Effects of Organic and Inorganic Fertilizers on Growth and Yield of Banana (*Musa* AAA cv. Malindi) in Oman

Dissertation presented to the Faculty of Organic Agricultural Sciences Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics

BY

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Dedication

To the spirit of my father and my great mother

To my brothers and sisters

To my dear wife, sons and daughters

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Summary

The Sultanate of Oman is located on the south-eastern coast of the Arabian Peninsula, which lies on the south-western tip of the Asian continent. The strategic geographical locations of the Sultanate with its many maritime ports distributed on the Indian Ocean have historically made it one of the Arabian Peninsula leaders in the international maritime trade sector. Intensive trading relationships over long time periods have contributed to the high plant diversity seen in Oman where agricultural production depends entirely on irrigation from groundwater sources. As a consequence of the expansion of the irrigated area, groundwater depletion has increased, leading to the intrusion of seawater into freshwater aquifers. This phenomenon has caused water and soil salinity problems in large parts of the Al-Batinah governorate of Oman and threatens cultivated crops, including banana (*Musa* spp.). According to the Ministry of Agriculture and Fisheries, the majority of South Al-Batinah farms are affected by salinity (EC_e > 4 dS m^{-1}). As no alternative farmland is available, the reclamation of salt-affected soils using simple cultural practices is of paramount importance, but in Oman little scientific research has been conducted to develop such methods of reclamation. This doctoral study was initiated to help filling this research gap, particularly for bananas.

A literature review of the banana cultivation history revealed that the banana germplasm on the Arabian Peninsula is probably introduced from Indonesia and India via maritime routes across the Indian Ocean and the Red Sea.

In a second part of this dissertation, two experiments are described. A laboratory trial conducted at the University of Kassel, in Witzenhausen, Germany from June to July 2010. This incubation experiment was done to explore how C and N mineralization of composted dairy manure and date palm straw differed in alkaline non-saline and saline soils. Each soil was amended with four organic fertilizers: 1) composted dairy manure, 2) manure + 10% date palm straw, 3) manure + 30% date palm straw or 4) date palm straw alone, in addition to un-amended soils as control. The results showed that the saline soil had a lower soil organic C content and microbial biomass C than the non-saline soil. This led to lower mineralization rates of manure and date palm straw in the saline soil. In the non-saline soil, the application of manure and straw resulted in significant increases of CO_2 emissions, equivalent to 2.5 and 30% of the added C, respectively. In the non-amended control treatment of the saline soil, the sum of

CO_2-C reached only 55% of the soil organic C in comparison with the non-saline soil. In which 66% of the added manure and 75% of the added straw were emitted, assuming that no interactions occurred between soil organic C, manure C and straw C during microbial decomposition.

The application of straw always led to a net N immobilization compared to the control. Salinity had no specific effect on N mineralization as indicated by the CO_2-C to N_{min} ratio of soil organic matter and manure. However, N immobilization was markedly stronger in the saline soil. Date palm straw strongly promoted saprotrophic fungi in contrast to manure and the combined application of manure and date palm straw had synergistic positive effects on soil microorganisms. In the last week of incubation, net-N mineralization was observed in nearly all treatments. The strongest increase in microbial biomass C was observed in the manure + straw treatment. In both soils, manure had no effect on the fungi-specific membrane component ergosterol. In contrast, the application of straw resulted in strong increases of the ergosterol content.

A field experiment was conducted on two adjacent fields at the Agricultural Research Station, Rumais (23°41’15” N, 57°59’1” E) in the South of Al-Batinah Plain in Oman from October 2007 to July 2009. In this experiment, the effects of 24 soil and fertilizer treatments on the growth and productivity of *Musa* AAA cv. 'Malindi' were evaluated. The treatments consisted of two soil types (saline and amended non-saline), two fertilizer application methods (mixed and ring applied), six fertilizer amendments (1: fresh dairy manure, 2: composted dairy manure, 3: composted dairy manure and 10% date palm straw, 4: composted dairy manure and 30% date palm straw, 5: only NPK, and 6: NPK and micronutrients). Sandy loam soil was imported from another part of Oman to amended the soil in the planting holes and create non-saline conditions in the root-zone.

The results indicate that replacing the saline soil in the root zone by non-saline soil improved plant growth and yield more than fertilizer amendments or application methods. Particularly those plants on amended soil where NPK was applied using the ring method and which received micronutrients grew significantly faster to harvest (339 days), had a higher average bunch weight (9.5 kg/bunch) and were consequently more productive (10.6 tonnes/hectare/cycle) compared to the other treatments.

Zusammenfassung

Das Sultanat Oman liegt an der Südostküste der Arabischen Halbinsel und grenzt an den südwestlichen Rand Asiens. Die geographische Lage des Sultanats und seine zahlreichen Häfen entlang des Indischen Ozeans machten es zu einem strategisch wichtigen und führenden Land in der Landwirtschaft und im internationalen See- und Transithandel der Golfregion. Dabei haben intensive Handelsbeziehungen über lange Zeiträume hinweg zu einer enormen Pflanzenvielfalt im Oman beigetragen. Die landwirtschaftliche Produktion im Sultanat Oman ist jedoch fast ausschließlich vom Grundwasservorkommen abhängig, dessen Entnahme gerade im letzten Jahrzehnt stark zunahm und zum Eindringen von Meerwasser in Süßwasserkörper (Aquifere) führte. Dieser Prozess beeinflusst den Wasser und Salzgehalt des Bodens in weiten Teilen des Al-Batinah Maskat Gebietes im Oman und damit die Kultivierung von Pflanzen, einschließlich der Bananenpflanze (*Musa* spp.). Dem Ministerium für Landwirtschaft und Fischerei zufolge ist insbesondere die Mehrheit der südlichen Al-Batinah Farmen von dem erhöhten Salzgehalt im Boden betroffen (EC_e> 4 dS m^{-1}).

Da kein alternatives fruchtbares Land den Bauern zur Verfügung steht, ist die Urbarmachung salzbeeinflusster Böden durch die Erarbeitung einfacher Kultivierungspraktiken von größter Bedeutung. Jedoch wurde im Oman bis dato nur wenig Forschungsarbeit geleistet um effektive Rückgewinnungstechniken zu entwickeln. Um diesem Mangel an Wissen zu begegnen, wurde diese Doktorarbeit, mit besonderem Schwerpunkt auf die Bananenpflanze, durchgeführt. Dabei wurde zuerst die Geschichte der Banane im Oman untersucht.

Eine Literaturrecherche über die Kultivierungsgeschichte der Bananenpflanze zeigte, dass dessen Genotypen nicht aus der Region der Arabischen Halbinsel stammen und vermutlich aus Indien und Indonesien über den Indischen Ozean und dem Roten Meer eingeführt wurden.

Im zweiten Teil der vorliegenden Dissertation werden die Ergebnisse zwei weiterer Studien präsentiert. Einem Laborexperiment an der Universität Kassel in Deutschland und wurde im Juni und Juli 2010 durchgeführt. Bei diesem Inkubationsexperiment sollte die Kohlenstoff (C)- und Stickstoff (N)-Mineralisierung von Kuhdung und Dattelpalmstroh auf alkalisch salzhaltigen und salzarmen Böden untersucht werden. Die Mineralisierung von C und N wurde in zehn Bodenproben untersucht. Dabei wurden zwei Bodentypen (salzhaltig und

salzarm) jeweils mit einem der vier organischen Düngerspezifikationen versetzt (1: kompostierter Kuhdung, 2: Kuhdung + 10% Dattelpalmstroh, 3: Kuhdung + 30% Dattelpalmstroh, 4: Dattelpalmstroh und 5: unbehandelte Kontrolle).

Die Ergebnisse zeigten, dass salzhaltige Böden geringere organische C-Gehalte und mikrobielle C-Biomasse aufwiesen als salzarme Böden, was zu niedrigeren Mineralisierungsraten von Kuhdung und Dattelpalmstroh im salzhaltigen Boden führte. In salzarmen Böden führte die Behandlung mit Kuhdung zu einer signifikant höheren CO_2 Emission, was dem 2,7fachen bzw. 30% des zugegebenen C entsprach. Im Gegensatz zu der unbehandelten Kontrolle mit salzarmen Böden erreichte die Summe des CO_2-C in der Kontrollbehandlung mit salzhaltigen Böden nur 55 % des organischen Kohlenstoffs im Boden. In dem 66% des zugegeben Kuhdungs und 75% des Dattelpalmstrohs emittiert wurden. Diesem liegt die Annahme zugrunde, dass keine Interaktionen zwischen organischem C im Boden, Kuhdung C und Dattelpalmstroh C während der mikrobiellen Zersetzung stattfindet.

Die Anwendung von Dattelpalmstroh führte immer zu einer Netto-N-Immobilisierung wobei diese im salzhaltigen Boden deutlich stärker war. Jedoch hatte der Salzgehalt keine wesentlichen Auswirkungen auf die N-Mineralisierung, was sich im CO_2-C/N_{min} Verhältnis bei Humus und Kuhdung widerspiegelte. Das ausgebrachte Dattelpalmstroh förderte das Wachstum von saprotrophen Pilzen stärker als Kuhdung. Die kombinierte Anwendung von Kuhdung und Dattelpalmstroh hatte synergetisch positive Auswirkungen auf die Bodenmikroorganismen. In der letzten Woche der Inkubation wurden Netto-N-Mineralisierungen in fast allen Behandlungen beobachtet. Die stärkste Zunahme der mikrobiellen C Biomasse wurde in der Kuhdung- und Dattelpalmstrohbehandlung gemessen. In beiden Bodentypen hatte Kuhdung keine Auswirkung auf die pilzspezifische Membran-Komponente Ergosterol. Im Gegensatz dazu führte der Einsatz von Dattelpalmstroh zu einem starken Anstieg des Ergosterolgehalts.

Die vorliegende Doktorarbeit zeigt auf, dass die Arabische Halbinsel eine hohe Anzahl an Bananenvarietäten beherbergt, welche potentiell ein weites Spektrum an Toleranzen oder gar Resistenzen gegenüber verschiedenen Umweltbedingungen aufweisen könnten. Damit stellt diese Region ein wichtiges „Reservoir“ genetischer Diversität dar, welches für die Nachhaltigkeit der wenigen Kulturbananensorten der Welt erforderlich ist. Der Austausch von salzhaltigen mit salzarmen, sandig lehmigen Böden in der Wurzelzone von Bananenpflanzen, die Vorbehandlung mit Kuhdung und anorganischem Dünger als auch die Anwendung der Ringdüngung sind geeignete Praktiken um salzbeeinflusste Böden im Oman urbar zu machen. Um adäquate Nutzungspraktiken und Anwendungstechniken zu bestimmen, sind weitere, detaillierte Untersuchungen notwendig, die unter anderem die Dungapplikation von Huhn oder Wiederkäuern und kompostiertem Dattelpalmstroh berücksichtigen sollten.

Wurde ein Feldversuch auf der Landwirtschaftlichen Forschungsstation Rumais (23 ° 41'15 "N, 57 ° 59'1" E) im Süden von Al- Batinah von Oktober 2007 bis Juli 2009 durchgeführt. In diesem Experiment sollten die Auswirkungen von 24 Düngerbehandlungen auf das Wachstum und die Produktivität des ersten Erntezyklus von *Musa* AAA cv. "Malindi" untersucht werden. Die Behandlungen fanden auf zwei verschiedenen Bodentypen statt (salzhaltig und salzarm) und bestanden aus zwei Applikationstechniken für Dünger (gemischt und Ringdüngung) sowie aus sechs Düngerspezifikationen (1: frischer Kuhdung, 2: kompostierter Kuhdung, 3: kompostierter Kuhdung und 10% Dattelpalmstroh, 4: kompostierter Kuhdung und 30% Dattelpalmstroh, 5: nur NPK, 6:NPK und Mikronährelemente). Um salzarme Bedingungen in der Wurzelzone der Pflanzen zu schaffen, wurden Lehmböden mit einem hohen Sandanteil aus einem anderen Gebiet des Omans importiert und in die Pflanzenlöcher ausgebracht. Die Ergebnisse wiesen darauf hin, dass die Ausbringung von importiertem salzarmen Boden im Wurzelbereich der Pflanzen zu einem besseren Wachstum und Ertrag führte als die Zugabe von Dünger oder der Art der Düngerapplikation. Insbesondere Pflanzen auf Böden mit Zugabe von NPK und Mikronährstoffen mittels Ringdüngung erreichten signifikant schneller den Erntezeitpunkt (339 Tage), hatten ein deutlich höheres Bündelgewicht (9,5 kg/Bund) und wiesen die höchste Produktivität von 10,6 Tonnen/ha/Zyklus auf.

Chapter 1. General introduction

1.1 Some notes about banana on the Arabian Peninsula

Bananas (*Musa* spp.) and plantains are staple food crops for millions of people in the tropics and subtropics (Frison and Sharrock 1998; De Langhe et al. 2010) and belong to the oldest domesticated plant species (Denham et al. 1996). Recent textual, linguistic, genetic and archaeological evidence suggest that South Asia is the origin of bananas and that the bananas presently found throughout the tropics all came from this area (Harries 1967; Nizami 1994; De Langhe et al. 2009; Fuller and Madella 2009; Perrier et al. 2011). The strategic location of the Arabian Peninsula at the intersection of several main Old World trade routes has made it an incubator for bananas coming from different continents of the world, in spite of dry episodes experienced by this region during the Holocene Age (Boivin and Fuller 2009). However, the history of domestication, origin of varieties as well as periods and routes of introduction of bananas to the Arabian Peninsula has not been extensively studied. Especially the lack of archaeological and historical evidence has given rise to a lot of speculation (De Langhe et al. 2009; Buerkert et al. 2009). Tracing the history of bananas in this region and understanding the drivers of their diversity under inhospitable conditions may help maintain and further develop banana cultivation in similar areas of the world, especially in light of predicted climate change.

1.2 Banana cultivation in Oman: Status quo and challenges

Banana is a monocotyledonous, herbaceous and evergreen perennial crop belonging to the Musaceae family. It is mainly eaten as a dessert fruit (Robinson 1996). Globally, banana is both an economically and socially important fruit crop in tropical and sub-tropical areas. In Oman, banana is the second most important fruit crop after date palm (*Phoenix dactylifera* L.) in terms of area and production. It occupies 10% of total cultivated fruit crop area and 16% of the total annual fruit production (MAF 2011). Al-Batinah and Dhofar Governorates are the most important banana growing areas accounting for 60% of the total cultivated area under banana in the country (MAF 2011). The strategic location of Oman as an ancient trading route between Far East countries, East Africa and the Indian subcontinent might be one of the reasons for the existence of the country’s genetic diversity in banana which is documented in more than 30 varieties maintained in the gene bank of the southern Oman Dhofar Governorate.

Recent climate modelling studies indicate that the Arab region may face increases in temperature between 2 to 5.5°C by the end of the 21st century and precipitation will decrease between 0 to 20% (Mustafa and Najeb 2008). Already at present agricultural production in Oman is severely limited by high ambient temperatures (average 40°C), low rainfall (<100 mm/year) and the fact that the majority of soils are sandy and have low levels of organic carbon (MAF, 1993). Owing to the arid climate, except in the Indian summer monsoon-influenced southern Omani Dhofar Governorate, all agricultural production in Oman is based on irrigation from groundwater sources which depend on rainfall to be replenished. Wells, springs and the *aflaj* system are the main sources of irrigation water and have been the secret of agricultural sustainability in Oman over the past decades (Norman et al. 1998; Siebert et al. 2007; Nash and Agius 2011). In Oman, between 80 to 90 % of ground water is used in agricultural production (Norman et al. 1998).

The most important limiting factor for agriculture sustainability in Oman is the fluctuation of annual precipitation. Kwarteng et al. (2009) noticed a negative trend for annual precipitation in Oman over the last two decades. Furthermore, in the last decade, there also was an area expansion of agriculture which resulted in excessive withdrawal of groundwater. This led to intrusion of seawater into the coastal aquifers whereby water and soil became saline (MAF 1993). About 50% of planted area at the northern Omani South Al-Batinah Governorate is irrigated with low quality water. This affects about 60% of the vegetables and fodder area and 40% of the land under fruit crops. About 3.5% of the banana plantations are irrigated with water < 2 dSm^{-1}, 3.2% with 2-3 dSm^{-1} and 1.9% with 3-5 dSm^{-1} (MAF 1993). As a result of this, many banana farms have been abandoned. Owing to the lack of alternative land, the development of effective methods for rehabilitation of these farms is essential.

