whether farmers will invest in inputs and labor that would increase yields under favorable conditions (Lobell et al., 2009).
The degree to which soil fertility or water availability is the most limiting factor depends on annual rainfall. For example, it has been concluded that in areas with annual rainfall above 250 mm availability of plant nutrients, particularly phosphorous and nitrogen, limits biomass production more than rainfall, while in the drier northern Sahelian climates water is the limiting factor (Breman and De Wit, 1983). Likewise, it has been concluded that in regions with about 400 mm rainfall, agricultural intensification is more difficult compared with regions of 600 mm rainfall, whereby with decreasing annual rainfall livestock is becoming the more important economic activity compared to crop production (Mortimore and Turner, 2005). Concerning cultivation of cotton and

maize in south-western Madagascar, it is reported to be particularly constrained by water availability in areas with less than 600 mm rainfall during the crop cycle (Rollin and Razafintsalama, 2001), which is almost always the case in the Mahafaly Plateau area.
Furthermore, in semi-arid areas a bigger constraint to agriculture than the total annual rainfall amount is the high spatial and temporal variability within years (Rockström et al., 2010). Seasonal dry spells are estimated to occur much more regularly than droughts and lead to severe yield reductions (Rockström et al., 2002). Several dry spells of 7 to more than 21 days have been observed in every year during our study period (Table 2.4).
Climatic conditions on the Mahafaly Plateau can thus be considered marginal for rainfed crop production, particularly concerning annuals which represent the majority of cultivated crops in the region. This is also reflected in the relative importance of risk management and coping strategies and the regular inability of farming activities to supply enough to household income and subsistence needs (Neudert et al., 2014, see chapter 1.2.3). With increasing climatic risk farmers adopt several coping strategies such as diversification in crop varieties, planting densities, water harvesting, sale of livestock as well as migration and off-farm income (Aune and Bationo, 2008). Also, Akponikpè et al. (2011) showed in Niger, that the dispersion of household fields increased inter-annual yield stability of a household and may serve as a risk reducing strategy against variable spatial rainfall patterns.
Farmers in Madagascar report perceived changes in weather since 2000, such as higher temperatures, lower rainfall, more variable rainfall, greater seasonal variability and stronger cyclones (Harvey et al., 2014). On the other hand, analyses of climate trends in Madagascar from 1901-2000 (Rabefitia et al., 2008) and in the South-West from 1935-1994 (Ferry et al., 1998) indicate only a slight temperature increase in the South since the 1950's while there is no trend in precipitation totals due to the high seasonal and interannual variability. However, the numbers of intense cyclones as well as wind speed have reportedly increased since the 1990's (Rabefitia et al., 2008). Hence, in view of the long history of recurrent droughts and changing periods of good and bad harvest years, it is questionable whether perceptions of locals can be equated with long term trends of climate change in Madagascar. Mertz et al. (2009) stress that farmers' perceptions about climate change are influenced by narratives and questions addressing climate while other factors than climate are often more important in changing livelihood strategies in the Sahel.
Nonetheless, according to Vololona et al. (2013), climate model predictions for Madagascar using the IPCC scenario A1B estimate decreases in annual rainfall by 50 to 200 mm in the South/South-West until 2050, as well as mean temperature increases by 1.5-2.5 °C. They also state that less rainfall and higher temperatures represent a challenge for the cultivation of the traditional annual crops in this area, and increase the probability of CMV infection, thus possibly counteracting the importance of cassava due

to its robustness in harsh climate. Consequently, Vololona et al. (2013) emphasize that more investment is needed to strengthen existing and develop new alternative income sources in view of the vulnerability of agricultural activities to climate change.

5.2.2.2 Opportunities to enhance water productivity

While water scarcity is considered the most important constraint for crop production in the Mahafaly Plateau area, water scarcity in semi-arid regions can be more attributed to unfavorable rainfall distribution and the regular occurrence of dry spells rather than the cumulative annual rainfall (Rockström et al., 2002). Furthermore, it is estimated that in extensive smallholder farming systems only 10-25% of rainfall water is used for crop production and the rest lost through soil evaporation, surface run-off and drainage (Rockström et al., 2002). There is thus opportunity to increase water productivity, i.e. the amount of crop produced per unit of water from rainfall and run-off, through management practices which involve the maximization of plant water availability, maximization of plants' capacity for water uptake, and supplemental irrigation during dry spells (Rockström et al., 2002). According to the same authors, risk aversion of farmers and hesitation to invest in fertilizers is directly linked to the occurrence of dry spells, and securing water availability through the mitigation of dry spells may be the entry point to improve farming systems and to increase farmers' time and capital investments.

Traditional technologies for *in situ* water harvesting to increase water availability at the field level include micro-catchment systems such as stone rows and contour bunds, planting basins called *Zaï* or *tassa*, straw mulching and half moons (Barry et al., 2008). Substantial sorghum and millet yield increases with stone rows or half moons have been reported in Burkina Faso (Barry et al., 2008). Similarly, Barro et al. (2008) found in Burkina Faso that *Zaï* planting holes with manure application of 300 g hole^{-1} increased sorghum grain harvest by 100% in “good" years and 200% in “bad" years, with mean annual rainfall of 800 mm. In Niger, planting millet in *Zaï* led to three-fold yield increases compared to flat surface under ca. 185 mm irrigation during the cropping cycle, whereas with 280 mm irrigation yields did not differ between planting techniques (Fatondji, 2002). The yield increasing effect of manure was also more enhanced with *Zaï* compared to flat planting. Fatondji (2002) and Fatondji et al. (2007) reported up to 68fold millet grain yield increases at optimum manure application rates of 1-3 t ha^{-1} deposited in *Zaï*, in soils with very low P and organic matter levels. Likewise, Kaboré and Reij (2004) report of sorghum yield increases between 38 and 310 kg ha^{-1} when planting in *Zaï* pits, whereas the application of manure further increased yield gains by 380 - 720 kg ha^{-1} (310 - 620% compared to control).

Evidence of the feasibility and effects of *Zaï* on crop growth in the study area is so far only anecdotal, and farmers are also subsidized in “food-for-work" programs or otherwise reimbursed for taking part in *Zaï* digging. Controlled trials over a range of rainfall patterns as well as with different pit size, density and fertilization are necessary in order to evaluate under which circumstances promotion of *Zaï* is agro-ecologically and economically feasible compared to alternative cropping methods. Preliminary trials conducted on the Mahafaly Plateau during the research period indicated that *Zaï* planting pits resulted in higher soil moisture immediately after a ca. 80 mm rainfall event as well as longer soil moisture retention compared to flat surfaces in soil depths of 10-15 cm. Due to a subsequent prolonged dry spell, soil moisture retention was however not sufficient to prevent complete maize and *Phaseolus lunatus* crop failure.