1.3 Salt-affected soils: Reclamation and management

Salinity is one of the greatest constraints facing agricultural production worldwide, particularly in arid and semi-arid countries where scarcity of water and high temperatures prevail. Improvement of crop growth and productivity in low fertility non-saline soils is rather easy to achieve and largely depend on economics. Early studies have demonstrated that application of organic and inorganic fertilizers increased growth and yield of bananas (Ghanta and Mitra 1993; Geetha 2000; Anchanam and Abdul Khader 1980; Halder et al. 2003;

Chattopadhyay 1986). However, obtaining economically attractive yields of banana is much more difficult in arid and semiarid areas such as Oman where salt-affected soils that are the results of accumulation salts into the soil due to the high temperatures, and insufficient rainfall for leaching prevail. In Oman, both factors have led to major increases in the salt concentration of irrigation water and agricultural soils (Siyal et al. 2002; Rietz and Haynes, 2003; Zaka et al. 2005; Baiyeri and Tenkouano 2008; Wairegi and van Asten 2010). Several methods have been proposed to reclaim salt-affected soils. Mahdy (2011) divided them into physical approaches (e.g. deep ploughing, sub soiling, sanding), chemical ones (e.g. gypsum, limestone), and biological ones (plant residues, manures), in addition to electro-reclamation (electric current). Others (Siyal et al. 2002; Hussain et al. 2001; Al-Ismaily and Walworth 2008; Abd el Moniem et al. 2008) considered leaching and the addition of soil amendments such as gypsum, manures, inorganic amendments as major avenues to reclaim saline soils. Integrated management approaches which include physical, chemical, biological and cultural practices could be an efficient way to reclaim salt affected soils (Zaka et al. 2005; Mahdy 2011). For example, Akhater et al. (2004) improved degraded physical properties of a saline-sodic soil by planting kallar grass (*Leptochloa fusa*). Also, Sadiq et al. (2007) showed in a recent reclamation study of saline-sodic soils that combining tillage and gypsum ($CaSO_4{\cdot}2H_2O$) led to improved soil chemical properties and increased rice and wheat grain yields.

It is well known that loading of the plant root zone environment with salts can affect the ability of plants to absorb nutrients and cause toxicity effects thereby leading to a decline in plant growth and productivity (Munns 2002; Parida and Das 2005; Massa et al. 2009). Therefore, an amelioration of the saline-root zone environment (Raviv et al. 1998; Burn et al. 2001; Massa et al. 2009) is a key factor to counter salinity stress. In this respect, different strategies have been proposed to deal with salt-affected soils. Grattan and Grieve (1999) favoured the application of excessive amounts of fertilizers in the root-zone to limit or mitigate of salt effects on plant growth, while Brun et al. (2001) advocated soilless-culture. This, however, is no solution for perennial plants like banana. To our knowledge, the approach to replace the saline soil in the immediate root environment by a non-saline soil and the application of organic and / or inorganic fertilizers to manage salt-affected soils have not been sufficiently studied, especially in Oman.

1.4 Soil organic matter turnover: Toward agro-ecosystem sustainability

In any agro-ecosystem, soil organic matter (SOM) whether fresh or composted plays a vital role in maintaining nutrient availability and thus plant productivity (Duong et al. 2011). However, this role is greatest in low fertility soils (Sall et al. 2003) where large fertility improvements may occur. Soil organic matter can improve physical, chemical and biological properties of a soil besides providing soil organisms with energy and plants with essential nutrients (Marinari 2000; Nyberg et al. 2006). Decomposition of organic matter in soil is the most important prerequisite to make these nutrients available, often through microbial biomass which is part of organic matter produced by soil microorganism (Benbi and Richter 2002; Jedidi et al. 2004). However, this process is affected by many factors such as the initial C/N concentration of the substrate (amendment), soil type and quality, soil pH, temperature, moisture, and secondary compounds in the substrate (e.g. tannins, lignin and cellulose), management practices and other soil properties (Smith 1979 and 1992; Dijajakirana et al. 1996; Tang and Yu 1999; Joergensen 2000; Hartz et al. 2000; Anderson and Nilsson 2001; Sall and Masse 2003; Griffin et al. 2005; Flavel and Murphy 2006). Duong et al. (2011) found that fine-textured compost mulches had larger effects on soil properties and growth of wheat than course-textured ones. Similarly, Abera et al. (2012) noticed that inorganic N released in the form as NH_4^+ and NO_3^- was larger in soils amended with pigeon pea (*Cajanus cajan* L. at a C/N ratio of 20.4) than with haricot bean (*Phaseolus vulgaris* L at a C/N ratio of 40.6). In the study on the effect of wheat, rape (*Brassica napus* L.) and alfalfa (*Medicago sativa* L.) residues on microbial communities, Pascault et al. (2010) noticed that alfalfa residues caused greater modifications of bacterial communities and their activity than wheat residues, indicating that biochemical composition and recalcitrant substances in plant residues is an important factor in this effect. Similarly, Lejon et al. (2007) noticed changes in the bacterial and fungal communities as a result of organic amendment application. In addition to livestock manures; cattle and ruminant manures (Schlecht et al. 2011; Siegfried et al. 2011), cereal and legume plant residues are commonly used as a resource of organic matter due to their rich-N (Formowitz et al. 2009; Abera et al. 2012). According to Formowitz et al. (2009), microbial biomass C, microbial biomass N, ergosterol concentration and cumulative CO_2-C production increased in the soil after application of legume and cereal roots residues soil. In laboratory a 135 day incubation experiment, Abera et al. (2012)

noticed an increase of the cumulative CO_2-C flux throughout the incubation period. On the other hand, incorporation of low-N plant residues such as corn (*Zea mays* L.; Khorsandi and Nourbakhsh 2007) and un-composted date palm (*Phoenix dacylifera* L. containing highly recalcitrant substances such as cellulose, see also chapter 3) to the soil are undesirable in case of short crop life cycles such as in vegetables due to their temporary N fixation (Favel and Murphy 2006). In contrast, other authors found that application of these materials combined with N-rich soil organic amendments is sometimes important to reduce nitrate leaching (Rocous et al. 1995; Mary et al. 1996; Vinten et al. 1998; Al Al-Shaikh et al. 2009). The study of Khorsandi and Nourbakhsh (2007) on the effect of manure and corn residues on N mineralization showed that mineralized inorganic N has increased from 64 to 86% in un-amended soil compared to manure and corn amended soil which ranged from 50 to 86% and thus reduced nitrate leaching. Such practices are important in hyperarid soil conditions like Oman that are characterized by high temperatures that could lead to increased decomposition rates of organic matter and thus rapid N mineralization (Burgos et al. 2006) and a lower N use efficiency for perennial crops such as banana. In Oman, large amounts of date palm residues produced are burned which could find use in agriculture. To his end, however, cultural practices must be developed to make use of these residues by studying the pattern of N-dynamics in case of their incorporation into the soil, alone or combined with manure.

1.5 Salinity and organic matter decomposition

In arid and semi-arid countries like Oman, soil salinity is part of many agro-ecosystems (Pathak and Rao 1998; Setia et al. 2010). Salinity affects soil microbial communities, can cause severe changes in the process of organic matter turnover (OMT; Wichern et al. 2006) and thus reduce the released of plant nutrients (Pathak and Rao 1998). The effects of salinity on soil microbial communities and OMT have been the subject of many recent studies (Mamilov et al. 2004; Tripathi et al. 2006; Wong et al. 2008; Yousif and Mubarak 2009; Rasual et al. 2009; Setia et al. 2010; Chowdhury et al. 2011) and they agree on the negative effects of salinity on the activity of microbial comminutes and thus OMT decomposition. It was observed that high salinity decreased CO_2 production and soil microbial biomass (Malik et al. 1979; Pathak and Rao 1998; Rietz and Haynes 2003; Wong et al. 2008). In a 19 day incubation experiment Setia et al. (2010)

noticed reduced soil respiration (CO_2-C) of up to 50% an EC_e of 5 dSm^{-1}. In early studies (McCormick and Wolf 1980; Bandyopadhyay 1983; Darrah et al. 1987; Gomah et al. 1989), it was noticed that N mineralization was depressed by increasing salinity. On the other hand, the negative effect of salinity on OMT is not consistent; it seems to be modulated by many factors such as soil pH, soil texture, contents of organic matter and cultural practices (Li et al. 2006a/b; Setia et al. 2010) as well as the ability of soil microorganism to adapt to osmotic stress induced by drought or salinity (Sparling et al.1989). In a laboratory experiment, Nourbakhsh et al. (2006) noticed that salinity did not significantly decrease N mineralization/immobilization in a soil amended with roots of wheat and barley, which suggest that initial N concentration of plant residues determines transformation trends of mineralized or immobilized N. This means that the interaction between the quality of plant residue and their effects on salinity merits further studies.

1.6 Research objectives

The aim of this investigation was:

1. To quantify N mineralization of composted manure and date palm in non-saline and saline soils of northern Oman.
2. To study the effects of salinity on soil microbial activities.
3. To elaborate cultural method to reclaim salt-affected soil through amending saline root–zone environment and fertilizer combinations.
4. To trace banana domestication in Arabian Peninsula through a literature review.

1.7 Research hypotheses

This PhD study aimed at testing the following research hypotheses:

1. Application of composted manure to alkaline hyper-arid soils of Oman improves their fertility and productivity.
2. Soil salinity decreases C and N mineralization.
3. Replacing the plant root zone in a saline soil by a non-saline sandy loam soil and adding mineral fertilizers will improve the growth and productivity of *Musa* AAA cv. 'Malindi'.

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Chapter 2. Bananas on the Arabian Peninsula: A Review of their domestication history

2.1 Introduction

Bananas have a long history of domestication and the role of mankind in their diffusion throughout the tropical and subtropical regions of the world has made them one of the most important fruit crops. Over the centuries, bananas have contributed to the stability of rural communities where they have provided work for farmers and reduced farmer migration to cities in search of alternate livelihoods (De Langhe et al. 2009). Bananas are cultivated in more than 100 countries and provide food for millions of people (De Langhe et al. 2009). Bananas rank fourth after rice, wheat and maize in terms of food crops (De Langhe et al. 2009). Eighty-seven percent of bananas produced globally are consumed locally (Biodiversity International 2012). Even in many countries of the Arabian Peninsula, bananas play an important role as a food crop, although this arid region has an ecologically unfavourable climate for banana cultivation. Banana production in Arabian countries accounts for 2% of the total world banana production and 1.5% of total area harvested (FAOSTAT 2010).

Over the past millennia, the banana domestication process has undergone different stages involving exploitation, hybridizations, somatic mutations and cultivation inside the natural habitat (De Langhe et al. 2009). Subsequent steps involved the dispersal of domesticated varieties outside their natural habitats, to different geographical regions of the world. This led to often unpredicted genetic changes in banana varieties (Buerkert et al. 2009; De Langhe et al. 2009).

Given the serious challenges in particular biotic and abiotic stresses facing sustainable banana production, in addition to local problems such as oasis modernization (Buerkert et al. 2009; Al-Saady et al. 2010; Opara et al. 2010), understanding and tracing banana diversity in the Arabian Peninsula is important. The diverse cultivars found in this region of the world include specially adapted varieties, not found anywhere else in the world. This chapter highlights the history of banana domestication in the Arabian Peninsula areas, particularly introduction and cultivation by reviewing papers that discuss linguistic, genetic and archaeological evidence as well as maritime routes that were perhaps used to introduce bananas to the Arabian Peninsula.

2.2 Banana domestication in the world

2.2.1 Classification and distribution of banana species

The exact date of banana domestication is still subject to speculation, but recent multidisciplinary evidence indicates that the first domestication stage took place about 4500 years before present day (BP) (De Langhe and de Maret, 1999; De Langhe et al. 2009). However, based on the archaeological evidence from New Guinea, Perrier et al. (2011) claimed that the cultivation of domesticated banana varieties started about 6500 years BP. Human contact and migration played a crucial role in the domestication of banana varieties outside their natural habitat (Mindzie et al. 2001; De Langhe 2009; Vrydaghs 2009; Perrier et al. 2011).

Banana belongs to the family Musaceae which includes three genera; Asian and African *Ensete*, Asian *Musella* and East Asian *Musa* (De Langhe et al. 2009; Perrier et al. 2011). All edible bananas belonged to the genus *Musa* (De Langhe et al. 2009; Perrier et al. 2011). Simmonds (1962) divided the genus of *Musa* into 4 sections (Figure 1): Eumusa which covers all of East Asia, except Eastern Melanesia, Rhodochlamys which is spread along the monsoonal mainland of Southeast Asia, Australimusa which is distributed from south-eastern Indonesia and the southern Philippines to Melanesia, and Callimusa which is presented in Southern Vietnam, Malaysia, Borneo and Sumatra. According to Simmonds and Shepherd (1955), most of the edible diploid and triploid bananas are formed by inter- and intra-specific crosses of *M. acuminate* (A) and *M. balbisianana* (B) and are classified into the groups representing both their ploidy and species composition, that is AA, AAA, AAB and ABB. Fuller and Boivin (2009) mentioned that most plantains belonged to the AAB group and most desert bananas to AAA.

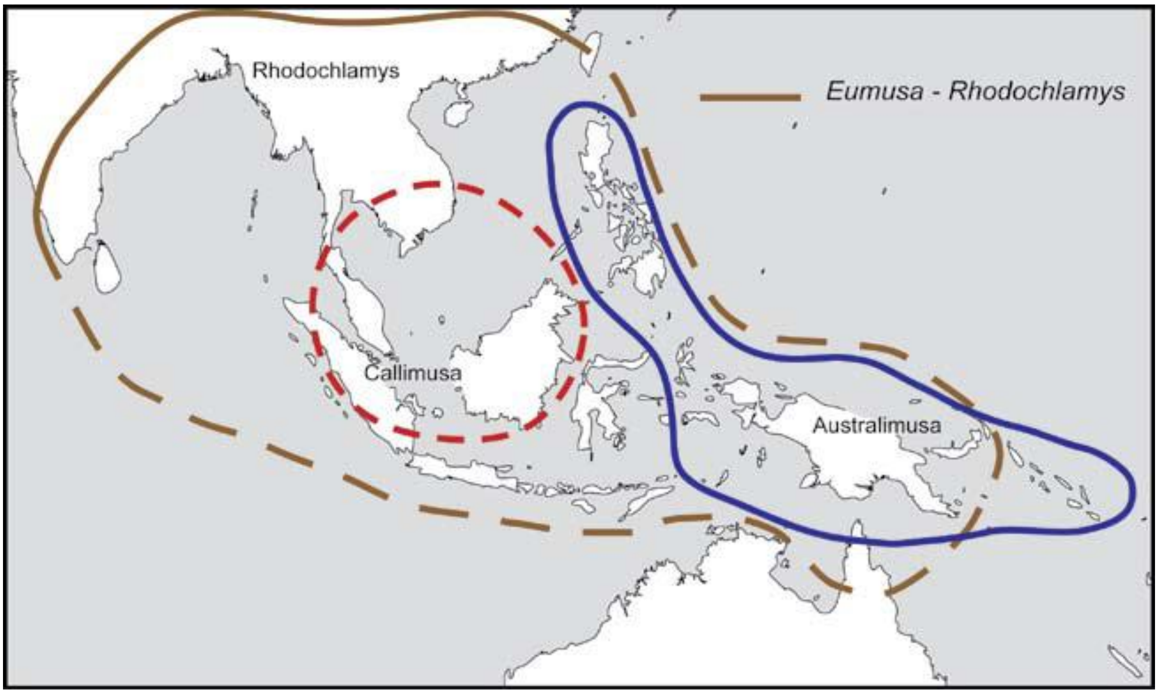

Figure 1. Distribution of *Musa* genus in East Asia (Simmonds 1962, altered from De Langhe 2009).

Secondary and tertiary distribution followed (Figure 2) and produced seven recognizable geographical areas each with a high density of specific cultivars (De Langhe 2009).

1) AA and AAA cultivars in the triangle between Indonesia, the Philippines and Melanesia (red line), with an exceptional density of AA cultivars in and around New Guinea (black oval);
2) Highland AAA bananas in the Great Lakes region of East Africa (East African Highland Bananas: EA-AAA 'Highlands'; area not shown on map in Figure 2) ;
3) AAB plantains in the rainforest zone of Africa (area not shown on map in Figure 2);
4) AAB Maia Maoli-Popoulu-Iholena cultivars in Oceania (dark grey line);
5) AB (brown oval) and other AAB (pale grey circles) cultivars in South India;
6) Eastern ABB cultivars in the Philippines and Vietnam (blue line - closed);
7) Western ABB cultivars in Northeast and South India (blue line - open).

Linguistic and cultural evidence indicates that West Africa was the earliest centre for growing AAB plantains, while specimen of the AAA group were the first grown in East Africa (De Langhe and Maret 1999; De Langhe 2009; Blench 2003). The great diversity of cultivars in these areas and Iron Age phytoliths of banana found in Cameroon support this evidence (Mbida et al. 2000).

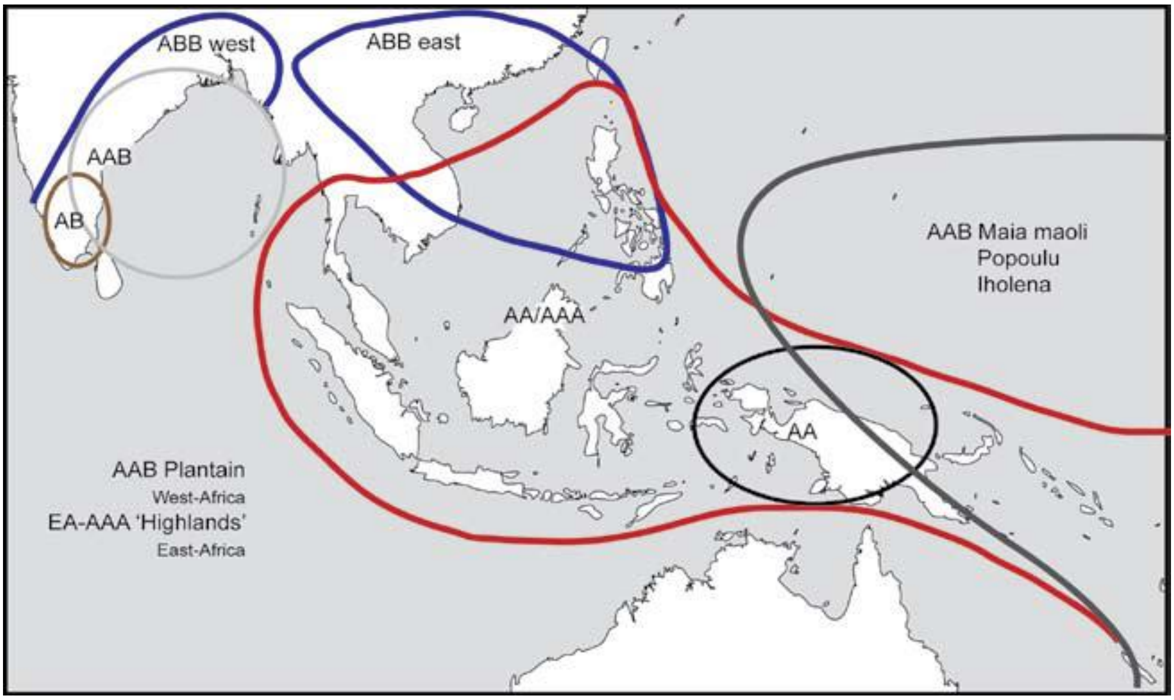

Figure 2. Distribution of the main banana cultivar groups (taken from De Langhe et al. 2009).

2.2.2 Origin and migration routes of banana species from natural habitat to other continents

Recent DNA and fingerprinting analyses of more than 400 wild and cultivated accessions, in addition to samples taken from Cameroon and Nigeria to better represent the diversity found in Africa, revealed that the islands of Southeast Asia and Western Melanesia likely are the main centre for the hybridization between different *M. acuminata* subspecies which generated edible diploids cultivar subgroups (AA cultivars; Perrier et al. 2011). Banana domestication passed through two stages: first the translocation from wild to edible diploids by hybridization of *M. acuminata* during the Holocene in New Guinea (Simmonds 1962; Perrier et al. 2011) and subsequently the development of edible triploids (AAA) from edible diploids (AA) via spontaneous triploidizations (Perrier et al. 2011). Most domesticated bananas are triploid, including the widely distributed commercial Cavendish group (Perrier et al. 2011). Lastly, Perrier et al. (2011)

used genetic, linguistic and archaeological data to determine the locations of banana groups. They suggested three contact areas of *M. acuminata* subspecies where the development of domesticated diploids took place: the Northern contact area with *malaccensis, microcarpa* and *errans* in South East Asia, Borneo and the Philippines; the eastern contact area with *errans* and *banksii* between the Philippines and New Guinea; and the Southern contact area with *banksii*, *zebrina* and *microcarpa* located between New Guinea and Java. It seems clear that the islands of Southeast Asia are the origin for all bananas and subsequently the different groups migrated to different areas of the world (Perrier et al. 2011). Based on this, Perrier et al. (2011) suggested two independent introduction events for triploid subgroups to Africa:

(i) AAA Mutika Lujugira and associated AAcv moved from the region between New Guinea and Java (Southern contact area) to East Africa;

(ii) AAB African Plantains moved from the Philippines and New Guinea (Eastern contact area) to Africa.

These hypotheses were also supported by Blench (2009) who mentioned that based on the botanical and linguistic evidence West African plantains (AAB) arrived from Southeast Asia earlier than 3000 BP. Similarly, Fuller and Madella (2009) hypothesized that the major diffusion of banana cultivars occurred in the later Iron Age, 2000 years BC. This is based on textual sources and historical linguistics from South Asia and China.

2.3 Banana domestication on the Arabian Peninsula

2.3.1 Geography of the Arabian Peninsula and early agriculture

The Arabian Peninsula is natural point of contact between the continent of Africa from the West and the Levant and Europe from the north and the continent of Asia from the east (Boivin and Fuller 2009). In most of the Arabian Peninsula, the desert climate is considered the most important agro-ecological factor to determine landuse. The Arabian Peninsula is located between two main rainfall patterns: the winter rains of the Mediterranean region and summer monsoon rains (Boivin and Fuller 2009). Digging wells and extracting water from aquifers supported agriculture in lowland oases and coastal regions which have insufficient rainfall (Edens 1993 and Blau 1999). The later development of the *aflaj* system (Magee 2005) leads to increased use of oases for agriculture and allowed the cultivation of different crops. Agricultural and accompanying maritime activities in the Arabian Peninsula have been triggered to a large extent by changes in climatic conditions over the Holocene period.

The early and middle Holocene (9000 to 2500 before Christ (B.C.) periods were characterized by relatively high rainfall intercepted by pronounced dry periods, in particular between 4000 to 4500 years B.C. (Boivin and Fuller 2009). During this period, settlements were established in the desert areas such as the Eastern Sahara or Arabian Desert from northern Egypt to Eritrea in the south and parts of Sudan and Ethiopia, which were inhabitated by Egyptian/Sudan groups (Hassan 1997; Fuller 1998). The Thar desert or Great Indian Desert (arid region in the north-western part of the Indian subcontinent) was settled by Mesolithic groups from India / Pakistan (Fuller 2006). Similarly, the An Nafud or Al-Nefud settlement (located in the Northern part of the Arabian Peninsula) was established and with vegetables and fruits were grown (Boivin and Fuller 2009).

In the mid-Holocene (6000 to 5900 BC), the conditions were wetter than at present and this was also the case for An-Nafud in the north of the Arabian Peninsula (Lézine et al. 1998). Based on the Al Hawa data from Yemen in the seventh millennium BC, different dry periods occurred, particularly from 6200 to 6000 BC when East Africa and South Asia became very dry (Alley and Ágústdóttir 2005, Madella and Fuller 2006). Potts (2008) mentioned that in the seventh millennium BC, Arabia was more attractive to the people than the Levant and Mesopotamia and this might have contributed to their migration to Arabia and the associated transfer of cultivated plant species from the Levant to Arabia. Evidence from northern Oman, the United Arab Emirates and the An-Nafud region indicates a period of aridity around 3800 BC called the 'Dark Millennium' during which even well established settlements collapsed (Uerpmann 2003). Additionally, evidence from the Awafi palaeolake in the United Arab Emirates indicates that during the period from 3900 BC and 3200 BC, two arid periods led to a general decline of vegetation and its disappearance in Eastern Arabia (Parker et al. 2004, 2006).

2.3.2 Introduction of crops to the Arabian Peninsula in the Bronze Age

The fertile periods in the early and middle Holocene experienced by the Arabian Peninsula and the establishment of agricultural settlements such as An-Nafud encouraged the entry of various agricultural crops including banana. Hammer et al. (2009) reported that about 21.3 % of plant species in the Arabian

Peninsula came from South and Southeast Asia, 20.6 % from the Near East and East Mediterranean and 15.4% from South America. This data supports the view of Boivin and Fuller (2009) who considered that most of the plants and animals in the Arabian Peninsula region are not native to this region. Despite the limited archaeological evidence of agriculture in the Arabian Peninsula the presence of agricultural equipment (Potts 1994), of ancient (3200 BC) irrigation systems in the highlands of Yemen (Harrower 2008) and the great areas of wheat and barley cultivation in some areas of the Arabian and Persian Gulf region indicate that agriculture has been practiced in this region for a long time.

Taking into accounts the geographical distribution of banana genotypes (Figure 2), it seems that the Arab/Swahili and Malagasy-Malay (after 600 AD) trade played a vital role in the early dispersal of banana across the Indian Ocean and Red Sea to the Arab world. Similar banana varieties are found in Oman and Egypt (Castillo and Fuller 2012). This trade route dispersal theory is supported by the discovery of remains of banana peels from the Arab trading period in Quesir al-Qadim located on the coast of the Red Sea (Van Der Veen 2011).

In general, data indicate that the early third millennium saw the introduction of different crops including banana from Africa, South and Southeast Asia to the Arabian region (Boivin and Fuller 2009). This has been confirmed by intensive presence of bread wheat in the Persian Gulf and the presence of the same variety in Asia particularly in the Indus region (Fuller 2003; 2006). This indicates the starting of crop migration from South Asia to the Arabian Peninsula. Also, in Yemen, Egypt and Nubia emmer wheat was dominant until the first millennium BC (Fuller 2004), suggesting genetic exchange between the Arabian Peninsula and North Africa.

According to Robinson (1996), banana is mentioned in the Holy Koran as the 'tree of paradise' and the name of the genus (*Musa*) is derived from the Arabic word Mouz. Ancient Egyptian drawings already show bananas and it is believed also that the Assyrian civilization, which extended its authority to the Nile, introduced bananas to the Middle East (Attif and Muhammad 2000). In 327 BC, the first accurate description of bananas appeared in Greek books after the invasion of India by Alexander the Great; however, it is believed that Arabs introduced bananas from India to the Middle East and North Africa (Attif and Muhammad 2000). Kinder and Hilgemann (1974) mention that the arrival of

Muslims in India, where a great variety of bananas exists, may have contributed to the introducing of bananas to the Arabian Peninsula.

Despite the long and ancient history of banana cultivation in the Arabian Peninsula, the archaeological and historical evidence is still limited. The exact origin, entry date and routes of banana introduction to this region remain a source of speculation. Since edible bananas reproduce vegetatively and not by seeds, their spread is particularly difficult to track (Vrydaghs et al. 2009).

Potts (1994) mentioned that banana arrived in south-eastern Arabia by the 9th Century. Historical and cultivation evidence suggests that the origin of the banana planted in Dhofar and Yemen described in Medieval times (Varisco 1994) was New Guinea/Indonesia (De Langhe and Maret 1999; Kennedy 2008) and the Valley of the Indus (Fuller and Madella 2001). Archaeobotanical evidence from Oman (Muweilah, Mleiha, Hili Bat, Ras al-Hamra, Ras al-Jinz), United Arab Emirates (Dalma, Umm an-Nar, Tell, Abraq, Muweilah, Mleiha, and Rumeilah and Yemen (Sabir, Hajar Bin Humeid, Hajar al-Tamrah, Haja al-Rayhani, Baraqish, Raybun and Khawlan sites: al-Raqlah, Jubabat al-Juruf, Wadi Yanaiim, Dhamar sites: Hayt al-Suad, al-Massanah) indicates that plants were domesticated in Arabian Peninsula between 1500-5000 BC, (Boivin and Fuller 2009) and bananas could therefore have been introduced even earlier than in the 9th century BC.

2.3.3 Banana genetic diversity on the Arabian Peninsula

Despite periods of drought experienced throughout the Arabian Peninsula in successive millennia, bananas have not vanished. This was previously noted in the report of a survey by De Langhe (2002) in some Arabian countries. He pointed out the existence of large banana genetic diversity in this region. The bananas found in the Middle East (Jordan, Egypt and Oman), belong to the subgroups AA, AAA, AAB, AB and ABB (De Langhe (2002). The crop may have undergone some modification over time, which made it more adapted to the arid regional conditions.

Genetic mutations and human practices such as cultivation of banana under the shade of date palm in the Interior Governorate of Oman to provide humid microclimate could be one of the factors which have contributed to the survival of this crop in this region. As mentioned previously, Southeast Asia is the main source of banana; however the bananas present on the Arabian Peninsula today did not necessarily come directly from Southeast Asia, but may have travelled through Africa or India, before reaching the habitats on the Arabian

Peninsula. However, this dispersal theory remains controversial. Buerkert et al. (2009) hypothesize that the AAA cultivar (cv. 'Umq Bir') recently discovered in the Upper Tiwi Valley of Oman reached there via East Africa, most likely Zanzibar, Madagascar or the Comoros islands where many AA and AAA cultivars are available. More than 31 accessions of banana were planted in 1997/1998 at the Salalah Agriculture Research Station of Dhofar Governorate, Oman. The origins of these accessions are the Comoros Islands, Zanzibar and India (De Langhe 2002). Recently, nine hybrid cultivars (FHIA) were introduced by INIBAP and evaluated under southern (Dhofar Governorate) and northern Omani (North Al-Batinah Governorate, Sohar) conditions with respect to yield and tolerance to biotic and abiotic stresses, especially Sigatoka and Panama disease as well as salt and heat stress. When banana varieties are transferred from one area to another, their names sometimes remain the same and in this case it is easy to trace them (De Langhe 2002). However, sometimes the names are changed immediately after arrival to a new place or after different generations which makes it more difficult to trace and identify them linguistically (Perrier et al. 2011). For example, in Yemen banana are called ‘Al-Mawaz Al-Hindi’ which means Indian Banana. In Egypt banana is also called ‘Hindi’. In Oman, the ‘Somali’ banana variety may have been introduced from Somalia by individuals while the ‘Malindi’ variety might have entered Oman from the town of Malindi located northeast of Mombasa, on the Indian Ocean. Similarly, the ‘Zanzibar’ variety likely is from the Island of Zanzibar (Tanzania). The ‘Fardh’ variety belongs to the Mysore group possibly having been introduced from near the town of Mysore in India, the plantain ‘Kenya’ from Kenya and ‘Abubaker Pilipino’ from the Philippines.

2.3.4 The role of the Arabian Peninsula in inter-regional and inter-continental exchange of crops

There has been a lot of discussion about the role of the Arabian Peninsula’s maritime ports in the transmission of plant materials, including banana, to different regions of the world. This role is supported through ancients tombs discovered in Bahrain and Kuwait, dating back to the second millennium BC and through Geniza records, pointing to an early contact of Arabs with South Asia (Nizami 1994). Also, Sangam literature reveals that Alexandria was a trade base for South Asia and the ancient city of Palmyra in Syria had an active trade with India (Nizami 1994). The long presence of Arabs in India is reflected by the use of the word *Hindi* as the suffix to Arabic terms such as Mauz Hindi, Ud Hindi and Tamar Hindi (Nizami 1994). Watson (1983) suggests that medieval Arab trade played a vital role in introducing banana to East Africa and Madagascar. This was confirmed by Sauer (1952) and Cleuziou and Tosi (1989) who believed that the Arabian Peninsula served as an intermediate region for the transmission of plant and animal materials from Asia and Africa throughout antiquity. Oman was the Gulf country to produce frankincense and copper and both trading goods likely played a major role in the inter-regional plant species exchange within in Arabian Peninsula as well outside Arabia (Hammer et al. 2009). The ancient trade between Gujarat and Arabia was particularly important during the second millennium BC and is considered to have triggered crop exchanges between Africa and South Asia (Boivin and Fuller 2009). The availability of African crops in Gujarat and Baluchistan during second millennium BC provides evidence that maritime contact between Gujarat and Oman and Dilmon extended to Yemen and Africa (Boivin and Fuller 2009). The discovery of African crop species at 33 archaeological sites in South Asia, dating back to the Middle Bronze Age (2000 BC) and Iron Age (300 BC) indicates that the exchange of crops between the two continents went both ways (Fuller 2003; Cooke et al. 2005). However, Boivin et al. (2009) believed that African crops did not transfer to the Arabian Peninsula in the Bronze Age due to the absence of agricultural communities during that time, unlike at the coastal region of Gujarat. However, Vansina (1990) believed that the introduction of AAB banana to the Upper Nile Great Lakes region of Africa occurred not from the coast but through North West Africa (Atiff and Mohamed 2000).