Similar to the *Zaï* technique, promising cassava yield increases have been obtained when stems were planted in planting pits amended with large amounts of organic matter, but controlled trials and an evaluation of the feasibility are also as yet lacking.

Tillage and use of soil scarifying appliances are also considered as *in situ* rainwater harvesting technologies (Barry et al., 2008) and in Tanzania use of animal drawn rippers and subsoilers resulted in increased water productivity compared to ploughs (Rockström et al., 2009). Okwach and Simiyu (1999) found that on crust prone soils zero tillage may rather lead to higher surface runoff and lower rainfall infiltration and hence lower yield levels.

Macro-catchment techniques consist of reservoirs and pools dug to catch and store runoff water (Barry et al., 2008). Such hand-dug pools as well as natural clayey depressions are already used in the Mahafaly Plateau area for rainwater harvesting and are an important water source for livestock during the rainy season. Farm pond storage systems with 100-250 m^3 capacity have been used in Kenya and Burkina Faso for supplemental irrigation of maize and sorghum during dry spells, while in China 30 m^3 storage tanks have supplied enough water for supplemental irrigation to increase water productivity of wheat by 20% and increase maize yields by 20 - 88% (Rockström et al., 2002).

While work is currently underway to estimate the amount of water available from catchment ponds in several villages of the Mahafaly Plateau, currently water amounts are presumably not sufficient to allow widespread irrigation of field crops, particularly in view of the cultural emphasis on livestock and the already limited water resources. Nonetheless, the construction of additional ponds on the Plateau may provide sufficient water for the irrigation of high-value crops and vegetable gardens.

There are often high labor requirements for rainwater harvesting, and the feasibility thus depends on labor opportunity costs and beneficial effects of increased water availability. It is estimated that 300 man-hours are necessary to establish one hectar of *Zaï*, and farmers in Burkina Faso extend field area under *Zaï* progressively according to labor availability (Kaboré and Reij, 2004). Fatondji (2002) and Rockström et al. (2002) argue that labor required for the digging of *Zaï* pits and catchment ponds is not necessarily a constraint as these can be prepared in the dry season outside the labor peak period. This also brings advantages compared to tillage, as crops can be planted early as soon as rains arrive (Kaboré and Reij, 2004). Experiments also indicated that *Zaï* collect dust and organic matter from wind and water erosion, therefore adding nutrients to the planting hole without the application of manure or compost by the farmer (Bayala et al., 2011; Fatondji, 2002).

Generally however, increased water availability also demands simultaneously increased nutrient availability in order to increase water and nutrient use efficiencies and to make use of synergistic effects (Pretty et al., 2006; Rockström et al., 2002). The use of small quantities of mineral fertilizer has thus been suggested, as yield increases have been found to be lower in the second year in *Zaï* presumably due to increasingly limited nutrient availability (Kaboré and Reij, 2004).

Overall, the choice of an appropriate rainwater harvesting method depends on the average rainfall, soil type and geographical location of the site (Barry et al., 2008). The efficiency of village ponds should thus also be optimized by positioning them in the landscape to make maximum use of run-off water, which is a challenge due to the gentle slopes in the Mahafaly Plateau area and demands some observation of run-off flows after rainfall events. In the particularly dry littoral zone rainwater harvesting techniques are not appropriate due to the sandy soils where rainwater infiltrates quickly and there is essentially no run-off.

According to Boyd and Slaymaker (2000), in Africa soil and water conservation (SWC) techniques have been most adopted in areas where there is a historic importance of crop production in the rural livelihood, land is scarce, climate is characterized by low rainfall with high annual variation, there is a marked topography and erosion easily observable, there is a market for high-value crops (partly due to proximity to an urban center) and relatively low opportunities or strategies for off-farm diversification and migration. Similarly, Bayala et al. (2011) point out that labor intensive techniques such as *Zaï* need to be developed and applied in conditions where people have no alternative but to reclaim their degraded lands due to high human and animal pressure. Furthermore, livelihood insecurity and a focus on meeting short-term objectives preclude investing in long-term SWC practices (Boyd and Slaymaker, 2000). Many traditional and ancient water harvesting and run-off farming systems found in Africa and Asia have thus deteriorated due to socio-economic factors including emigration as well as rainfall decreases (Critchley et al., 1994). Structures often require substantial labor and social organisation for maintenance and if there are alternative employment and income options elsewhere and outside the farming sector, the incentive breaks down. Furthermore, if animal draught and mechanization are introduced, farmers are less willing to invest the manual labor required for most water harvesting structures (Critchley et al., 1994). Moreover, larger water catchment structures beyond the field scale require effective land management as well as farmer organization and are therefore more complex to implement (Rockström et al., 2002). The Mahafaly are traditionally livestock keepers, while land is perceived to be abundant, the topography is rather gentle, there is so far no market for high-value crops and people already employ various off-farm diversification strategies for livelihood security and historically have been migrating temporarily or permanently out of the region. These conditions will hinder the adoption of SWC techniques in the absence of favorable policies. Overall, Vohland and Barry (2009) warn of the increasing promotion of rainwater harvesting techniques by NGOs and extension services in Africa and Asia and the relatively low rates of adoption and farmer participation as well as sometimes negative effects of inappropriate techniques.

There has been growing interest in the promotion of micro-irrigation or drip-irrigation in small-scale vegetable garden systems in the study area. Field observations indicated that these systems are often not adopted by farmers, but supplied micro-tubes rather deteriorate while farmers revert to traditional watering methods. On the other hand, durable and high-quality drip systems in smallholder vegetable gardening in the Sahel have been shown to reduce labor, water and energy costs and achieve higher yields compared to traditional irrigation methods (Woltering et al., 2011). However, it is emphasized that use of durable equipment is essential, yet requires higher investment compared to often promoted low-cost alternatives such as micro-tubes, which do not withstand harsh sun insulation and handling by inexperienced farmers (Woltering et al., 2011). Furthermore, successful adoption of drip-irrigation systems required simultaneous availability of adapted vegetable seeds and emphasis on specific management packages as well as technical training and support of farmers. Smaller systems of 25-120 m^2 also tended to be abandoned as savings in labor and yield improvements were not substantial enough due to economies of scale. Subsidies and/or access to credits are also required in most areas for initial investment (Woltering et al., 2011). Similarly, a review of smallholder irrigation projects in Africa showed that cheapest irrigation technology is not necessarily the most appropriate and economically sustainable (Burney and Naylor, 2012). Furthermore, it was shown that institutions and the functioning of farmer groups can hinder or improve implementation and continuation of irrigation projects, which calls for adaptive learning and participatory methods to develop appropriate institutions (Burney and Naylor, 2012).