2.3.5 The role of maritime routes in transferring plants to Arabia

The Indian Ocean

The transfer and exchange of plants outside their natural habitats was not limited only to the land roads, but maritime routes played an essential role in the transmission process. However, the role of maritime routes in the transport of crop plants to new areas is still subject to much speculation. Blench (2003) suggested three maritime routes to transfer plants species between Africa and India. The first route was between Northwest India and Egypt, across Iran, the second was a shipping route (The ‘Sabaean Lane’) that linked Oman, Egypt, India and Africa, across the Sea Red and the Indian Ocean, and the third route run between the West Indian coast and East Africa across the open sea. The Arabian Peninsula has played an important role in maritime trade since the Bronze Age and therefore also in the exchange and dispersal of plant genetic resources across the Indian Ocean (Fuller and Boivin 2011). Furthermore, archaeological discoveries in the Arabian region support this hypothesis: Chinese coins found at Al-Qualify in eastern Saudi Arabia give evidence of the role of Arabian Gulf ports in ancient trade with the Far East (Cribb and Potts 1996). Moreover, Fuller and Boivin (2009) viewed that the north-western Indian Ocean was one of the earliest long-distance maritime routes in the world. It allowed the significant exchange of livestock (e.g. cattle) and crops like bananas and taro (*Colocasia esculenta*) as early as 2000 BC. Also, the latter authors stated that the first biological exchange was in the Bronze Age / Chalcolithic (3000–1200 BC) along the circumference of the Arabia Peninsula and northern Indian Ocean where domesticated species were transferred between the Savannahs of India and northeast Africa and Yemen. Fuller and Boivin (2009) supported their view by claiming that at the end of the 3rd and 2nd millennium BC, there was a crop transfer between eastern Africa and South Asia through the Indian Ocean and along the southern coast of Arabia. Also, Sauer (1952) and McMaster (1962) mentioned that the eastern coasts of the Arabian Peninsula contributed to the transfer of Southeast Asian bananas to Africa. Blench (2003) mentioned that in the early medieval period, plants were introduced into West Africa by Arabs. This shows that the coastal ports contributed greatly to the exchange of plant resources between continents. The maritime ports between the Indian subcontinent (Figure 3) and Oman established in the middle of the 3rd millennium BC fostered the cultural and commercial relations and also contributed to the exchange of plant materials (Al Jarrow 2011; Al-Wagad 2011). This is supported by archaeological discoveries in the port of Sumahram in the Dhofar Governorate were Indian statues, pieces of pottery and coins dating from the 1st millennium BC (Albright 1982) were unearthed as were Indian potteries in the port of Sohar (Al Jarrow 2011).

Figure 3. Ancient Indian ports with trade links to ports in the southern Arabian Peninsula (altered form Al Jarrow 2011).

An intensive maritime trade between Gujarat and Arabia in the 2nd millennium BC is considered to be the starting point of plant species exchange between Asia and Africa. The evidence for this is the availability of African crops in Baluchistan during that period. This indicates that maritime trade between Gujarat and Oman was strong and extended to the west of the Arabian Peninsula towards Yemen and Africa (Fuller and Boivin 2009).

Over centuries Omani coastal were a route of transit trade between the countries of the Far East (India, China and the East Indies) and the Arabian Peninsula countries as well as Iraq, the Mediterranean Sea countries and East Africa. Muftah (2011) also suggested that commercial ships in their trip between the coastal Omani ports and India to and on to China might have used three different maritime routes (Figure 3). The first route starts in Basra in Iraq, heads towards the Eastern coast of the Gulf, stops in Ciraf (Bu Shar) in Southern Iran, then reaches Sohar and Muscat to cross the Indian Ocean to Coolum Meli south of Almalbar on the Indian coast. The second route stretches from Muscat to Polien on the Indian coast, then continues to Serindep (Sri Lanka) and Kelah port and finally reaches Khanfo in China. The third route begins in the Omani ports of Dhofar and Merbat, goes to Kalikot or Coolum Meli and then directly to China.

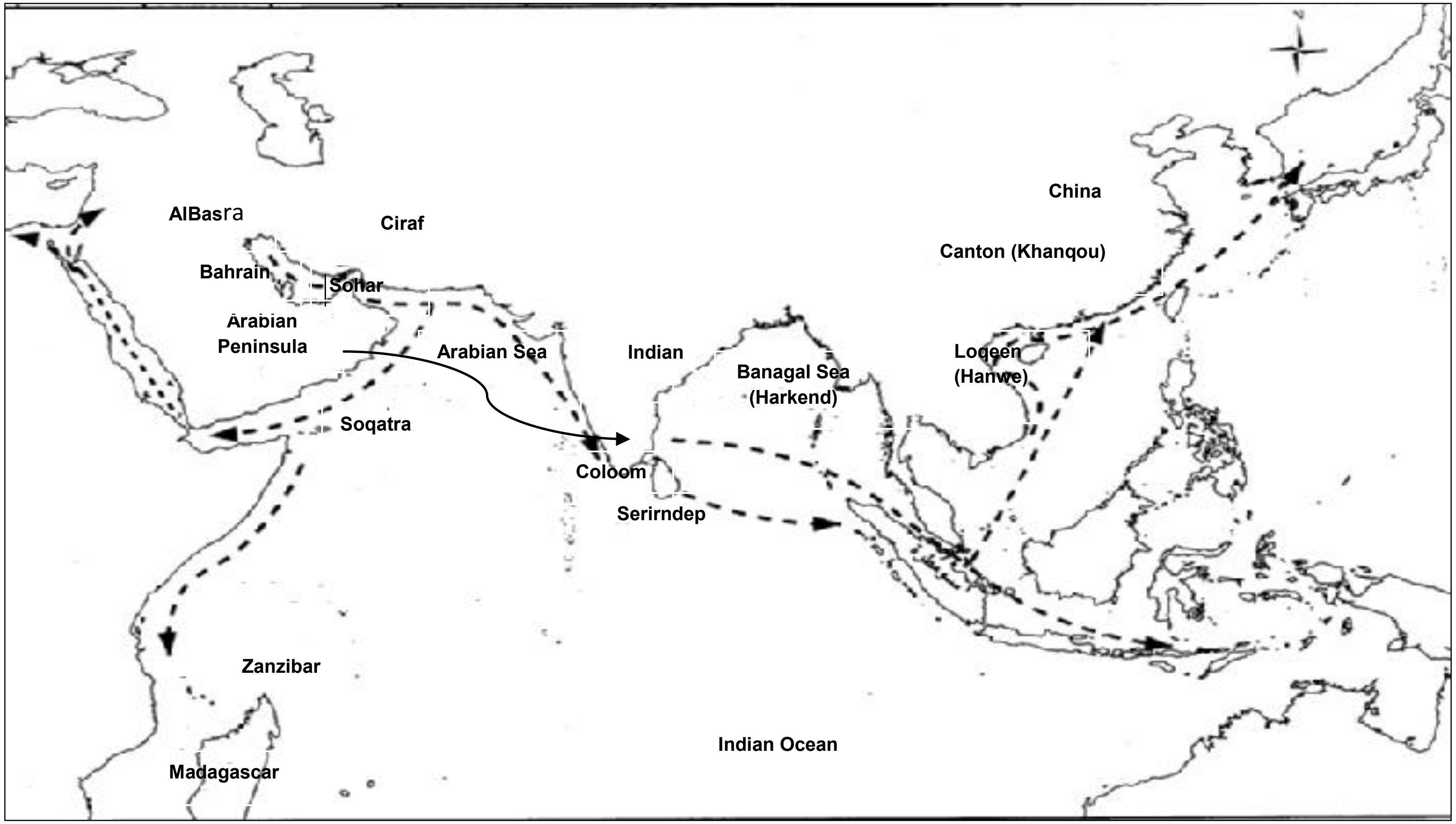

Figure 4. Trade routes and sea ports between the Arabian Peninsula, India and China (altered from Al-Wagad 2011; Muftah 2011).

Archaeological discoveries at Ras al-Jinz and Ras al-Had in the Sharqia North Governorate of Oman, dating back to the third millennium BC, yielded remains of boats and Indian rings from the Bronze Age to the 5th millennium BC (Jūtīli et al. 1983). This provides evidence for ancient relations between Oman and the civilizations of Mesopotamia, Sindh and Africa. Michael (1994) mentioned commercial maritime routes to India from the Strait of Harmuz, through Ras al-Had in northern Oman directly to the Eastern Indian coast. This sea route linking Oman and India may have greatly contributed to the direct existence of banana diversity in Dhofar and coastal cities such as Sohar and Tiwi (Figure 5). This hypothesis is supported by Muftah (2011) who mentioned that India, China and Southeast Asian Islands were the main sources of commodities to the coastal Omani ports and then to other regions of Arabian Peninsula. He also added that bananas and coconuts (*Cocos nucifera*) were the most important fruit crops imported from India to Oman in Medieval times.

Figure 5. Regional distribution of banana cultivars groups in Oman (De Langhe 2002; Al-Saady 2010).

The Red Sea Trade: Incense routes

Most scholars agree that the ‘Land of Punt’, a mining region in southern Egypt played an essential role in the maritime trade in the Red Sea during the 3rd millennium. Electrum, slaves, and particularly frankincense (*Boswellia sacra*) and myrrh (*Commiphora myrrha*) were traded from Punt via the Red Sea (Boivin and Fuller 2009). The Arabian frankincense species is native to Dhofar in Oman and Hadhramout in Yemen, while other species of frankincense are native to northern and western Ethiopia and Eritrea (*B. papyrifera*), some areas of Sudan and West Africa (Boivin and Fuller 2009), Somalia (Hepper 1969) and the Island of Socotra (Boivin and Fuller 2009). The genus of Myrrh tree (*Commiphora*) is native to southern and eastern Ethiopia, Somalia, Yemen, southwest Saudi Arabia and the coastal plains of Oman (Boivin and Fuller 2009). All of these countries also cultivate banana and it is therefore likely that there was an intensive exchange of banana germplasm between these countries. Archaeological evidence from Barbar, Umm-an-Nar, Tall Abraq, Hili, Wadi Suq, Ras al-Hamra, Ras al-Hadd, Ras al-Jinz, and as-Suwayh confirm the prosperity of the Red Sea trade during the 3rd millennium (Boivin and Fuller 2009). It can therefore be hypothesized that trade of frankincense and myrrh via the Red Sea contributed to the exchange of plant genetic sources such as bananas between Africa, India and the Arabian Peninsula.

2.4 Conclusions

While the debate on the origins of banana domestication is on-going, evidence presented in this chapter suggests that the islands of Southeast Asia and Southern China are the primary sites of banana domestication followed by subsequent phases of pre-historic cultivation and translocation to other parts of the world. Owing to the desert climate conditions in many areas of the Arabian Peninsula and based on linguistic, genetic, archaeological and maritime route data, it can be concluded that domesticated banana cultivars presently found in this area are not indigenous to the region. Humankind maintained these varieties over the ages, despite unfavourable climatic conditions. Whether domesticated banana varieties were introduced directly from their natural habitat or arrived via Africa or India cannot be clearly determined at this stage. The ancient commercial relations between the Arabian Peninsula, East Africa and India may have played a key role in introducing banana to the Arabian Peninsula. The Gulf ports, in particular those of Oman, seem to have effectively contributed to the exchange of plant genetic resources including bananas between the Arabian Peninsula and the Indian subcontinent, Africa and China. Oman's strategic location and its wealth of frankincense and copper were factors that made it an important transit centre for the exchange of plant genetic resources, including different banana subgroups.

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Chapter 3. Effects of composted dairy manure and date palm straw on properties of non-saline and saline Omani low organic matter soils

Abstract

A 56-d incubation experiment at 30ºC was carried out to study how salinity affects C and N mineralization of composted dairy manure and date palm straw, two important sources of soil organic matter and nutrients, in alkaline Omani soils. Two soils, a non-saline sandy loam and a saline sandy soil, were amended with manure, manure plus low straw, manure plus straw and sole straw. In the saline soil, the sum of CO_2-C reached only 55% of soil organic C in the non-amended control in comparison with the non-saline soil, 66% of the added manure and 75% of the added straw. The application of straw led always to a net-N immobilization in comparison with the control, but in most cases also with the initial values. The N immobilization was markedly stronger in the saline soil. In the first week, net-N immobilization occurred in nearly all treatment, whereas in the last week, net-N mineralization was observed in nearly all treatments. The strongest increase in microbial biomass C was observed in the manure + straw treatment. In both soils, manure had no effect on the fungi-specific membrane component ergosterol. In contrast, the application of straw resulted in strong increases of the ergosterol content.

Key words: Ergosterol, Organic amendments, Microbial biomass, N mineralization, Salinity

3.1 Introduction

In arid regions such as Oman, soil organic matter turnover can be considerably altered by management practices such as addition of organic fertilizers and irrigation, which contrasts with the situation in humid climates (Lal 1989). This dynamic situation enhances the risk of mismanagement, leading to a rapid breakdown in soil fertility (Powlson et al. 2001), especially if the soils become affected by salt through irrigation with saline groundwater or insufficient drainage (Keren 2000; Rietz and Haynes 2003). The effects of salinity on soil microorganisms and microbially mediated processes have been increasingly investigated over the past decade (Zahran 1997; Rietz and Haynes 2003; Tripathi et al. 2006). However, the dimension and the direction of the effects observed on microbial C and N mineralization, microbial biomass and microbial community structure are not consistent and seem to depend on environmental conditions, such as soil pH, anion composition, texture, and soil organic matter level (Li et al. 2006a/b). At present, our knowledge regarding the function of microbial biomass as a sink and source of plant nutrients in sub-tropical soils is insufficient, considering the large variety of environmental conditions and management practices observed. In hyper-arid northern Oman, one of the most important sources of organic fertilizers are N-rich ruminant manures (Schlecht et al. 2011; Siegfried et al. 2011); another important source is date palm straw (Khiyami et al. 2008; Ali 2011; Alkoiak et al. 2011; Ghehsareh et al. 2011). However, the low N and high lignin concentration of this material might cause problems in Omani soils, especially when saline, because under these conditions the contribution of saprotrophic fungi to the microbial community is most likely low (Zahran 1997; Pankhurst et al. 2001; Sardinha et al. 2003). Fungi dominate the decomposition of nutrient poor and recalcitrant organic residues, such as straw (Bowen and Harper 1990; Cheshire et al. 1999). A reduction in the decomposition rate of organic fertilizers in saline soils may increase the risk of N immobilization and thus reduce the supply of inorganic N to plants (Flavel and Murphy 2006).

Consequently, the central aim of the current incubation experiment was to study how salinity affects C and N mineralization of dairy manure and date palm straw in alkaline Omani soils. Microbial biomass C and N are useful indicators of microbial performance in saline soils (Tripathi et al. 2006; Sardinha et al. 2003; Muhammad et al. 2008). The fungi-specific membrane component ergosterol has been successfully used as a biomarker for fungal biomass in many soils

(Jorgensen and Wichern 2008), including in saline environments (Sardinha et al. 2003; Wichern et al. 2004), but never in irrigated Omani soils

3.2 Materials and methods

3.2.1 Sample preparation and experimental layout

Composite soil samples of two soils, a sandy saline and non-saline sandy loam were taken at 0-20 cm depth from the agricultural research station at Rumais (23°41' 15 N, 57°59' 1 E) in south Al-Batinah, Oman. The soils were air-dried and sieved (< 2 mm). Aged (2 years) composted cow manure was obtained from a factory in Oman, air-dried and milled. Fresh date palm straw was obtained from Rumais, chopped to 5 mm pieces and air-dried. Basic properties of the soils (Table 1) and organic amendments (Table 2) were analyzed prior to the incubation experiments.

Table 1. Basic chemical properties of two soils (a non-saline and a saline soil) from Oman prior to incubation.

Properties	Non-saline soil	Saline soil
Soil pH	8.5	7.9
EC_e (dS m^{-1})	1.8	11.9
Sand (%)	54	84
Silt (%)	37	6
Clay (%)	9	10
Carbonate (%)	26	31
Soil organic C (mg g^{-1} soil)	4.5	2.1
Total N (mg g^{-1} soil)	0.5	0.3
Extractable NH_4-N (µg g^{-1} soil)	3.5	4.2
Extractable NO_3-N (µg g^{-1} soil)	1.3	102.6

Table 2. Basic chemical properties of composted dairy cow manure and date palm straw prior to incubation.

Properties	Composted manure	Date palm straw
pH	8.4	5.3
EC_e (dS m^{-1})	8.1	0.9
Total C (mg kg^{-1})	240	521
Total N (mg kg^{-1})	18	4.1
Total P (mg kg^{-1})	6.2	0.3
Total K (mg kg^{-1})	25.0	7.7
Extractable NH_4-N (µg kg^{-1})	11.6	43.4
Extractable NO_3-N (µg kg^{-1})	2650	19.2
Lignin (mg kg^{-1})	145	84
Cellulose (mg kg^{-1})	289	450
Acid detergent fibre (mg kg^{-1})	434	534

A 1600 g oven dry sample of each soil was placed into a plastic container, covered with plastic bags, rewetted to 45% water holding capacity and incubated for 7 days at 30ºC. Thereafter, the soils were mixed with dairy manure compost and date palm straw according to the treatments; (T1) non-amended control, (T2) only composted dairy manure (3.6 mg C g^{-1} soil), (T3) composted dairy manure (3.6 mg C g^{-1} soil) + low date palm straw (0.59 mg C g^{-1} soil), (T4) composted dairy manure (3.6 mg C g^{-1} soil) + high date palm straw (1.76 mg C g^{-1} soil), and (T5) sole date palm straw. All treatments were placed in sealed 1500 ml glass jars (400 g soil mix per jar), and incubated for 8 weeks at 30^{o}C in the dark as a completely randomized design with four 4 replicates. All treatments were kept at 50% water holding capacity throughout the incubation period.