Irrigation through buried clay pots has been reported to increase yields of annuals and establishment of perennial crops and trees compared to alternative irrigation methods, to reduce weed growth due to the selective water supply and to save water due to lower drainage especially in sandy soils (Bainbridge, 2002). Their use can be advantageous to smallholders as they are reportedly less prone to clogging than drip irrigation tubes, do not need water pressure systems and generally are more sturdy and need less maintenance (Bainbridge, 2007). Buried clay pots have also been shown to retain salinity in irrigation water and reduce soil salinity (Bainbridge, 2007; Vasudaven et al., 2011), and can serve as rainwater collection tanks during rainfall events (Bainbridge, 2002). The clay pot technique is currently being tested by some organizations in the Mahafaly area and merit controlled studies, documentation and farmers' assessment, as they are locally produced and available from the regional membership-based farmers organization Maison des Paysans (MdP).

5.2.3 Availability and quality of planting material

More than 99% of seed in southern Madagascar is accessed through the informal sector, i.e. through own stock, local markets and social ties (McGuire and Sperling, 2013b; Randrianatsimbazafy, 2012). Coral Guerra (2014) found that a majority of interviewed farmers are forced to buy seed in some circumstances, such as when seed quality declines during storage, seed stock is consumed during food shortage or after complete harvest failure in the previous year.

However, seed secure farmers are not necessarily the ones that produce all their seed, but those that have access to all the seed they need. Seed access means that people have sufficient cash or other means to buy or barter for available seed of acceptable quality, while seed availability entails that sufficient quantities of seed can be obtained within reasonable spatial proximity and in a timely manner regarding critical sowing periods (Sperling, 2008). Seed security is determined by availability and access as well as quality of available seed. The latter includes both the quality of the actual seed, i.e. seed health and usability, as well as varietal characteristics that are acceptable to the farmer (Sperling, 2008). It is essential to determine which is the most limiting factor in a region when designing interventions with the aim to increase seed security (Sperling, 2008). Sperling and McGuire (2010) point out that seed aid interventions are often conducted without a thorough analysis of needs, the functioning of the existing seed sector as well as an evaluation of impacts on this sector and on farming systems. Seed aid interventions can thus have negative effects by narrowing crop diversity, crowding out seed enterprises and undermining farmers' adaptive capacity by making them rely on repeated seed aid (Sperling and McGuire, 2010).

Regular distribution of free seed by donors, as is takes place in most years in villages of the Mahafaly region, may thus hinder the establishment of a sustainable local seed system (Morlat and Castellanet, 2012). Commercial seed producers are reported to have difficulty to establish themselves in south-western Madagascar, as after good years farmers use their own seed, while after bad years seed donations distort the seed market (Eliane Gomez, personal communication, 01.06.2014). Likewise, it has been pointed out that small seed-producer groups in Madagascar have been selling to relief aid and donor organizations at a higher price, thus failing to serve the farmers as their primary client base (McGuire and Sperling, 2013b).

Additionally, often promoted “modern varieties" are not necessarily adapted to the agroecologies or low-input conditions of seed aid recipients due to unknown genotype-by-environment interactions in highly-stressed areas, such that local varieties often outperform modern ones (Sperling and McGuire, 2010). For instance, a short-cycle maize variety (CIRAD 204) that has been tested in an additional field trial within our study (Hanisch et al., 2013) was observed by farmers to germinate later than local seed, which has been confirmed by subsequent seed germination trials. Fast germination can be considered an adaptation to the environment of the Mahafaly Plateau, where a combination of high intensity rainfall and regular dry spells require the maximum use of stored soil moisture immediately after sowing. This characteristic may thus be more crucial than the duration of the crop cycle. Likewise, farmers reportedly found that maize varieties introduced in the past were not adapted to the local climatic conditions (Coral Guerra, 2014), while promotion of sorghum in southern Madagascar has been hampered as the majority of farmers rejected the crop due to bird attacks and low germination of available sorghum seed (McGuire and Sperling, 2013b).

Observations also indicate that donors have been distributing seed with questionable origin and adaptedness in villages of the Mahafaly Plateau, and without sufficient testing of seed quality, such as germination rate, before distribution (D. Rakotomalala, WWF Toliara, personal communication, March 2014). These regular distributions of new germplasm may also interfere with the establishment of well adapted landraces within the region.

A seed security assessment in southern Madagascar (Ambovombe region, figure 1.1) for the 2012-2013 season revealed that seed availability was not a major constraint as there was sufficient seed available on local markets, and that seed distributions would not have alleviated this constraint (McGuire and Sperling, 2013b). What has been pointed out is the lack of innovations available to farmers regarding new crop species and varieties, and resulting lack of crop diversity (McGuire and Sperling, 2013b).

While farmers in the Mahafaly Plateau region grow up to 30 different crops (Sulama WP 6 Socioeconomics, 2014), there is a strong reliance on cassava, while the suitability of maize can be questioned due to its high dependence on favorable rainfall and fertile soils. Vololona et al. (2013) emphasize that, in order for farmers to be able to better adapt to climate changes, they will need the support of agricultural research and extension to develop, test, and multiply crop varieties that are better suited to the current and future climate conditions. New varieties but also new crops (or crops that are not currently as widely used) might also need to be introduced. Particularly, with maize increasingly stressed by higher temperatures and by drier conditions in the south, crops such as sorghum or millet that are more resilient in hot, dry conditions should be tested (Vololona et al., 2013).

Farmers in the Mahafaly region often need to buy any seed available on the market which in times of shortage is often of low quality (Coral Guerra, 2014, Lloyd Blum, personal communication, 22.05.2014). Low germination of commercially available vegetable seeds as observed in our study exemplifies this problem. The non-availability of planting stock of vegetatively propagated plants (cassava and sweet potato) through formal markets is particularly precarious. Even the resistance of varieties bread to be resistant to CMV often breaks down within 5-10 years due to the spread of infested planting material through informal channels, while farmers in southern Madagascar have virtually no access to new planting material (McGuire and Sperling, 2013b, see chapter 2.5.4).