3.2.2 Analysis of soil chemical properties

Analysis of soil texture was carried out after pre-treatment with H_2O_2, HCl and suspension in sodium polyphosphate using a combined sieving and pipette method (Blume et al. 2011). Soil pH was measured using a soil water ratio of 1:2.5. Electrical conductivity (EC) was estimated using a soil water suspension of 1:5, which was converted to EC values in saturation extract (EC_e). Sub-samples of dried soil material were homogenized in a ball mill. Total C and total N in soils and straw were determined using a Vario Max CN analyzer (Elementar, Hanau, Germany). Soil organic C was measured as total C minus carbonate C, which was measured gas-volumetrically after the addition of HCl (Blume et al. 2011). Inorganic N in the form of ammonia (NH_4^+) and nitrate (NO_3^-) was measured weekly using a 10 g samples from each treatment. To extract N from soils, 40 ml of 0.5 *M* K_2SO4, were added to each soil sub-sample and filtered through a Whatman 595 1/2 filter paper. The N in filtrate was then quantification using photometric detection (Evolution ii, Alliance Instrument, Salzburg, Austria). Soil moisture content was also determined weekly, using an additional 10 g sub-sample of soil from each treatment.

3.2.3 Soil microbial indices

Microbial biomass C (Vance et al. 1987) and microbial biomass N (Brookes et al. 1985) were estimated using fumigation-extraction The 0.5 M K_2SO_4 extracts produced for N-extraction were used to determine organic C, which was as CO_2 by infrared absorption after combustion at 850°C using a Dimatoc 100 automatic analyzer (Dimatec, Essen, Germany). Microbial biomass C was calculated as E_C

$/k_{EC}$, where E_C = (organic C extracted from fumigated soils) - (organic C extracted from non-fumigated soils) and k_{EC} = 0.45 (Wu et al. 1990). Total N in the extracts was measured by chemoluminescence detector. Microbial biomass N was calculated as E_N $/k_{EC}$, where E_N = (total N extracted from fumigated soils) - (total N extracted from non-fumigated soils) and k_{EN} = 0.54 (Brookes et al. 1985). The fungal cell-membrane component ergosterol was extracted from 2 g soil with 100 ml ethanol by oscillated shaking at 250 rev min^{-1} for 30 min according to Djajakirana et al. (1996). Ergosterol was determined by reversed-phase HPLC with 100% methanol as the mobile phase and detected at a wavelength of 282 nm. Cumulative soil respiration was measured weekly as CO_2-C. To do so, test tubes containing 30 ml 0.5 *M* NaOH were placed at the bottom of 1500 ml jars. The trapped CO_2 was back-titrated with 0.5 M HCl after addition of 0.5 M $BaCl_2$ solution.

3.2.4 Statistical analysis

All results presented in the tables are expressed on an oven-dry basis (about 24 h at 105°C). Statistical analyses were carried out using GenStat Release 11.1 (VSN International, Hemel Hempstead, UK). The significance of soil and treatment effects were first tested with a two-way analysis of variance (ANOVA) followed by a soil-specific one-way ANOVA, using Fisher’s PLSD-test (protected least significant difference) as a post-hoc test. Data were ln-transformed to normalize distribution.

3.3 Results

In the non-saline soil, the application of composted dairy manure led to a significant decrease in soil pH by 0.19 units and a 1.3 dS m^{-1} increase in electrical conductivity (Table 3). Similar changes were observed when manure applied with date palm straw. When only date palm straw was applied, the pH increased significantly by 0.05 units, though EC_e did not change. In the saline soil, the application of manure alone led to a 0.23 unit decrease in soil pH, while mixed applications of manure and straw did not significantly change pH. Though manure applications increased electrical conductivity, these changes were not significant in saline soil.

Table 3. Effects of an 8-week incubation period on the soil chemical properties of a non-saline and a saline soil from Oman containing different organic amendments

Treatment	**pH-H_2O**	**EC_e (dSm^{-1})**	**ΣCO_2-C ($\mu g\ g^{-1}$ soil)**	**Net-N_{min} ($\mu g\ g^{-1}$ soil)**
Non-saline soil				
Control	8.49 b	2.0 b	200 e	9.5 b
Composted Manure	8.30 c	3.2 a	290 d	16.1 a
Manure + low date palm straw	8.27 c	3.4 a	490 c	6.8 c
Manure + high date palm straw	8.26 c	3.3 a	10003 a	-5.5 d
High date palm Straw	8.54 a	2.0 b	710 b	-5.4 d
Saline soil				
Control	7.89 a	11.4 a	110 e	5.3 b
Composted Manure	7.66 b	11.9 a	170 d	10 .3 a
Manure + low date palm straw	7.89 a	12.1 a	310 b	-2.0 c
Manure + high date palm straw	7.91 a	12.1 a	630 a	-16.8 d
High date palm Straw	7.94 a	11.0 a	560 b	-19.1 d
Probability values				
Treatment	<0.01	<0.01	<0.01	<0.01
Soil	<0.01	<0.01	<0.01	<0.01
Soil × Treatment	<0.01	<0.01	<0.01	<0.01
CV (± %)	1.4	0.8	1.4	

CV = pooled coefficient of variation between replicate incubations (n = 4); different letters with a column indicate a soil-specific difference (PLSD-test, *P* < 0.05).

The non-saline control soil emitted 200 µg CO_2-C g^{-1} soils over the 8-week incubation period at 30ºC (Table 3). The application of manure and straw resulted in significant increases of CO_2 emissions, equivalent to 2.5 and 30% of the added C, respectively. In the saline soil, the sum of CO_2-C reached only 55% of soil organic C in the non-amended control in comparison with the non-saline soil. In which 66% of the added manure and 75% of the added straw were emitted, assuming that no interactions occurred between soil organic C, manure C and straw C during microbial decomposition.

For both soils, net-N mineralization occurred at the end of the 8-week incubation period at 30ºC in the control and in the manure treatment (T2), compared to initial values (Table 3). In both soils, the ratio of CO_2-C to net-N_{min} was 21 in the control soils and roughly 13 for the additional amounts of CO_2-C and net-N_{min}, assuming that no interactions occurred between soil organic matter and manure. The application of straw led always to a net-N immobilization in comparison with the control, but in most cases also with the initial values. The N immobilization was markedly stronger in the saline soil. The net-N mineralization rate ranged from -2.4 µg N g^{-1} soil d^{-1} (week 1, manure + straw treatment) to 1.3

µg N g^{-1} soil d^{-1} (week 5, manure treatment) in the non-saline soil (Figure 1a) and from –2.4 µg N g^{-1} soil d^{-1} (week 1, straw treatment) to 2.0 µg N g^{-1} soil d^{-1} (week 4, manure treatment) in the saline soil (Figure 1b). In the first week, N immobilization occurred in nearly all treatment, whereas in the last week, net-N mineralization was observed in nearly all treatments.

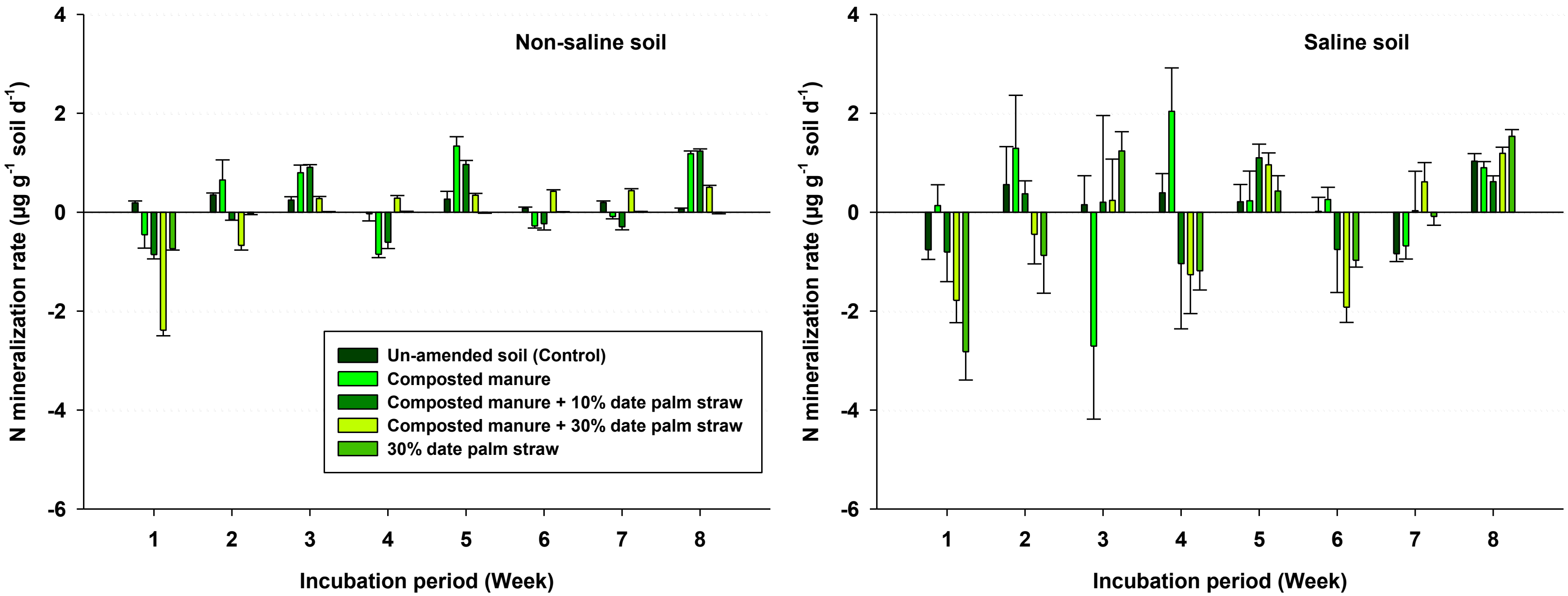

Figure 1. Mean N mineralization rates in the two soils - (a) non-saline, (b) saline soil - from Oman with different organic amendments over an eight-week incubation period.

In the non-saline control soil, the contents of microbial biomass C, microbial biomass N, and ergosterol exceeded those in the saline soil by 44, 50 and 260%, respectively (Table 4). In the non-saline soil, the organic amendments generally increased microbial biomass C and N. Manure has stronger effects on microbial biomass N than date palm, while date palm straw has more effects microbial biomass C than manure, leading to increased microbial biomass C/N ratios. The strongest increase was observed in the manure + straw treatment. A significant positive effect on microbial biomass C was only observed in this treatment. Manure had no effect on the ergosterol content nor on the ergosterol to microbial biomass ration in both soils. In contrast, straw application generally resulted in strong increases in ergosterol content and ergosterol to microbial biomass C ratio. The highest value of this ratio was observed in the only sole straw treatment (T5) in both soils.

Table 4. Contents of microbial biomass C, N, ergosterol and the respective ratios in two soils from Oman with different organic amendments at the end of the 8-week incubation experiment.

Treatment	Microbial biomass C ($\mu g\ g^{-1}$ soil)	Microbial biomass N ($\mu g\ g^{-1}$ soil)	Microbial biomass C/N	Ergosterol ($ng\ g^{-1}$ soil)	Ergosterol / microbial biomass C%
Non-saline soil					
Control	49 c	9.0 c	5.5 c	36 c	0.8b
Composted Manure	65 c	16.0 a	4.1 d	30 c	0.5b
Manure + low date palm straw	95 b	12.7 b	7.4 b	102 b	1.1b
Manure + high date palm straw	164 a	16.5 a	9.9 a	295 a	1.8a
High date palm Straw	97 b	15.0 ab	6.5 bc	229 a	2.4a
Saline soil					
Composted Manure	34 b	6.0 a	6.9 a	10 c	0.3c
Manure + low date palm straw	31 b	6.3 a	5.2 a	15 c	0.7c
Manure + high date palm straw	37 b	7.4 a	4.9 a	67 b	2.0bc
High date palm Straw	66 a	7.9 a	8.8 a	170 a	2.9b
Composted Manure	33 b	4.3 a	8.1 a	167 a	5.1a
Probability values					
Treatment	<0.01	<0.01	<0.01	<0. 01	<0.01
Soil	<0.01	<0.01	NS	<0.01	<0.01
Soil × Treatment	<0.01	0.01	NS	NS	<0.01
CV (± %)	8.1	15	17	8.7	53

CV = pooled coefficient of variation between replicate incubations (n = 4); different letters with a column indicate a soil-specific difference (PLSD-test, $P < 0.05$).

3.4 Discussion

3.4.1 Soil properties

Both soils were characterized by low contents of soil organic matter and microbial biomass. The average content of microbial biomass C in the studied present control soils constituted less than 10% of the global average of 330 µg g^{-1} soil (Wardle 1998) and only a third of the average in non-saline Pakistani soils under rain-fed arable land-use management (Khan and Jorgensen 2006). In non-saline soils of the oasis Balad Seet, located in the nearby Hajar mountain range of northern Oman, microbial biomass concentrations were only moderately above the worldwide average but these soils had substantially higher organic C (Wichern et al. 2004). Compared to soils studied by Djajakirana et al. (1996), the ratio of the fungal cell-membrane component ergosterol to microbial biomass C was relatively high in our soils, especially in the saline soil, although salinity is thought to negatively affect soil fungi (Badran 1994; Pankhurst et al. 2001; Sardinha et al. 2003).

The mean soil organic C content reached nearly 90% of the average in the soils from Potohar (Khan and Jorgensen 2006), leading to low microbial biomass C to soil organic C ratios of 1.1% in the non-saline soil and 1.6% in the saline soil. The microbial biomass C to soil organic C ratio is an important indicator for the availability of organic matter to soil microorganisms (Anderson and Domsch 1989; Jorgensen 2010). Such low ratios are very unusual for soils from arid and semi-arid regions (Jenkinson et al. 1991; Dlamini and Haynes 2004; Wichern and Jorgensen 2009; Khan and Jorgensen 2006; Muhammad et al. 2008). Their causes cannot be explained by the present experiment, but are possibly related to (1) very low applications of organic residues over large periods of time, (2) excessive irrigation and (3) strong salinization. On these soils, efforts should be made to improve soil organic matter levels, e.g. by adding compost or organic manures (Goshal and Singh 1995).

The ratio of basal respiration to microbial biomass, the metabolic quotient qCO_2, is an important index for substrate use efficiency and for the age structures of the microbial biomass (Anderson and Domsch 1990; Dilly 2005), i.e. the higher the qCO_2, the less efficient and the younger the mean age of the microbial population. The metabolic quotients qCO_2 were 73 and 58 (mg CO_2-C d^{-1} g^{-1} microbial biomass C) in the non-saline and saline soils, respectively. These values were relatively high, but not excessive (Muhammad et al. 2008; Jorgensen 2010) and revealed the typical inverse relationship with the microbial biomass C to soil organic C ratio (Anderson and Domsch 1990; Jorgensen 2010). The lower contents of microbial biomass C and soil organic C in the saline soil are apparently not caused by negative salinity effects on the soil microbial community but due to a lower C input by roots (Ghollarata and Raiesi 2007). For this reason, the contents of microbial biomass C and soil organic C regularly decrease with increasing salinity in long-term salt affected soils (Sarig and Steinberger 1994; Sarig et al. 1996; Batra and Manna 1997; Rietz and Haynes 2003; Tripathi et al. 2006; Yuan et al. 2007; Khan et al. 2008).

3.4.2 Decomposition of date palm straw and dairy manure

The mineralization of date palm straw is in the range reported in the literature, considering the difference in incubation temperature and incubation length (Khiyami et al. 2008; Ali 2011; Alkoiak et al. 2011; Ghehsareh et al. 2011). The same is true for the composted diary manure (Hartz et al. 2000; Griffin et al. 2005; Morvan and Nicolardot 2009; Peters and Jensen 2011). The considerably lower C mineralization rate of manure compared to date palm straw was likely due to the high percentage of recalcitrant components (Bosshard et al. 2011) present in manure after strong microbial decomposition of the feed in the cattle gut (van Vliet et al. 2007). The significant, but small increase in salinity and the decrease in pH by manure application did presumably not affect microbial mineralization processes. However, both effects should be considered if manure is applied to soils sensitive to changes in pH and especially salinity.

The application of date palm straw can strongly enhance the fungal community, which has been repeatedly observed for wheat straw (Henriksen and Breland 1999), maize straw (Potthoff et al. 2008) and jute fibers (Chander et al. 2002), but so far not for date palm straw. An ergosterol to microbial biomass C ratio > 1.0 indicates the accumulation of ergosterol in dead fungal tissue as observed by Mille-Lindblom et al. (2004) and Zhao et al. (2005) under conditions of rapid fungal turnover (Jorgensen and Wichern 2008). Manure application fosters the growth of bacteria, in part due to its origin from the anaerobic environment of the rumen and in part due to high temperatures during storage in farmyard heaps.