The lack of new crop varieties, coupled with the often observed lack of suitability of introduced seed to agroecologies or farmers' preferences, indicates that seed quality may thus be a considerable concern rather than availability of seed of already existing crop species in the Mahafaly area.

McGuire and Sperling (2013b) suggest to increase farmers' access to new crop varieties in southern Madagascar through multiple channels, such as demonstrations and decentralized variety testing with leader farmers, market traders, farmer organizations and other village groups and committees, or local stores. Decentralized seed production also needs to complement selection by research institutions in order to cover the range of agro-ecological conditions while at the same time, long-term subsidized seed production and purchase should be discouraged (McGuire and Sperling, 2013b).

Acoording to Andrianasolo and Razafintsalama (2013), interesting crops for farmer seed multiplication on the Mahafaly Plateau include *Vigna unguiculata*, *Vigna radiata*, *Cajanus cajan*, non-edible cover legumes (*Mucuna pruriens*) and cereals (millet, sorghum). GRET is attempting to tackle these constraints in the Ambovombe region since 2007 through selection and experimentation with improved varieties of maize, sorghum, millet and legumes, newly introduced drought resistant species such as *Phaseolus lunatus* varieties and pigeon pea, and selection of local germplasm (McGuire and Sperling, 2013b; Morlat and Castellanet, 2012). Furthermore, GRET maintains a seed production center, works with a network of farmer seed multipliers and established seed selling boutiques in surrounding villages (McGuire and Sperling, 2013b; Morlat and Castellanet, 2012). However, the system is so far not autonomous, depends on subsidies and is thus sometimes criticized for distorting the seed market, even though subsidies are planned to be temporary and primarily intended to spur farmers interest in better quality seed (McGuire and Sperling, 2013b; Morlat and Castellanet, 2012).

Cultivar choices of sub-Saharan Africa smallholders are also highly influenced by factors other than grain yield, such as biomass production for fodder or yield stability across a range of rainfall conditions, by local food habits, markets and traditions (Tittonell and Giller, 2013). Furthermore, farmers attempt to maximize production and/or profit for the entire cropping system rather than the yield or profit of an individual crop (van Ittersum et al., 2013). Availability of as well as access to new crops and varieties that also correspond to farmers' preferences can be enhanced by seed fairs and vouchers, as proposed by Sperling et al. (2004). These also do not endanger the local seed market as local traders benefit from taking part in seed fairs.

5.2.4 Socio-economic, political and cultural factors

The majority of methods of cropping system intensification that are in theory able to alleviate constraints due to biophysical factors hinge on the existence of favorable socio-economic conditions for farmers to be able and willing to adopt them, particularly in areas with low production potential (Dzanku et al., 2015).

Smallholder farmers in SSA are known to be hesitant in adopting new technologies due to low market price incentives of agricultural products, lack of investment capital and access to credit, labor shortage, high opportunity costs and risk aversion due to an unstable ecological and socio-political environment (Alene and Coulibaly, 2009; Breman et al., 2001; Schlecht et al., 2006; van Keulen and Breman, 1990). Access to inputs, quality seed, and information in rural areas, as well as restoration of infrastructure are considered essential to make a shift towards more intensified cropping systems possible in south-western Madagascar (Dabat et al., 2008; Rollin, 1997).

Koning and Smaling (2005) argue that the absence of producer friendly price policies, fertilizer subsidies and food import tariffs may be to a large degree responsible for observed soil degradation in Africa as farmers are not investing to increase land productivity even in areas with increasing population density and land shortage. Accordingly, the postulated situations where farmers develop indigenous methods for better land management and where increased population densities lead to more intensification only occur in those situations where market conditions are favorable (de Ridder et al., 2004; Koning and Smaling, 2005). Profitability of nutrient input depends not just on yield gains but access to input and output markets, prices and opportunity costs (de Ridder et al., 2004; Place et al., 2003). Bayala et al. (1998) found in south-western Madagascar, that manure use was more determined by the monetary value of the crop than by soil fertility, and farmers using manure were found to apply it preferably to fertile "black" soils than to "red" soils, as well as to cotton and maize cash crops than to other food crops. In this regard, the majority of farmers in the study area were found to be subsistence oriented (Coral Guerra, 2014).

A census study in Madagascar by Minten and Barrett (2008) determined that remoteness, i.e. the quality of transport and infrastructure, partly explained the food security status of villagers in terms of the number of food insecure and the length of the lean period. Remoteness was also related to adoption intensity of innovations whereby more remote communes have statistically significantly lower likelihood of adoption due to poor information flow, weak marketing incentives, or unsuitability of promoted innovations to the specific, unobserved characteristics of a remote area. Likewise, Dzanku et al. (2015) found across several African countries that yield gaps were lower with increasing

agricultural extension contacts.
South-western Madagascar is among the most remote regions, where in 2009 it took at least 8 up to more than 26 h to reach an urban area (Vololona et al., 2013). According to Coral Guerra (2014), the majority of interviewed farmers on the Mahafaly Plateau rely on elders in the village for advice regarding agricultural practices, followed by 34% claiming to ask no-one for advise and 12.5% having received advise from NGO technicians, while reportedly no farmer has received advise from governmental services. Furthermore, less than 10% of households report to have adopted or be engaged in any innovative cropping or animal husbandry methods in recent years (Sulama WP 6 Socioeconomics, 2014), and the majority of people surveyed by Hänke and Barkmann (2012) and Coral Guerra (2014) state that no innovations regarding tools, crops or external inputs were introduced in the last years and decades. This low occurrence of local innovations indicates the low adaptive and innovation capacity of the local population in the Mahafaly region.
Randrianarisoa and Minten (2001) found that among various parameters primary education of the household head had the highest effect on farm productivity across Madagascar, leading to an 8 percent increase in agricultural production compared to households where the head did not finish primary school. On the Mahafaly Plateau, 72% of the adult population was estimated to be illiterate, with 87% having received no formal education (Neudert et al., 2014). Another survey in the study area found that about 40% of interviewed farmers did not send all their children to school, and the reasons given were the need for boys to herd animals as well as lack or poor quality of schools (Coral Guerra, 2014). According to Manon (2014), farmers' associations supported by MdP had difficulty to get established and become independent due to low education levels, a certain lack of trust regarding the use of membership fees and credit repayments, or lack of information. On the other hand, Manon (2014) found that members of the farmers' associations supported by MdP saw the advantages in working as a group to cultivate together some land with more modern techniques, exchanging experiences between the members, receiving technical advice and alphabetization offered by MdP.
The issues around access to credit and existing rural credit systems in the study area were documented by Coral Guerra (2014) and Manon (2014). Manon (2014) concluded that credit would enable a better commercialization of cassava harvest as farmers mostly sell cassava immediately after harvest at low prices due to need for cash in this period, and often have to re-buy cassava at doubled prices during the hunger period, leading to decapitalization. Farmers in the study area rely almost exclusively on informal credit (Coral Guerra, 2014), and no formal credit system is currently in place (Manon, 2014). A formal EU-funded storage credit system organized by MdP ended in 2008 due to non-repayment of credits (partly due to lack of understanding of the credit system), theft of storage, and inefficiency of the bank (Manon, 2014). It is concluded that better education and information regarding the credit system is necessary. While community funds

may alleviate the problems resulting from dependence on the bank, lack of trust and insecurity are constraints to this approach (Manon, 2014).
Developments in information technology and energy generation can overcome some of the constraints of poor infrastructure and access to information and credits, such as mobile phones (including mobile banking), radio and solar power (Hazell et al., 2010; Poulton et al., 2010).

There is controversy regarding the role subsidies should play. Any form of subsidy is sometimes regarded as not economically sustainable (McGuire and Sperling, 2013b; Morlat and Castellanet, 2012), is reported to have led to indebtedness of African countries due to unsustainable costs of subsidy programs, and may encourage too many workers and poor people to continue nonviable agricultural activities for too long (Hazell et al., 2010). However, the private sector has not been able to fill the gap of providing inputs and services to poor smallholder farmers in remote areas (Hazell et al., 2010).
Sanchez et al. (2009) argue, giving the example of successful input subsidies in Malawi, that “smart subsidies" for inputs are needed for some years to lift poor farmers lacking any capital out of the poverty trap, until they are able to self-sustain economic growth. Smart subsidies are measures that promote input markets without crowding out private investments, and include demonstration packs, vouchers, matching grants and loan guarantees (Morris et al., 2007).
Subsidies in the form of vouchers or community work programs are also proposed to enhance local demand and purchasing power (Bryceson, 2002). According to Poulton et al. (2006), there is limited potential for agricultural growth without simultaneous stimulation of demand, which tends to be low in rural Africa due to low incomes and consumption among others. The same need for enhancing local demand and purchasing power also applies to the ability of farmers to develop income-generating activities from non-agricultural products and services (Bryceson, 2002; Dorward et al., 2003).
According to Poulton et al. (2006), intensification needs the development of supply chains around smallholder farmers with simultaneous and complementary investments in all links in the supply chain, and it is of importance to identify the critical elements of a supply chain where investment and subsidies will have widest effects. Furthermore, subsidies need to be large enough and continue long enough to effectively shift expectations and structures within the supply chain, and investments need to promote complementary private sector investment rather than crowding it out or inhibiting it (Poulton et al., 2006).
In this regard, the following policy priorities towards sustainable development were suggested by Hazell et al. (2010) and Dorward (2013): The first steps require the investment in public goods of infrastructure, agricultural research, and extension (Dorward, 2013; Hazell et al., 2010). In the next phase, the government's role is to provide development of institutions, input subsidies and coordination of the supply chain which

have to kick-start markets, while the state has to retreat from these interventions in time to allow the private sector to step in and develop (Dorward, 2013; Hazell et al., 2010). Sanchez (2002) also states that long-term investments as well as community-based projects are necessary that integrate agriculture, education and health, as problems are often interrelated. Intensification measures that include soil and water conservation infrastructure, especially those that work at the landscape scale, also require subsidization in the medium-term as economic returns are often only obtained after a considerable time lag.

In this regard, the low capacity and accountability of the Malagasy state remain a considerable constraint in the development of southern Madagascar. A factor that is contributing to lack of state capacity and is hindering efficient use of resources is the prevalence of corruption in Madagascar. The country ranked 127 out of 177 countries in 2013 (Transparency International, 2014). Furthermore, weak Malagasy governance is reflected in the development of governance indicators as determined by the World Bank: control of corruption, government effectiveness, political stability, regulatory quality, rule of law and accountability indices have all been declining drastically since 2007 (World Bank, 2014).

The weakness of state intervention to support farmers is exemplified in the absence of preventive control strategies against often disastrous locust outbreaks due to the low capacity and inefficiency of the national anti-locust center. Madagascar has been depending on support by FAO and international donors to be able to combat the latest outbreaks, which caused considerable crop damage in the South-West (FAO, 2014b). Currently there is concern that international funds for aerial spraying may not be available in time to be able to complete the FAO-led anti-locust program successfully (FAO, 2014b, 2015).

Vololona et al. (2013) point out that in Madagascar, a stable political environment and aggressive policies aimed at improving agricultural productivity and diversification of the economy would be required for effective climate change mitigation and adaptation. In the absence of a functioning state intervention and farmer-friendly policies, Hazell et al. (2010) see an opportunity that donors may be able to play a role in creating incentives for policy makers, rewarding improved governance, introducing and encouraging more participatory processes such as stakeholder forums to discuss issues and hold public agencies accountable for their performance, and supporting local farmers organizations.

The low adoption rates of technologies or new institutions by farmers in Madagascar are, besides lack of infrastructure and information, also attributed to contrasting survival strategies and the traditionally important exchange of resources within the social network (Dabat et al., 2008). Similarly, agricultural extension efforts in the South-West are considered to have failed to reach farmers and improve adoption of technologies due to the hesitation of farmers towards new technologies and their anticipated disrupting effects in social cohesion among families and clans (Laha, 2011). The same holds for attempts to hand over regulation of preserved forest resources to the local population (e.g. GELOSE - GEstion LOcale SEcurisée), which are considered to have failed and have led to sometimes even higher pressure on resources due to the disruption of traditional rights systems (Thibaud, 2010; Thielsen, 2014). Likewise, Blanc-Pamard and Fauroux (2004) assert that past participatory approaches in southwestern Madagascar have been an illusion as investigators wrongly assumed that democratic forms of governance were also inherent in the local culture. Manon (2014) found that the two existing farmer associations in the study area are consisting of family members with the family chief as the associations president due to the need of trust, thus retaining the traditional social structure.