An interesting result of the present incubation experiment is the synergistic effect of the combined application of manure and date palm straw, which lead to maximum microbial biomass and lower ergosterol to microbial biomass C values. This supports the view that the reduction of saprotrophic fungi improves C sequestration by increasing the formation of microbial biomass and lowering the microbial C turnover (Scheller and Jorgensen 2008; Heinze et al. 2010).

3.4.3 Salinity effects on the manure and date palm straw decomposition

In the organic fertilizer treatments, less CO_2 evolved from the saline soils than from the non-saline ones, suggesting a moderate salinity effect on this process, as mineralization of added C does not necessarily depend on the soil organic C content (Witter and Kanal 1998). The present observation is consistent with Wichern et al. (2006) and Khan et al. (2008), but in contrast to Rasul et al. (2006) and Li et al. (2006b), who did not measure differences in the mineralization of added substrate to CO_2, although the soils differed significantly in their content of microbial biomass C and soil organic C.

Salinity had no further specific effects on N mineralization in the control and in the manure treatment as observed by Luna-Guido et al. (2000), Rasul et al. (2008, 2009) and Khan et al. (2008), contrasting the view that salinity has strong effects on this process (Darrah et al. 1987; Pathak and Rao 1998; Yousif and Mubarak 2009). However, this view has been mostly obtained from incubation experiments, in which soils have been exposed to salinity for short periods (Darrah et al. 1987; Pathak and Rao 1998). Interesting is the stronger N immobilization after date palm straw addition to the saline compared with the non-saline soil. Although less substrate was mineralized to CO_2, more N was immobilized in microbial residues, indicating a stronger microbial turnover in the saline soil after date palm straw application in comparison with the non-saline soil. This view is supported by the ratio of ΣCO_2-C to microbial biomass C in the date palm straw treatments, which were 7.3 g CO_2-C g^{-1} microbial biomass C 56 d^{-1} in the straw treatment of the non-saline soil and 17.0 in the respective treatment of the saline soil. This contrasts the differences in the qCO_2 values between the two soils, suggesting a different behaviour of the autochthonous and the substrate-derived microbial biomass. The very low relative and absolute increase in microbial biomass in the saline soils, caused by their low contents of microbial biomass is a typical feature of many experiments using soils with different microbial biomass contents (Bremer and Kuikman 1994; Witter and Kanal 1998) and thus not necessarily caused by salinity.

3.5 Conclusions

The Omani saline soil had lower contents of soil organic C and microbial biomass C than the non-saline soil. This led to lower mineralization rates of manure and date palm straw in the saline soil. Salinity had no specific effects on N mineralization as indicated by the CO_2-C to N_{min} ratio of soil organic matter and manure. Date palm straw strongly promoted saprotrophic fungi in contrast to manure and the combined application of manure and date palm straw had synergistic positive effects on soil microorganisms.

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Chapter 4. Effects of organic and inorganic fertilizers addition on growth and yield of banana (*Musa* AAA cv. Malindi) on a saline and non-saline soil in Oman

Abstract

Water availability and soil salinity limit crop productivity in arid and semiarid regions such as Oman. The objective of this study was to examine the effects of amending a saline plant root zone soil with a non-saline sandy loam soil, of organic and inorganic fertilizers, and of different placement methods on growth and yield of banana (*Musa* AAA cv. 'Malindi'). A total of 24 treatments comprising six fertilizer amendments, two soil types and two different application methods were tested. The amendments included four organic amendments *versus* un-composted dairy cow manure (FDM); composted dairy cow manure (CDM); CDM + 10% date palm straw (CDM + 10%DPS) by weight, and CDM + 30% date palm straw (CDM + 30% DPS) and two inorganic amendments (NPK and NPK plus foliar micronutrient spray, NPK+micro). The results revealed that neither soil amendments, fertilizer applications methods nor fertilizer composition significantly affected pseudostem height or girth, or leaf area. There was a significant difference ($P<0.05$) in the number of leaves at flowering between Saline-Ring-NPK plants (8.2 leaves/plant) and Amended-Mixed-NPK and Amended-Ring-NPK+micro plants (14.0 and 13.8 leaves/plant, respectively). Amended-Ring-NPK+micro was significantly early flowering (267 days) compared to the other treatments. Amended-Ring-NPK+micro plants were harvested significantly earlier (in 339 days) than plants on saline soil. Amended-Ring-NPK+micro produced significantly higher average bunch fresh weight (9.5 kg/bunch/cycle) than all other treatments, followed by Amended-Mixed-NPK+micro (5.9 kg/bunch/cycle)

Key words: Amendments, Application methods, Dwarf Cavendish, Manure types, Mineral fertilizers, Yield components

4.1 Introduction

Banana is the most important tropical fruit crop. In 2010, banana and plantain (*Musa* spp.) were grown on over 10 million hectares worldwide and total production was about 138 million tons (FAOSTAT 2010). In Oman, bananas are grown on 3,720 ha and typically planted at a distance of 2 x 1.5 m resulting in a plant density of 3,333 plants/ha, with a total annual production of 56,700 tonnes (15.2 tonnes/ha) (FAOSTAT 2010). The Dwarf Cavendish (*Musa* AAA) cultivar 'Malindi' is one of the most important cultivars grown in Oman due to its short stature and the sweetness of its fruit. It is a major source of income for a large number of farmers, particularly in the regions of Al-Batinah and Dofar.

Bananas need large quantities of mineral nutrients for high yields when grown in humid tropical areas with light soils and low fertility (Robinson 1996). Under such conditions, N should be added up to eight times per cycle to compensate for leaching losses. In Oman, chemical fertilizers alone or in combination with either dairy cow manure (MAF 1993) or other ruminant manures (Schlecht et al. 2011; Siegfried et al. 2011) are used to provide nutrients to intensively managed banana. Bolaños et al. (2003) found that application of inorganic fertilizers and different sources of organic matter to the mother plants of plantain cv. 'Dominico hartón' positively affected pseudostem height and girth, but treatments were not significantly different. Similarly, Navarro (2001) observed no statistical differences in plant height, plant girth or bunch weight when comparing non-fertilized control cv. 'Cachaco' plantain with plants fertilized either with only organic fertilizer, only inorganic fertilizers or with a combination of organic and inorganic fertilizers. Al-Harthi and Al-Yahyai (2009) noticed that leaf number, leaf area, pseudostem height, and stem circumference of non-fertilized control plants were neither significantly different nor produced better vegetative growth when compared to fertilized plants. However, fertilized plants produced better total bunch weight and total fruit than non-fertilized control plants.

Mostafa (2005) found that fertilizing cv. 'Williams' banana with 500 g N per plant as ammonium sulphate applied at seven intervals and 600 g K per plant as potassium sulphate at 4 intervals increased pseudostem height, girth, number of leaves, leaf area and bunch weight, and reduced time to flowering and harvest compared to unfertilized plants. Abd el Moniem (2008) found that fertilizing cv. 'Williams' banana plants with the recommended N rate from organic and mineral sources enhanced yield and weight of banana hands and fingers. Sibaja (1991) observed that semi-circular application of fertilizers around suckers of *Musa* AAA produced the highest yield as compared to other application methods tested. Baiyeri and Tenkouano (2008) found no significant differences between manure placement methods for specific leaf area (SLA) of the whole plant or leaf-3 at 5 months after transplanting (MAT) using a PITA 14 plantain hybrid. However, in the same experiment manure application significantly increased SLA at 3 MAT as compared to un-manured plants. In Oman little research has been done on organic and inorganic banana fertilization and application methods.

Recently, the use of date palm (*Phoenix dactylifera*) residues as an organic soil amendment has been intensively studied in the Middle East, where large amounts of this material is produced as a by-product of date cultivation (Khiyami et al. 2008; Al-Shaikh et al. 2009; Alkoaik et al. 2011; Ghehsareh et al. 2011; Yusuf Sleh Sirgi Ali, 2011). According to Khiyami et al. (2008) and Alkoaik et al. (2011), date palm produces about 20 kg of dry leaves per cycle. Hence, in arid regions like Oman where date palms are extensively cultivated, the use of these residues to improve soil properties makes economic and environmental sense. However, low N and high concentration of lignin in this substance may be an obstacle to soil microbial activity and derived substrate decomposition (Zahran, 1997; Pankhurst et al. 2001; Sardinha et al. 2003). This may be particularly significant in low fertility soils, as predominating in the Oman Al-Batinah lowlands with their low organic matter content and high salinity. The soils on half of the farms in this region are saline (MAF 1993). As no alternative land is available, the reclamation of salt-affected soils via simple mechanisms is of paramount importance.

The most common method of reclaiming saline soils is their flooding with sweet water, allowing the salts to be leached beyond the root zone of plants (Donahue et al. 1983). However, it is difficult to use this method in Oman where there is little water to begin with, and the water that is available is not always of sufficient quality. Amending the soil in the initial rooting zone of plants may be an alternative form of reclaiming saline soils. To explore this option, we tested the effects of amending the soil in the planting hole on the growth and productivity of the first crop cycle of *Musa* AAA cv. 'Malindi'. Our hypothesis was that replacing the plant root zone in saline soil by a non-saline sandy loam soil and adding fertilizer combinations will improve the growth and production of *Musa* AAA cv. 'Malindi'.

4.2 Materials and methods

4.2.1 Experimental site

The field experiment was conducted at the Agricultural Research Station, Rumais (23°41'15" N, 57°59'1" E) in the South of Al Batinah Governorate, Oman from October 2007 to July 2009. In this region the average daily temperature ranges from 19.5°C in January to 41.0°C in July, with an annual precipitation of 100 mm.

In September 2007, large planting holes (70 x 70 x 70 cm) were dug to apply organic amendments and/or replace saline soil with non-saline sandy loam soil (soil amendments). In October 2007, banana plants were transplanted into the field in holes of approx. 30 x 30 x 30 cm in the centre of the larger holes previously dug. Inorganic fertilizers were then applied and a bubbler irrigation system (discharge: 4 l per minute of a water with an electrical conductivity of 0.6 dS m^{-1}) was installed. Taking in the consideration the age of the plant and weather conditions, all plants were irrigated every two days in winter and daily in summer. Each plant received 16 L per irrigation event for the first 4 months (October to January), thereafter the quantity increased to 20 L until the end of the experiments, as recommended by the Omani Ministry of Agriculture and Fisheries. Every week, newly emerged suckers around the mother plant were cut to the soil surface using a knife. The experimental plants were managed according to the recommendations of the Omani Ministry of Agriculture and Fisheries.

4.2.2 Soil and organic amendments analysis

To determine soil type, electrical conductivity (EC_e) and pH of soils, composite soil samples were collected from 0-20 cm depth of the experimental field and from the pile of imported non-saline sandy loam soil prior to establishing the experiment. The EC_e was measured using a soil-to-water suspension of 1:5. Soil pH was measured using a soil-to-water ratio of 1:2.5. Concentrations of acid detergent fibre (ADF), cellulose and lignin were measured according to Van Soest et al. (1991) method.

4.2.3 Planting material

Suckers from the highly productive ‘Malindi’ plants were used as planting material. The suckers were removed from mother plants in September 2007, roots and a corm cut and shoots trimmed. They were initially planted in pots (30 cm x 30 cm) filled either with field soil or imported sandy-loam soil for one month before being transplanted into the field in October 2007.

4.2.4 Treatments

For the experiment conducted from October 2007 to July 2009 a completely randomized design was used with 6 replicates and 24 treatments (2 soil types x 6 fertilizer combinations x 2 fertilizer application methods).

Soil Amendments

As the soil of the research station was saline, half of the treatments consisted in amending the soil in the planting hole (70 x 70 x 70 cm) dug one month prior to transplanting the banana plants into the field. These large planting holes were dug 3 x 3 m apart, to yield a planting density of 1,111 banana plants/ha. Half the holes were then refilled with non-saline sandy loam soil imported from another part of Oman; collected from the shores of the valleys ('Amended soil'). The other planting holes were refilled with original soil ('Saline soil') and the replaced saline soils were transported away from the experimental site.

Fertilizer combinations and application methods

Samples of fresh and composted manure and of date palm straw were collected and analyzed for basic chemical properties. These data was used to calculate the amount of manure necessary to provide each banana plant with 400 g N, as recommended by the Omani Ministry of Agriculture and Fisheries (MAF 1995).

The six fertilizer combinations, four organic and two inorganic comprised:

1. FDM: 100% un-composted (fresh) dairy cow manure (39.0 kg dry weight)
2. CDM: 100% composted dairy cow manure (22.2 kg dry weight);
3. CDM+10%DPS: 100% composted dairy cow manure and 10% date palm straw by weight (2.2 kg dry weight)
4. CDM+30%DPS: 100% composted dairy cow manure and 30% date palm straw by weight (6.7 kg dry weight)
5. NPK: urea (N), triple super phosphate (P) and potassium sulphate (K)
6. NPK+micro: urea (N), triple super phosphate (P), potassium sulphate (K) and foliar micronutrients

All organic fertilizers used (FDM ,CDM and DPS) were applied only once, either mixed in with the top 20 cm of the soil in the planting hole ('Mixed application') or in a ring at a depth of 20 cm in the planting hole ('Ring application'), one month prior to transplanting of banana suckers. The holes were then irrigated once to allow for initial release of nutrients.

Inorganic fertilizers (N: urea; P: triple super phosphate; and K: potassium sulphate) were applied either by spreading on the soil surface around the plant at a distance of approx. 30 cm from the base of the plant and mixed into the top layer of the soil by hand (‘Mixed application’) or by burying it under 5-10 cm of soil that had been removed in a ring around the plant at a distance of 30 cm from the base of the plant (‘Ring application’).

The quantity of urea applied was calculated such as to provide the plant with 400 g N. The quantity of triple super phosphate and potassium sulphate applied was calculated to provide the plant with the same amount of P and K available in 39 kg of fresh dairy manure (FDM), i.e., the amount of FDM necessary to provide the plant with 400 g N. Micronutrients were applied onto the banana leaves using a backpack sprayer containing a solution of the foliar micronutrient fertilizer Fertilon® Combi 2 (Münster, Germany: Zn: 4.0%; Fe: 4.0%; Mn: 3.0%; Cu: 0.5%; B: 1.5%; Mo: 0.05%; Mg: 1.3%; S: 1.3%) at a concentration of 1 g/l water. The doses and application dates of organic, inorganic and micronutrient fertilizers are presented in Table 1.

Table 1. Doses and dates of ring and mixed applications of organic and inorganic fertilizers to soils and of foliar applications of micronutrients to leaves of *Musa* AAA cv. 'Malindi' plants in a banana soil salinity experiment in Al-Batinah of Oman.

Date of Application	FDM	CDM	CDM+10%DPS	CDM+30%DPS	NPK	NPK+micro
Sep-07	FDM: 39.0 kg	CDM: 22.2 kg	CDM: 22.2 kg DPS: 2.2 kg	CDM: 22.2 kg DPS: 6.7 kg	-	-
Oct-07	-	-	-	-	P: 100 g	P: 100 g
Dec-07	-	-	-	-	N: 70 g P: 50 g K: 50 g	N: 70 g P: 50 g K: 50 g
Feb-08	-	-	-	-	N: 100 g P: 50 g K: 75 g	N: 100 g P: 50 g K: 75 g micro: 5 L
Apr-08	-	-	-	-	N: 120 g P: 69 g K: 120 g	N: 120 g P: 69 g K: 120 g
Jun-08	-	-	-	-	N: 150 g P: 68 g K: 140 g	N: 150 g P: 68 g K: 140 g micro: 7 L
Aug-08	-	-	-	-	N: 150 g K: 210 g	N: 150 g K: 210 g
Sep-08	-	-	-	-	N: 140 g K: 300 g	N: 140 g K: 300 g micro: 11 L
Oct-08	-	-	-	-	N: 140 g K: 315 g	N: 140 g K: 315 g
TOTAL	FDM: 39.0 kg	CDM: 22.2 kg	CDM: 22.2 kg DPS: 2.2 kg	CDM: 22.2 kg DPS: 6.7 kg	N: 870 g P: 337 g K: 1210 g	N: 870 g P: 337 g K: 1210 g micro: 23 L

†FDM: Fresh Dairy Manure, CDM: Composted Dairy Manure and DPS: Date Palm Straw - applied to planting hole before transplanting plants; N: urea [$CO(NH_2)_2$], P: triple super phosphate [$Ca(H_2PO_4)_2.H_2O$] and K: potassium sulphate [K_2SO_4] - applied to surface soil; micro: Fetrilon® Combi 2 soluble foliar micronutrient fertilizer solution - applied to leaves at a concentration of 1 g/L H_2O using a backpack sprayer.

4.2.8 Data collection

Vegetative growth

Dates of planting, flowering and harvest were collected to calculate days from planting to flowering (DTF) and to harvest (DTH) and from flowering to harvest (FF: Fruit Filling). At flowering, pseudostem height from the soil level up to the last two leaves (V-shaped) and girth (cm) at 10 cm above the soil level were measured and the number of leaves per plant was counted. To calculate leaf area (m^2), the length and width of the third fully expanded leaf were measured at flowering as described by Attia et al. (2009) and Al-Harthi and Al-Yahyai (2009).

Yield parameters

At harvest, fresh bunch weight (kg) was measured. The number of hands per bunch and total number of fingers per bunch was counted. Three individual middle fingers of the second hand were used to measure average fruit weight as recommended by Mustaffa et al. (1998) and Alvarez et al. (2001). Total yield (kg/ha/cycle) was calculated based on bunch weight and the number of plants per hectare (1,111 plants/ha).

4.2.9 Data analysis

All data were tested for normal distribution using the Shapiro-Wilk test. Analysis of variance (ANOVA) was done on normally distributed data (plant growth parameters, fruit weight, bunch weight, total yield, total number of fruits per bunch and DTF) using GenStat Release 11.1 (VSN International, Hemel Hempstead, UK). Data of DTH, FF and number of hands per bunch were Ln-transformed to normalize distribution of residuals. The Tukey-test was used to test mean separation between factors.

4.3 Results and discussion

4.3.1 Soil and manure analysis

An experimental soil is classified as saline if its EC_e is > 4 dS m^{-1} (Al-Busaidi and Cookson 2003). The saline field soil in our experiment was characterized by an EC_e of 11.9 dS m^{-1}, while the imported non-saline soil had an EC_e of 1.8 dS m^{-1}, but the pH of both soils was alkaline. The saline and non-saline soils had a $CaCO_3$-concentration of 26 % and 31 %, respectively. While the saline field soil had a sandy texture, the imported non-saline soil was a sandy loam (Table 2).

Table 2. Basic physical and chemical properties of the experimental soils used for a banana soil salinity experiment in Oman.

Properties	Non-Saline soil	Saline soil
EC_e (dS m^{-1})	1.8	11.9
pH (1:2.5)	8.5	7.9
Sand (%)	54	84
Silt (%)	37	6
Clay (%)	9	10
$CaCO_3$ (%)	26	31

The composted manure had an EC_e of 8.1 dSm^{-1} compared to fresh dry manure (4.3 dS m^{-1}), while date palm had an EC_e of 0.90 dS m^{-1} (Table 3). Both manures are alkaline, while date palm was acidic. Lignin was high in fresh and composted manure compared to date palm straw. The macronutrient concentrations (N, P and K) in organic amendments were relatively low. The amounts of N, P and K contained in the manures were used to calculate their quantities applied to the plants in non-manure treatments. Manure and date palm straw had high contents of lignin, cellulose and acid detergent fibre.

Table 3. Basic chemical properties of fresh and composted dairy cow manure and of date palm straw used in a banana soil salinity experiment in Oman.

Properties	Composted Dairy Manure (CDM)	Fresh Dairy Manure (FDM)	Date Palm Straw (DPS)
ECe (dS m-1)	8.4	4.6	0.90
pH (1:2.5)	8.1	7.8	5.3
Total N (mg kg^{-1})	18	10.3	4.1
Total P (mg kg^{-1})	6.2	3.97	0.3
Total K (mg kg^{-1})	25.0	15.5	7.7
Lignin (mg kg^{-1})	145	100	84
Cellulose (mg kg-^{1})	289	277.2	450
Acid Detergent Fibers (mg kg-^{1})	434	377.2	534

4.3.2 Vegetative growth

Neither soil amendments, fertilizer applications methods nor fertilizer compositions had a significant effect on pseudostem height or girth, or on leaf area at flowering (Table 4). Treatment effects were only significant for the number of leaves at flowering between Saline-Ring-NPK plants (8.2 leaves/plant) and Amended-Mixed-NPK and Amended-Ring-NPK+micro plants (14.0 and 13.8

leaves/plant, respectively). Replacing the saline field soil in the root zone with non-saline soil improved the growth of ‘Malindi’ plants compared to those planted in saline soil. However, replacement soil plants did not reach the average size of ‘Malindi’ plants grown under optimum conditions in Oman (pseudostem height, 180 cm; MAF 1995). The maximum height attained by our plants was 129.3 cm for the amended Saline-Ring-NPK+micro plants. For optimum yield, the number of functional leaves at flowering stage should be 10-15 leaves (Robinson 1996). The plants grown on the amended soil had 10-14 leaves, while those on saline soil had 8 - 11 leaves. In studies on non-saline soil where the effects of different inorganic fertilizers on cv. ‘Williams’ were studied, the number of leaves ranged from 12-13.6 leaves (Mostafa 2005 Al-Harthi and Al-Yahyai 2009). In general, plant growth on amended soil was better than on saline soil, suggesting that our fertilizer amendments alone were not able to improve plant growth sufficiently to offset the negative effects of salinity. In a study on cv. 'Sindhri' banana, leaf area, plant biomass and water contents decreased significantly due to NaCl stress (Al-Haq et al. 2011). Under saline soil conditions, growth of plants is inhibited by ion cytotoxicity, osmotic stress and unbalanced nutrients, which may the retard metabolic activity inside the plant (Allakhverdiev et al. 2000; Zhu 2002) and inhibit photosynthetic activity (Parida and Das 2005). These effects of salts on plants may explain the observed general weaker growth of cv. ‘Malindi’ plants on saline soil compared to those plants on amended soil.

Table 4. Effects of soil amendments, fertilizer application methods and fertilizer composition on vegetative growth of *Musa* AAA cv. 'Malindi' in a soil salinity experiment in Oman.

Treatments			Pseudostem height (cm)	Pseudostem girth (cm)	Leaf area at flowering (m^2)	No. of leaves at flowering
Saline Soil	Mixed Application	FDM*	117.4NS	45.2NS	3.7NS	11abc
		CDM*	88.8	34.5	2.9	10abc
		CDM+10%DPS*	108.8	40.0	3.2	9ab
		CDM+30%DPS	108.5	41.8	3.3	10abc
		NPK	95.8	34.8	3.3	11abc
		NPK+micro	108.0	41.1	4.0	10abc
	Ring Application	FDM	110.2	43.3	3.7	10abc
		CDM	101.7	38.1	3.4	11abc
		CDM+10%DPS	99.7	38.3	3.2	10abc
		CDM+30%DPS	106.7	38.3	3.2	11abc
		NPK	92.0	33.8	3.1	8a
		NPK+micro	107.4	38.0	3.4	10abc
Amended Soil	Mixed Application	FDM	123.0	50.2	4.0	12abc
		CDM	115.7	44.8	4.1	11abc
		CDM+10%DPS	127.7	44.0	4.1	11abc
		CDM+30%DPS	117.7	44.8	3.8	12abc
		NPK	127.8	48.8	4.6	14c
		NPK+micro	128.2	51.2	4.7	13abc
	Ring Application	FDM	124.2	47.5	4.5	14bc
		CDM	127.5	47.0	4.4	11abc
		CDM+10%DPS	119.2	45.3	4.3	12abc
		CDM+30%DPS	128.7	47.2	4.4	14bc
		NPK	125.3	49.3	4.7	11abc
		NPK+micro	129.3	51.3	5.2	14c
Soil Amendment (S)			<0.001	<0.001	<0.001	<0.001
S x F			0.003	<0.001	0.042	0.481
S x M			NS	NS	NS	NS
S x F x M			NS	NS	NS	0.046
CV %			10.4	10.3	18.5	18.2

*FDM=Fresh dry manure; CDM=compost dry manure; DPS= date palm straw, Means in columns with similar letters are not significantly different ($P < 0.05$) according to Turkey-test, NS= not significant

4.3.3 Yield parameters

None of the treatments significantly affected fruit filling (FF), fruit weight, number of hands/bunch or fingers/bunch (Table 5). However, a significant difference was observed in days to flowering (DTF) between Amended-Ring-NPK+micro (267 days) plants and Ring-NPK+micro, NPK, Ring-CDM, Mixed-NPK+micro, Mixed-NPK and Mixed-CDM plants in saline soil (405, 387, 340, 333, 372 and 365 days, respectively). On both soils, all plants, except Amended-Mixed-NPK (93 days) plants, needed less than 3 months from flowering to harvest (fruit filling: FF), which is unusual. In saline soil, Ring-FDM plants flowered significantly earlier (286 days) than Mixed-CDM, Mixed-NPK, Ring-NPK+micro and Ring NPK plants (372, 372, 387 and 405 days, respectively). In amended soils, fertilizer combinations and application methods did not significantly affect DTF. Amended-Ring-NPK+micro plants were harvested significantly earlier (339 days) than those Ring-NPK+micro, Ring-NPK, Mixed-NPK and Mixed-CDM plants on saline soil (494, 465, 457 and 453 days, respectively). In saline soil, a significant difference in DTH was only observed between Mixed-FDM plants (354 days) and Mixed-CDM, Mixed- NPK, Ring-NPK+micro and Ring NPK plants (453, 457,465, and 494 days, respectively). In contrast, in the amended soil no interaction between fertilizer combinations and application methods was detected.

Aside from high yields, early flowering and bunch harvest are important for banana farmer because these dates determine when harvesting activities take place. In general, time to flowering was faster on the amended soil than on the saline soil. Under Omani conditions, using optimum cultural practices, DTH of cv. ‘Malindi’ banana is 330 days (MAF 1995). In our study, Amended-Ring-NPK+micro and Amended-Mixed-FDM plants needed 339 and 346 days, respectively. Despite the unusual experimental pot conditions, our results seem reasonable. In a comparative study on ‘Dwarf Cavendish’ and ‘Williams’ banana, crop maturation intervals (i.e. DTH) were 483 and 465 days, respectively and days to fruit ripening ranged between 108 and 200 days (Robinson and Nel 1985). In their study on the effect of inorganic fertilizers on growth and yield of cv. ‘Williams’ in Oman, Al-Harthi and Al-Yahyai (2009) recorded crop-cycles (DTH) ranging between 423 and 450 days and days to fruit ripening between 107 to 119 days. In our study, crop development for the plants receiving inorganic fertilizer and CDM treatments in both application methods on the saline soil were within this range. However, the general crop development in other treatments was much slower, while it was within the range for the same variety grown under optimum conditions in Oman. The number of days for fruit filling was the only unusual period (less than 3 months). In a study on the effect of salinity on different varieties of rice, Khatun et al. (1995) determined that salinity delayed flowering. Similarly, Peter et al. (2002) found that 4 g/l NaCl delayed flowering of *Iris hexagona* (Iridaceae). In our study, plants on the amended soil flowered earlier and were generally harvested earlier than those on saline soil, indicating that salinity may also delay flowering of banana.

Amended-Ring-NPK+micro plants produced significantly heavier bunches (9.5 kg/bunch/cycle), followed by Amended-Mixed-NPK+micro (5.9 kg/bunch/cycle). The general trend was that plants on amended soil produced heavier bunches compared to those on saline soil. Neither soil amendments, fertilizer applications methods nor fertilizer compositions significantly affected fruit weight, number of hands/bunch and number of fingers/bunch (Table 5). Amended-Ring-NPK+micro plants were significantly more productive (10.6 tonnes/hectare) than all other plants, followed by Amended-Mixed-NPK+micro plants (6.6 tonnes/hectare).

Despite of our experiment having been carried out on a nutrient poor saline soil, the two highest yielding treatments (Amended-Ring-NPK+micro and Amended-Mixed-NPK+micro, with yields of 9.5 and 5.9 kg/bunch, respectively) exceeded the average bunch weight per plant in Oman (4.6 kg/bunch/cycle at the typical density of 3,333 plants ha^{-1}) and FAO production data (FAOSTAT 2010). The significant interaction between soil amendments, fertilizer application methods and fertilizer composition in this study revealed that replacing the saline soil around young banana with a non-saline sandy loam and ring-applying inorganic fertilizers can counteract the negative effects of salinity on banana yields during the first cycle, though not those on plant growth. However, even with these amendments, banana yields were still lower than those on the non-saline soil with good cultural practices.

For optimum yield, number of leaves at flowering should be no less than 10 (Robinson 1996). It was observed that Amended-Ring-NPK + micro plants, which had the greatest average bunch weight also, had the greatest number of leaves at flowering and leaf area. This may be the reason for the high average bunch weight of plants in this treatment. The yield effects of organic fertilizer amendments were much lower than those of NPK+micro. The high contents of lignin in manures may have retarded the decomposition of dry matter and nutrient release (Alexander 1977). Also, the low macronutrient content of manures and their high EC_e and pH may have contributed to this weak performance. In contrast, quick dissolution of applied chemical fertilizers and their distribution in the soil solution enables the plant root system to absorb the nutrients easily (Polat et al. 2008). Generally, the incorporation of fertilizers into the soil with the 'Ring method' gave better yields than mixing fertilizers with the top 20 cm of soil in the 'Mixed method'. This may be due to increased N use efficiency via reduced N volatilization losses, leaching and denitrification (Eghbal and Power 1999; Reiman et al. 2009). High soil salinity and sodicity affects the movement of nutrients from soil to plants and thus reduces crop yields (Al-Busaidi and Cookson 2003). An interesting effect of combined application of date palm straw and composted manure is the observed increase in plant size, as well as earlier fruit ripening and subsequent harvest. This could be due to the ability of DPS to increase soil microbial biomass and lower the microbial C turnover (Scheller and Jorgensen 2008; Heinze et al. 2010) and therefore increase the release of nutrients necessary for vegetative growth. This confirms the role of date palm straw as a soil conditioner, as suggested by earlier work (Hegazi et al. 2007; Khiyami et al. 2008; Alkoaik et al. 2011; Almadini 2011; Ghehsareh et al. 2011; Ghehsareh and Kalbasi 2012). This effect of date palm straw requires further research.

Table 5. Effects of soil amendments, fertilizer application methods and fertilizer composition on yield and yield components of Musa AAA cv. 'Malindi' in a soil salinity experiment in Oman.

Treatments			DTF (days)	FF (days)	DTH (days)	Bunch weight (kg)	Fruit weight (g)	No. of hands	No. of fingers	Yield (kg/ha)
Saline Soil	Mixed Application	FDM*	288 abc	66 NS	354 ab	3.8 abcd	55.9 NS	6.4 NS	65 NS	4193 abcd
		CDM*	365 defg	88	453 cde	2.7 abc	57.8	4.5	42	3030 abc
		CDM+10%DPS*	309 abcde	70	378 ab	3.6 abcd	61.2	6.0	56	4043 abcd
		CDM+30%DPS	314 abcde	74	388 abc	3.0 abc	53.3	5.0	49	3278 abc
		NPK	372 efg	85	457 cde	2.3 ab	58.2	4.3	37	2581 ab
		NPK+micro	333 bcdef	74	407 abcd	3.3 abcd	56.6	6.3	57	3704 abcd
	Ring Application	FDM	286 abc	82	368 ab	3.3 abcd	56.8	5.8	56	3622 abcd
		CDM	340 cdef	75	415 bcd	2.7 abc	59.8	4.7	40	3031 abc
		CDM+10%DPS	318 abcde	72	390 abcd	2.7 abc	59.2	4.7	44	2952 abc
		CDM+30%DPS	305 abcd	69	374 ab	2.9 abc	54.9	5.2	49	3256 abc
		NPK	387 fg	78	465 de	2.2 a	57.6	3.9	34	2399 a
		NPK+micro	405 g	89	494 e	4.2 abcd	92.1	5.0	43	4706 abcd
Amended Soil	Mixed Application	FDM*	269 ab	77	346 ab	5.0 abcd	68.7	6.6	73	5591 abcd
		CDM*	304 abcd	70	374 ab	4.0 abcd	61.3	6.7	63	4450 abcd
		CDM+10%DPS*	309 abcde	58	367 ab	5.2 bcd	62.6	6.3	58	5744 bcd
		CDM+30%DPS	303 abcd	58	361 ab	3.8 abcd	57.0	5.8	59	4261 abcd
		NPK	273 ab	93	366 ab	4.3 abc	62.5	6.0	71	4750 abcd
		NPK+micro	279 abc	62	341 ab	5.9 d	77.7	7.5	80	6591 d
	Ring Application	FDM	272 ab	76	347 ab	5.6 cd	74.7	7.0	79	6187 cd
		CDM	290 abcd	64	353 ab	5.5 cd	69.5	6.8	78	6120 cd
		CDM+10%DPS	298 abc	59	356 ab	4.4 abcd	62.0	6.0	67	4883 abcd
		CDM+30%DPS	297 abc	59	356 ab	5.0 abcd	66.1	6.3	70	5585 abcd
		NPK	274 ab	83	357 ab	4.6 abcd	63.4	6.0	75	5050 abcd
		NPK+micro	267 a	72	339 a	9.5 e	89.5	8.0	122	10576 e

Probability values

	DTF (days)	FF (days)	DTH (days)	Bunch weight (kg)	Fruit weight (g)	No. of hands	No. of fingers	Yield (kg/ha)
Soil Amendment (S)	<0.001	0.007	<0.001	0.001	<0.006	<0.001	<0.001	<0.001
S x F	<0.001	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	<0.001
S x M	0.239	0.890	0.236	0.006	0.086	0.001	0.045	0.006
S x F x M	0.046	0.462	0.019	0.034	0.231	0.568	NS	0.034
CV %	9.6	22.9	9.0	33.1	25.3	16.9	24.1	33.1

*FDM=Fresh dry manure; CDM=compost dry manure; DPS= date palm straw. Means in columns with similar letters are not significantly different ($P < 0.05$) according to Turkey-test, NS= not significant.