Reluctance to invest in land management is also often attributed to forms of land ownership. 80% of farming land in Madagascar is acquired by traditional heritage systems, as well as by clearing of forest land (Casse et al., 2004). In the SuLaMa study area, Coral Guerra (2014) found that all interviewed farmers owned their land by traditional rights, and there was no land market in place. The restructuring and security of land ownership are considered a requirement to give incentive for intensification, but these are tied to long-term investments which require the absence of political crises (Dabat et al., 2008). On the other hand, Critchley et al. (1994) pointed out that the relationship between tenure and conservation measures may not be so strict, as farmers who establish conservation structures on land also claim ownership of the land. As in Madagascar, farmers claim land through field clearing and fencing, traditional land ownership would not necessarily inhibit other field activities such as intensification measures. Randrianarisoa and Minten (2001) found that the form of land ownership (traditional or legal property rights) did not have an influence on agricultural productivity of farmers across Madagascar. According to Boyd and Slaymaker (2000), African farmers considered land tenure to be secure independent of the nature of ownership (traditional or official), and investing in SWC practices was not influenced by land ownership.

Development and implementation of technologies that would reduce yield gaps have been found to be more prevalent in land-scarce areas (Lobell et al., 2009). For example, practices of efficient nutrient cycling are more likely to be in place in areas with high population density and high land values (Leeuw et al., 1995), while the use of inorganic fertilizers in Africa was found to be triggered at population densities above 40-60 inhabitants km^{-2} (de Ridder et al., 2004). Population densities in southern Madagascar are with 19 inhabitants km^{-2} (2011) low compared to the rest of the country and other African countries (African Development Bank Group, 2014). Nevertheless, projections for Madagascar until the year 2050 estimate population numbers from 49 mio to 73 mio inhabitants depending on fertility and mortality assumptions, up from 21 mio in 2010 (UNPOP, 2013), and arable land per person has diminished from 1,2 ha in 1985 to 0,86 ha in 2005 (Dabat et al., 2008).

5.3 Role of agriculture within sustainble livelihoods of the Mahafaly Plateau

While 99% of the population in the Mahafaly Plateau area are engaged in agriculture, the majority of people also depend on off-farm activities as coping and risk management strategies throughout the year (Neudert et al., 2014). Investing in farming activities thus may increasingly entail opportunity costs due to the existence of alternative and more profitable income sources, e.g. from wage labor, migration, trade, and natural resource mining.

In this regard, while the role of agricultural intensification for development has been pointed out (see chapter 5.1), this is contrasted by developments of deagrarianization in SSA. Deagrarianization is defined as a long-term process of occupational adjustment, income earning reorientation, social identification and spatial relocation of rural dwellers away from strictly agricultural-based modes of livelihood (Bryceson, 2002). According to Bryceson (2002), there has been a rise in household income from nonagricultural activities observable in SSA since the 1990's, due to the halt of farmer friendly policies such as input subsidies or provisioning of important infrastructure as well as increasing land scarcity. De Ridder et al. (2004) similarly point out that if market attractiveness does not develop and the local population continues to increase, farmers finally have to quit agriculture and switch to off-farm employment and migration. Henderson et al. (2014) found that climate change, i.e. decreasing water availability, significantly spurred urbanization across SSA over the last 50 years, and drier conditions lead to a shift out of farming activities. Outmigration in southern Madagascar in the past has similarly been triggered in periods of prolonged droughts (Bayala et al., 1998; Dagnon and Beauval, 1993; Fauroux, 2000; Thibaud, 2010). Furthermore, the inability of the state to curb recurring locust infestations, which need to be tackled on a regional and national level, may further drive farmers out of farming due to frequently experienced dramatic crop losses, while the resulting dependency on relief aid can be regarded as highly unsustainable.

While Bryceson (2002) reports that engaging in off-farm activities has been shown to be positively related to household wealth, this relationship is not so clear for households on the Mahafaly Plateau (Neudert et al., 2014). Bryceson (2002) thus stressed the need for rural and local policies that support occupational diversification and specialization, and pointed out the danger of social demoralization and political instability. In this regard, it can be argued that rising insecurity in southern Madagascar is partly related to the fact that increasing amounts of the farming population lack alternatives to make a living.

In rural development it is recognized that a focus on the agricultural sector alone is restrictive and out-dated, due to the wide portfolio of activities in rural people's livelihoods, especially in view of a fast changing ecological and socio-economic environment

(Amekawa, 2011; Bayala et al., 2011; Scoones, 1998, 2009). After all, in contrast to the focus on closing yield gaps and agricultural intensification, farmers do not necessarily have productivity enhancement as their primary or only goal (Coe, 2003b; Klapwijk et al., 2014).

These developments draw attention to a general perspective on the current and future livelihoods in the Mahafaly region and southern Madagascar, in order to identify to what degree interventions focusing on agricultural intensification should be supplemented with interventions focusing on the generation of alternative income sources.

5.4 Recommendations for research and intervention

Several core recommendations result from the discussion in this chapter for interventions aiming at agricultural intensification or development in general. They revolve around the need to enhance coordination between stakeholders, mainly through sharing a common framework of objectives, indicators and assessment tools for better monitoring and documentation of interventions, more emphasis on participatory approaches and capacity building, and long-term investment. These lessons and recommendations are in line with those already expressed by others in the context of south-western Madagascar (see Appendix A), derived from experiences elsewhere in SSA (AGRA, 2014), as well as from six decades of African agricultural research and development efforts according to a survey by Mutsaers and Kleene (2013).

A number of project interventions are currently in place in the Mahafaly Plateau region (namely GIZ, ACF, AVSF, WFP, WWF, regional NGOs and governmental organizations). Within the regional stakeholder platform that these organizations are members of, the lack of regular participation by key actors in monthly meetings and the need to increase synergies and complementarities between interventions have been expressed (Sous-Cluster Sécurité Alimentaire et Moyens de Subsistance, 2015b). While there is increasing effort to establish data collection and monitoring systems related to food security and to better coordinate relief aid and short-term interventions, there is no common explicit framework in place for medium- to long-term development.

Bryceson (2002) and Hazell et al. (2010) suggest that consortia of governmental agencies, NGOs, private businesses and local farmer organizations should become involved in a common vision of regional potential and development. Ganzhorn (2010) has proposed better coordination and communication between stakeholders in south-western Madagascar as well as documentation and reviews of project results, that are accessible in a literature data base, as well as the need for longer-term interventions and inter-disciplinarity.

There is an urgent need to systematically document intervention and assessment methods, the rationality behind choosing to introduce specific technologies over others, as well as results, including yield performance of introduced methods and farmers' assessments of constraints and opportunities. Where this information is reported, it should be more explicitly made available and discussed among stakeholders. Furthermore, there may be a publication and reporting bias towards positive results, which hinders learning from past mistakes.