4.4 Conclusions and recommendations

Replacing the saline soil in the initial root zone of banana plants with a non-saline sandy loam soil and adding a combination of NPK mineral fertilizer with micronutrients incorporated at 5-10 cm depth 30 cm from the base of the plant (Ring application) may be a favourable practice to alleviate the effects of salt-affected soil on banana in Oman. This led to increased plant growth and productivity of *Musa* AAA cv. 'Malindi'. Application of mineral fertilizers alone to a saline soil did not improve growth or productivity of banana cv. 'Malindi'. The poor quality of the dairy manures used likely minimized their expected positive effects on banana growth and yield. The combined effect of date palm straw and composted manure on plant growth of field-grown banana requires further study.

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Chapter 5. General discussion

5.1 Maritime routes and banana genetic diversity on the Arabian Peninsula

All banana varieties in the world, including the ones found on the Arabian Peninsula, originated from material of Southeast Asia, which is the primary centre of dissemination of banana to other regions of the world (Chapter 2). Archaeological, linguistic and textual evidence indicates that banana was introduced to and further developed on the Arabian Peninsula a few millennia BC ago. Whether today's varieties arrived directly from their natural habitats in Southeast Asia and China or through India and East Africa needs to be further investigated. Despite the often millennia-old existence of important ancient maritime trade between Oman and Southeast Asia and China (Al Jarrow 2011; Al-Wagad 2011; Muftah 2011), lacking existence of banana phytoliths, make it difficult to determine whether bananas came directly from Southeast Asia or via India and East Africa. Two factors support the argument that India and East Africa are the main sources of bananas on the Arabian Peninsula. The first is the existence of year-round important ports along the Gulf, particularly in Oman and corresponding ports on the western coast of the Indian subcontinent (Figure 4, Chapter 2) between which Gulf traders could navigate within two weeks (Al-Wagad 2011). This proximity facilitated the renewal of banana varieties in case of their extinction during drought periods which may have contributed to continued existence of banana on the Arabian Peninsula over centuries. The second factor is the similarity of many banana cultivars in India and East Africa to what is available on the Arabian Peninsula (De Langhe 2002; Buerkert et al. 2009) as well as linguistic evidence.

A survey of some Arabian countries (De Langhe et al. 2002) suggests a considerable richness of banana genetic diversity on the Arabian Peninsula that been maintained over centuries, despite the harsh environmental conditions in the region. Buerkert et al. (2009) noted that the new triploid *Musa acuminata* found in Umq Bir (Upper Wadi Tiwi), Oman is likely a strain from humid regions that has adapted to the arid conditions in Oman. Local somatic mutations could have caused such adaptation and allowed introduced banana to survive the harsh environmental conditions of the Arabian Peninsula characterized by drought, salinity, high temperatures and biotic stresses (Careel et al. 2002; De Langhe et al. 2009). The continuous availability of water in irrigated agriculture and the shade of date palms have created local micro climates allowing banana to thrive. Further work is needed to conserve, genetically classify and develop breeding programs for banana on the Arabian Peninsula in order to enhance the multi-stress tolerance of this crop (Al-Saady et al. 2010; Opara et al. 2010).

5.2 Effects of composted dairy manure and date palm straw decomposition on chemical and biological behavior of alkaline non-saline and saline soils

Most Omani soils are alkaline, calcareous and have a low content of soil organic C (Al-Busaidi and Cookson 2003; Zhao et al. 2009). In such soils, the availability of plant nutrients is limited and thus plant growth (Ahmed et al. 2007; Sall et al. 2003). Soil pH is a key factor controlling the availability of micro- and macronutrients in the soil (Naidu and Rengasamy 1993). Recent studies (Motavalli et al. 1995; Yan et al. 1996; Tang and Yu 1999; Yan et al. 2000; Change et al. 2007; Wahba 2007; Formowitz et al. 2009) reported changes in soil pH pattern as a result of the application of organic amendments. In our study, the application of composted dairy manure alone to either non-saline or saline soils led to a reduction in soil pH by 0.2 units (Chapter 3, Table 3). The high $CaCO_3$ content in both soils (Chapter 3, Table 1) may have buffered larger pH changes (Mahdy 2011). Changes in soil pH after manure application could be attributed to the formation of organic acids as a result of organic matter decomposition via glycolytic pathway (Tang and Yu 1999). Similar to our results, Mahdy (2011) noticed a pH reduction in two soils (EC_e > 4 dSm^{-1}) grown with alfalfa (*Medicago sativa L.*) and fertilized with inorganic and organic soil amendments. Similarly, Duong et al. (2011) found that the application of composted manure to soils planted with wheat resulted in a reduction of the soil pH and Bulluck et al. (2002) observed a declining soil pH after the application of organic amendments to a vegetable field.

Generally, manure with or without date palm straw increased the electrical conductivity of the soil (EC_e). This is in accordance with results of previous studies on compost application by Sarwar et al. (2008) and Ghehsaresh et al. (2011) on composted date palm residues. However, Mahdy (2011) noticed a decrease in EC_e after application of soil amendments on alfalfa grown under greenhouse conditions, indicating that this helps in ameliorating the detrimental effects of salts by replacing ions. In our study the increase in EC_e after application of composted manure may be partly attributed to high salt levels in the soil with an EC of 8.1 dS m^{-1}. Sarwar et al. (2008) considered solubility of salts by acidic compounds an important reason for an increasing EC_e after the application of organic amendments to the soil and also showing that low EC_e and high cellulose in the straw can prevent straw degradation by soil microbes. Our results are in agreement with the results of the studies where amending soils with 30% date palm straw mitigated EC_e in the non-saline soil and slightly reduced it in the saline soil (Chapter 3, Table 3). However, Abbasi et al. (2009) noticed increase of EC_e in a soil amended with sole white clover residues and grown with a maize crop, indicating that changing soil EC_e can be related to initial contents of organic matter and crop type.

Besides their importance as a source of soil organic matter, organic amendments affect soil biological properties, in particular microbial communities and their activity. The presence of microbial communities in the soil is an indicator for its soil fertility (Ahmed et al. 2006). Recent studies showed large changes in biological soil properties after the addition of organic amendments (Bastian et al. 2009; Rasul et al. 2009; Zhao et al. 2009; Pascault et al. 2010). In our study, the biological behaviour of the experimental soils was strongly altered after the application of manures and date palm straw (Chapter 3) whereby the amounts of MBC and MBN produced varied according to soil type and organic treatments. This was also observed by Jedidi et al. (2004) and Rasul et al. (2009). In the non-saline soil, the average amount of MBC and MBN produced as a result of manure and date palm addition was significantly higher than in saline soil (Chapter 3, Table 4). This supports our hypothesis that soil microbes in saline soil were less efficient in decomposing organic matter than in non-saline ones. This may be due to the high amounts of salts in the soil that may have affected the activity of microbial enzymes (Frankenberger and Bingham 1982). Formowitz et al. (2009) and Wichern et al. (2006) made similar observations on decomposing maize residues in an acidic Alfisol and Utisol. Date palm straw yielded higher levels of microbial biomass C than that obtained from the application of cereals and legumes (Formowitz et al. 2009), but these levels were nonetheless lower than those reported by Warldle (1998) (330 µg g^{-1}) as the global average. The levels of MBC and MBN in the present study are comparable with the results of Khan and Joergensen (2006) on Pakistani soil, but lower than values reported from abandoned terrace soils in northern Oman (Wichern et al. 2004), probably due to the high amounts of manures applied by farmers in that region.

The increase in MBC and MBN in non-saline and saline soils after application of date palm straw and composted manure compared to composted manure alone indicates a synergistic effect of date palm straw and manure on the quantity of soil microbes. Wichern et al. (2006) came to similar conclusions when they incorporated maize residues into the soil. The present study also suggests the presence of recalcitrant substrates such as lignin and cellulose in manure which may be retarded the growth of soil microbes that decompose organic matter (Bosshard et al. 2011). These substances need a longer time to decompose than that time available for our study (Vanlauwe et al. 1996). The microbial biomass C/N ratio is usually used to describe and identify the microbial population (Moore et al. 2000). Our results indicate considerable variation in the C/N ratio between treatments within the same soil as well as between the two soils, indicating different microbial communities for the soils as also observed by Wichern et al. (2006). This difference may be due to changes in cell morphology of microbes (Sardinha et al. 2003). Another reason could be a differential nature in soil properties, especially pH, texture and also initial contents of organic matter (Moore et al. 2000). After 8 weeks of incubation, average biomass C/N ratio was within the range reported by Jenkinso (1976) and Anderson and Domsch (1980) However, in our study, sole addition of composted manure in non-saline soil did apparently not affect the microbial biomass community except that it was lower than in the un-amended soil. In the other treatments, the fungal microbial biomass dominated as compared to the un-amended soil. In the saline soil, the application of composted manure alone or with low straw led to a switch from a fungi dominated microbial biomass community to a bacterial dominated one compared to the un-amended soil. In contrast composted manure with high straw and sole date palm straw led to a dominance of the fungal community (Chapter 3, Table 4). Our results are in line with those in other arable soils (Jorgensen 1995; Anderson and Domsch 1980). In contrast, our values were lower than those observed by Formowitz et al. (2009) and Khan and Jorgensen (2006) in semi-arid subtropical soils and by and Dinesh et al. (2003) and Salamanca et al. (2006) in humid tropical soils, where in some treatments the C/N ratio was > 10. The increase in biomass C/N ratio in some treatments in our study may be due to the dominance of the fungal community (Dilly et al. 2003). This was confirmed by high ergosterol and ergosterol to microbial biomass C ratios which are good indicators for saprotrophic fungi (Joergensen and Wichern 2008).

The ergosterol (fungal cell membrane) content has been widely used to detect concentration of fungi in the soil (Diajakirana et al. 1996; Joergensen 2000; Wichern et al. 2006). In our study, after amending of soils with organic amendments, the ergosterol content concentration in non-saline soil was significantly higher than that in saline soil, indicating high fungal colonization. This is in line with Jorgensen (2000). Moreover, combined application of date palm straw and composted manure increased the ergosterol contents compared to composted manure alone in both soils. This increase was larger in the non-saline soil, indicating a stimulation of fungal communities and their rapid turnover by date palm straw (Joergensen and Wichern 2008).

The ratios of ergosterol to microbial biomass C in our study were higher than those reported from wet tropical forests soils under teak and padauk (Dinesh et al. 2003) as well as from tropical soils amended with residues from different trees species (Salamanca et al. 2006). This may reflect adaptation of microorganisms to high osmotic pressure induced by salts (Wichern et al. 2006).

5.3 Effect of salinity on C and N mineralization

Carbon dioxide (CO_2) evolution is widely used to measure organic matter decomposition, that is organic C mineralization (Ahmed et al. 2007; Formowitz et al. 2007 and 2009; Walpola et al. 2010; Setia et al. 2010; Abera et al. 2012; Setia et al. 2012). In the present study (Chapter 3), after 56 days of incubation, the cumulative CO_2-C evolved in the un-amended saline soil was significantly lower than that in the un-amended non-saline soil, suggesting that the high concentration of salts and low content of soil organic C in the saline soil did not hamper the capability of soil microbes to perform their metabolic activities in mineralizing organic carbon (Conde et al. 2005; Rasul et al. 2009). This result is in the line with Wong et al. (2008) and Setia et al. (2010 2011; 2012) who found that C mineralization was higher at low EC_e than at high EC_e. Addition of organic residues activates soil microorganisms, especially fast growing groups (Setia et al. 2012). Our results showed that soil incorporation of organic amendments regardless of whether they were manures or date palm straw led to a different CO_2-C release. However, these were lower in the saline than in the non-saline soil, indicating that the initial content of residues and soil quality played an important role in the activation of soil microbes (Setia et al. 2012). Such effects were also reported by Ahmed et al. (2007) on soil amended with composted and raw organic wastes, by Rasul et al. (2009) from a saline and alkaline soil amended with sugarcane filter cake amended with glucose and by Walpola et al. (2010) from saline and non-saline soils amended with three types of animal manures.

The present study indicates that cumulative CO_2-C released from the non-saline soil amended with composted dairy manure alone was higher than that from the saline soil, suggesting that microbes in the saline soil were less efficient than those in the non-saline soil. This result is in agreement with Setia et al. (2010 and 2011), but contrary to Walpola (2010). On the other hand, addition of date palm straw, particularly, 30% straw together with composted manure led to increase CO_2-C release in both soils with larger amounts in the non-saline soil than in the saline soil, indicating the synergistic role of straw. Another interesting result in this study was that the addition of sole date palm straw to the soils led to significant increases in cumulative CO_2-C evolved

Despite the increase of N mineralization in un-amended non-saline as compared to saline soils, salinity had only small effects on this process (Pathak and Rao 1998; Yousif and Mubarak 2009), particularly taking into account the low levels of soil organic carbon (Chapter 3, Table 1). This point to the many interacting factors governing N mineralisation such as salt type, soil microbes and their reaction to salinity and soil type (Laura 1976; Wichern et al. 2006).

The significant increase of net N mineralization in the non-saline and saline soil after addition of sole composted manure as compared to un-amended soils indicates the high metabolic activities of soil microorganisms when decomposing organic matter, despite the presence of high contents of recalcitrant substrate such as lignin (Chapter 3, Table 3). This result is in agreement with Al-Ismaily and Walworth (2008) who observed that net N mineralization in a manure-amended sandy loam was greater than in the un-amended soil. Owing to recalcitrant components in date palm straw and its high C/N ratio (Chapter 3, Table 2), composted manure could hamper the decomposition of organic matter by soil microorganisms. Similar to our findings, Khorsandi and Nourbakhsh (2007) found that application of corn residue associated with manure reduced the flush of inorganic N in a non-saline soil and Muhammad (2011) observed a reduction in N mineralization after the combined application of N fertilizer and sugarcane, maize and sorghum residues. Our results support the view that addition of low quality residue with a high quality N source (mineral fertilizer or manures) could regulate N mineralization/immobilization balance and thus increase N use efficiency (Heal et al.1997; Sakala et al. 2000; Sall et al. 2003; Gentile et al. 2009). The application of palm straw is likely to reduce rapid decomposition of organic matter which may be of advantage for perennial crops in hot arid regions such as Oman with its high temperatures (Gentile et al. 2009), but of disadvantage when growing annual crops such as vegetables which need a rapid nutrient supply. Nitrogen immobilization after sole application of un-composted date palm straw into soils indicates intensive microbial turnover which supports the frequently reported result that application of residues with a wide C/N ratio causes N immobilization (Fu et al. 1987). Palm straw should therefore not be used alone as a fertilizer unless composted (Favel and Murphy 2006; Khiyamai et al. 2008; Ali 2011; Alkoiak et al. 2011; Ghehsareh et al. 2011; Amadini 2011). This is in line with the results of Cayuela et al. (2009) for wheat and cotton and those of Muhammad (2011) for cotton, sugarcane, maize and sorghum residues, but in contrast to the results of Kurdali (2012) who found that sesbania green manure is a promising bio-reclaiming material for saline soil as it improved sorghum plant growth.

5.4 Enhancing banana growth on saline soils

Our approach to replace the saline soil in the root zone of banana with a non-saline soil and adding fertilizers is an option to reclaim salt-affected soils and enhance banana production, but such an approach would be very investment intensive. The stunted growth of banana plants in the saline soil as compared to those in the non-saline soil indicates that the addition of soil amendments and irrigation with high quality water were apparently insufficient to leach the salts beyond the root zone. However, this does not negate the positive role of fertilizers and irrigation with good water in mitigating detrimental salt effects (Grattan and Grieve 1999). The superior of the 'Ring method' with respect to yield and yield components in this study (Chapter 4, Table 4) supports the view soil incorporation of mineral fertilizers often has important agronomic advantages (Eghball and Power 1999; Schilke-Gartley and Sims 1992; Baiyeri and Tenkouano 2008). This may at least be partly due to increased N use efficiency following a reduction of leaching and volatilization losses (Reiman et al. 2009; Webb et al. 2010).

Increase of growth and yield of banana fertilized by fresh dry manure (containing low concentrations of recalcitrant substrate; Chapter 4, Table 3 and 5) as compared to plants amended with composted manure supports the view that recalcitrant components such as lignin and cellulose in composted manure may have caused delayed growth.

Combined application of date palm straw and composted manure led to early flowering, ripening, and harvesting of banana plants as compared to applications of only composted manure. This suggests to that date palm straw may have interacted with manure as was observed in the laboratory incubation experiment (Chapter 3), leading to increased microbial biomass production and low microbial C turnover. However; more studies are needed to verify the role of date palm straw in triggering nutrient release from composted manure.

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