Coordination would also enable the promotion of whole management packages which may be better than promoting single components due to the interaction between factors, and to make use of synergies and complementary activities, in line with the need for coordinated supply chain development and service provision to farmers as emphasized by Poulton et al. (2006) and Poulton et al. (2010). For example, the supply of new seed varieties, support and training of farmers, support of farmer organizations, development of agro-ecological methods, subsidized supply of material and construction of vital infrastructure through “food-for-work" programs, access to credit, school education, are all tackled by various stakeholders but as yet insufficiently coordinated or not effective.

Systematic documentation and coordination of implemented methods and their performance as well as panel studies with a large farmer data set and recording of field, climate and management data would also enable the identification of yield potential and yield determining factors, and as such provide entry points for intervention or further cropping system improvement across the region (Tittonell and Giller, 2013; van Ittersum et al., 2013). The variation of observed yield in introduced methods between farmers and years can serve as an estimation of risk for the farmer who is interested in adopting a method, while the correlation of performance with other measured parameters can lead to more precise advise, i.e. under which conditions introduced methods work best, and thus further reduce risk (Coe, 2003a). Similarly, decentralized collection of rainfall data in trial villages across the region would enable to estimate how an introduced method performs across rainfall patterns (Coe, 2003a).

Dorward et al. (2004) outline a participatory method to establish with rural people their livelihood assets and related functions (using the example of livestock keeping), as well as priorities and goals, in order to develop indicators for assessment of changes. For the planning of interventions regarding seed security, it is also highly advisable to pay attention to seed market developments and the state of seed supply, in that components of seed security (seed availability, access, quality) should be considered and assessed continuously (McGuire and Sperling, 2013a; Sperling, 2008; Sperling et al., 2004, see chapter 5.2.3). The seed security assessment in southern Madagascar by McGuire and Sperling (2013b) can serve as an orientation. Their assessment recommends a move away from short-term, gap-filling interventions and towards strategic investment in smallholder–driven variety development, seed production, and agricultural marketing systems (McGuire and Sperling, 2013b).

5.5 Conclusions

This research investigated the constraints and opportunities for more intensified and sustainable cropping systems on the Mahafaly Plateau, as well as field-tested some of the feasible options in on-farm trials. Application of local livestock manure, which is one of the few resources of fertilization immediately available to farmers, indicated that yield increases could be obtained in cassava and cereal fields compared to extensive traditional systems, but with time lags, high risk of failure and corresponding opportunity costs. Improving manure quality, mainly through better storage conditions and timely application, may substantially increase fertilization potential, which needs to be investigated further. Water availability and yield declines through pests and diseases remain the primary constraints in yield enhancement of rain-fed crops. Vegetable production can be a feasible diversification strategy in the littoral zone for food security and possibly for income, but more research is necessary to identify best adapted crop species, good quality seed supply, and appropriate management systems.

Overall, there remains a strong need for more research on the performance of traditional cropping systems as well as promising alternatives including those already implemented and promoted on the Mahafaly Plateau, as well as for better documentation, central collection and dissemination of results. Furthermore, the focus on yield enhancement and short-term results needs to be balanced by more attention to system resilience over the long term in view of the dynamic climatic and ecological conditions. There remain several crucial issues that need to be tackled on a nation-wide scale, as they are difficult to handle by local or regional (non-governmental) interventions, let alone farmers, such as the recurring invasions of locust swarms, as well as the deteriorating state of road infrastructure.

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Appendices

A. Literature list: Agricultural research in south-western Madagascar

Recommendation/ intervention	**References**	**Remarks**
Use of the plough	ALT (Andrew Lees Trust) (2011); Dagnon and Beauval (1993); de Haut de Sigy (1965); Jenny (1975); Le Thomas (1946); Randrianasolo (1974); Rollin (1997)	hesitation among the local population, difficulties due to insufficient draught power or general lack of access to ploughs (Le Thomas, 1946; Service des Eaux et Forêts, 1961)
Use of ox-drawn weeding equipment and comparison with herbicides, to reduce labor	Rollin (1997)	
Use of plough on land otherwise protected against erosion instead of no-till	Serpantié (2009)	
Use of light mechanical soil tillage better than ox-drawn plough	Ministère du Développement Rural (1973); Service des Eaux et Forêts (1961)	even though expensive and has to be practiced with caution, i.e. in contour
Criticism of mechanical soil tillage	Dagnon and Beauval (1993)	
Conservation agriculture	Andrianasolo and Razafintsalama (2013); Bayala et al. (1998); Blanc-Pamard et al. (2005); Naudin et al. (2003); Rollin (1997); Rollin and Razafintsalama (2001)	constraints; three principles of conservation agriculture should not be treated as exclusive and as the only available options (Serpantié, 2009)
Incorporation of cereal crop residues	Jenny (1975); Tourte and Dumont (1976)	

Rotations of crops and with cover and forage crops	Bied-Charreton et al. (1981); Dagnon and Beauval (1993); de Haut de Sigy (1965); Naudin et al. (2003); Ratsimbazafy (1983); Rollin (1997); Tourte and Dumont (1976)	use of rotation difficult to promote in current system as farmers prefer to plant all available land with crops (maize, sorghum) (Service des Eaux et Forêts, 1961)
Rotation and intercropping in cassava	Dostie et al. (1999)	
Socio-economic analyses of constraints related to crop rotations	Bayala et al. (1998)	
Protected fallow for 5-6 years and rotation thereof	de Haut de Sigy (1965)	
Mulching	Bayala et al. (2011); Blanc-Pamard et al. (2005); Naudin et al. (2003); Tourte and Dumont (1976)	
Use of wind-breaker hedges	Bied-Charreton et al. (1981); Charfi (1981); Le Thomas (1946); Ministère du Développement Rural (1973); Ramohavelo et al. (2014); Service des Eaux et Forêts (1961)	needs long term investment (Service des Eaux et Forêts, 1961), Charfi (1981) estimates crop productivity increases of at least 25% with wind hedges, and additional net revenues of 75%, Le Thomas (1946): one line of elephant grass protects two lines of young cassava stems

Agroforestry	Bayala et al. (1998); Ramohavelo et al. (2014); Serpantié (2009); Vautravers and Ravelomandeha (2012)	
Use of manure	Bayala et al. (1998); Dagnon and Beauval (1993); Jenny (1975); Le Thomas (1946); Serpantié (2009)	difficult to find in sufficient amounts (Ramohavelo et al., 2014; Service des Eaux et Forêts, 1961), use of manure preferable due to high costs of mineral fertilizer (Rollin, 1997)
Use and production of improved manure	Tourte and Dumont (1976)	
Use of maximum available manure in cassava	Le Thomas (1946)	
Socio-economic analyses of constraints related to manure use	Bayala et al. (1998)	
		Dagnon and Beauval (1993) estimated that 6 t ha^{-1} year^{-1} of manure from livestock corrals would be available to farmers, and estimates that this would be sufficient to replace nutrients exported from soils termed "sables roux"
Use of small doses of mineral fertilizer / in combination with manure	Dagnon and Beauval (1993); Tourte and Dumont (1976)	fertilizer gives technical advantage but no economic advantage due to high cost to farmer (Randrianarivelo, 2000; Rollin, 1997)

Diversification	Bayala et al. (1998)	
Introduction of short-cycle and drought tolerant varieties	Bayala et al. (1998); Cluster Sécurité Alimentaire et Moyens de Subsistance (2014); Groupe de Travail de Développement Rural 2 (2001); SuLaMa (2011); Vautravers and Ravelomandeha (2012); Vololona et al. (2013)	maize and sorghum(Dagnon and Beauval, 1993; Ravonjiherinaina, 2011; Service des Eaux et Forêts, 1961), millet, peanuts, *Vigna* ssp. (Tourte and Dumont, 1976)
Substitute maize with millet and sorghum as maize not adapted to this dry environment	ALT (Andrew Lees Trust) (2011); Rollin (1997); WFP and Unicef (2011)	
Diversify with soja, sesame, onion and beans to reduce dependence on one buyer	Rollin (1997)	
Use of legumes for fertilization	Bayala et al. (1998); Naudin et al. (2003)	
Improvement of Cassava cropping, especially new varieties	Dagnon and Beauval (1993); McGuire and Sperling (2013)	
Vegetables /house gardens	Cluster Sécurité Alimentaire et Moyens de Subsistance (2014); Ramohavelo et al. (2014); Vautravers and Ravelomandeha (2012)	
Dry season crops	Cluster Sécurité Alimentaire et Moyens de Subsistance (2014)	

Regional selection/breeding for adapted varieties	Ministère du Développement Rural (1973)
Decentralized seed production, in farmers' milieu	Dagnon and Beauval (1993); McGuire and Sperling (2013)
Integrated pest management	Bayala et al. (1998)
Use of pest and insect resistant varieties	Bayala et al. (1998)
Plant protection (young plants of maize against insects)	Dagnon and Beauval (1993)
Testing different planting densities and depths and seeding techniques (mechanical, manual)	Dagnon and Beauval (1993); Jenny (1975); Tourte and Dumont (1976)
Planting of of fodder shrubs and general improvement of grazing lands and fodder availability	Bayala et al. (1998); Ministère du Développement Rural (1973); Poupon (1957); Rollin (1997)
More use of crop residues for livestock fodder	Bayala et al. (1998)

Focus on animal husbandry	de Haut de Sigy (1965)	Promotion of higher consumption and Economic importance of livestock products without dismissing the social-cultural value (with education, change of culture), as no future in agriculture alone (zone Itomboina, Miarintsoa, Andremba)
Tackling water availability	Bayala et al. (1998); de Haut de Sigy (1965); Rasolofoharinoro et al. (1992); Ratsimbazafy (1983); Vautravers and Ravelomandeha (2012)	
Use of planting basins for more efficient use of rain water	Bayala et al. (1998); Service des Eaux et Forêts (1961)	
Scarification and tillage to increase water infiltration	Bayala et al. (1998)	
Water desalinization stations	Rasolofoharinoro et al. (1992)	
Improvement of processing and harvest storage facilities	Bayala et al. (1998); Dagnon and Beauval (1993); Dostie et al. (1999); Ministère du Développement Rural (1973); Thouillot and Maharetse (2010)	

Access to credit and inputs, infrastructure	Bayala et al. (1998); Dagnon and Beauval (1993); de Haut de Sigy (1965); Groupe de Travail de Développement Rural 2 (2001); McGuire and Sperling (2013); Ministère du Développement Rural (1973); Morlat and Castellanet (2012); Rasolofoharinoro et al. (1992); Ravonjiherinaina (2011); Razafimandimby (2008); Razanaka et al. (2001); Vautravers and Ravelomandeha (2012)
Technical advise and effective farmer organizations for better marketing and negotiation power towards state and buyers	Bayala et al. (1998); Dagnon and Beauval (1993); Groupe de Travail de Développement Rural 2 (2001); Razanaka et al. (2001)
Stakeholder coordination and documentation of results	Bayala et al. (1998); Ganzhorn (2010); Morlat and Castellanet (2012); Poupon (1957); Rasolofoharinoro et al. (1992); Razanaka et al. (2001)

Education & capacity building	Dabat et al. (2008); Dagnon and Beauval (1993); de Haut de Sigy (1965); Groupe de Travail de Développement Rural 2 (2001); Neudert et al. (2014); Ranomenjanahary et al. (2005); Rasolofoharinoro et al. (1992,?); Razafimandimby (2008); Vololona et al. (2013); WFP and Unicef (2011)	
Necessity of long-term investment	Dabat et al. (2008); Morlat and Castellanet (2012); Richard and Ratsirarson (2013); Service des Eaux et Forêts (1961); Vololona et al. (2013)	Due to low adoption potential (farmers fluctuating, migration dynamics, changing household economies)
Participatory approaches	Bayala et al. (1998); Dagnon and Beauval (1993); McGuire and Sperling (2013); Neudert et al. (2014); Ramohavelo et al. (2014); Rasolofoharinoro et al. (1992); Ravonjiherinaina (2011); Razafimandimby (2008)	
Taking into account socio-cultural aspects of local population	Bayala et al. (1998); Blanc-Pamard and Fauroux (2004); Morlat and Castellanet (2012); Richard and Ratsirarson (2013); Unicef (2011)	

Study impact of research on crop productivity	Bayala et al. (1998)	
Investigation of factors inhibiting adoption of techniques	Bayala et al. (1998)	
Promotion of alternative income sources (e.g. crafts, fishing, tourism)	Bayala et al. (1998); Casse et al. (2005); Ministère du Développement Rural (1973); Neudert et al. (2014); SuLaMa (2011); Vololona et al. (2013)	Without alternative livelihood opportunities no conservation of forest resources possible (Casse et al., 2004)

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