Gaseous and leaching losses of carbon and nitrogen in irrigated organic farming of a coastal oasis in Oman

Effects of manure quality and cropping system

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Summary

Gaseous and leaching losses of carbon and nitrogen in irrigated organic farming of a coastal oasis in Oman

Effects of manure quality and cropping system

Little experimental data exist regarding direct application of manure in irrigated subtropical organic cropping systems. While effects of manure quality on crop growth are well documented for temperate regions, such data are scarce for the arid tropics and subtropics. Therefore effects of different carbon/nitrogen (C/N) ratios and different ratios of structural/soluble carbohydrates (NDF/SC) in manure applied to irrigated organically grown vegetables were investigated during a two years field experiment in Sohar, northern Oman.

The manure was from water buffalos fed with two diets with a C/N ratio of 11.0 and 27.2, and a ratio of structural (NDF, i.e. cellulose, hemicellulose, lignin)/soluble carbohydrates (SC, i.e. sugars and starch) of 2.1 and 16.1, respectively. These diets yielded two manure types with a C/N ratio of 19 and a NDF/SC ratio of 17 (ORG1) and 25 and 108 (ORG2). The manures were split-applied to a surface irrigated sandy soil in northern Oman at respective 16 and 12 t ha^{-1} (ORG1) and 22 and 16 t ha^{-1} (ORG2) for 2007/8 and 2008/9, such that at total of 590 kg N, 251 kg P, and 320 kg K ha^{-1} was applied. The control treatment was an equivalent amount of nutrients applied in mineral fertilizers (MIN). The manure was air dried for seven days and crushed before application to the soil. Differences in phosphorus and potassium concentrations between manures were compensated by supplemental application of mineral fertilizer.

The relevant factorial cropping system consisted of a two-year crop rotation comprising radish (*Raphanus sativus* L.) followed by cauliflower (*Brassica oleracea* L. var. *botrytis*) and carrot (*Daucus carota* subsp. *sativus*). Radish was transplanted at first on all of the experimental plots as soon as the ambient temperatures in Sohar were tolerable for vegetable cultivation in begin of October. After a radish cultivation of 40 days, a second application of manure was conducted and subsequently carrot and cauliflower were cultivated during a cropping period of 90 days. The same rotation sequence was repeated during the winter season in Oman 2007/8 and 2008/9. The typical vegetable cultivation period in the Al Batinah plain of northern Oman lasts from September – May, as in the remainder of the year high air and soil temperatures prevent economic cultivation of vegetable crops in open fields. Irrigation of the experimental field of 46 mm was done manually with a frequency of three days. Yield levels strongly varied over years ($P<0.001$). Despite consistently higher yields on ORG1 compared to ORG2 plots, these differences were not significant. Cauliflower yield, stem diameter and plant height ($P<0.001$) as well as the ascorbic acid concentration in radish root ($P<0.01$) were significantly increasing with higher

availability of NPK from ORG2 plots over ORG1 plots to the mineral fertilizer equivalent while carrots root length, in contrast, was increasing from ORG1 plots over mineral fertilizer plots to ORG2 plots ($P<0.001$).

Laboratory experiments were conducted to determine sorption and desorption properties of mixed-bed ion exchange resins (sorbent) which were also used in the described field experiments for measurement of leaching losses. Ion concentration in freely percolating water and the infiltration flow rate greatly varies in cultivated soils and therefore it was necessary to analyze the effects of these factors on recovery rates of the sorbent. Dissolved nitrate (41.6 mM NO_3^- and 166.5 mM NO_3^-), ammonium (63.9 mM NH_4^+ and 256.1 mM NH_4^+), phosphate (3.5 mM PO_4^{3-} and 13.9 mM PO_4^{3-}) and potassium (16.1 mM K^+ and 63.9 mM K^+) were factorially combined and added at flow rates of 5 l at 3 and 9 hrs to plastic cartridges containing the exchange resin:sand mixture. Six extractions with 1 M NaCl desorbed > 90% of the added ions. For nitrate (NO_3-N) apparent recovery rates averaged 99% (± 6), for ammonium (NH_4-N) 100% (±8) and for phosphate (PO_4-P) 109% (± 6). Apparent recovery rates of potassium (K) were with 151% (±12) erroneously high and likely reflected contamination of the exchange resin:sand mixture. Ion concentration of the solution did not affect recovery rates of any of the studied ions, but PO_4-P recovery depended on flow rate ($P<0.01$). It was summarized that the quantification of leaching losses of P and K from soils with the described ion exchange resin - sand mixture requires pre-treatment by a thorough cleaning procedure to remove adsorbed contaminating ions particularly from the quartz sand used.

Organic vegetables grown in hot and arid areas require large amounts of irrigation water and high application rates of manure or compost. These production systems were suspected to be inefficient in terms of nutrient use leading to increased emission of greenhouse gases and leaching of nutrients. Therefore gaseous emissions of NH_3, N_2O, CO_2 and CH_4 were measured over 24 months in the above described organic cropping systems experiment near Sohar, northern Oman, using a closed chamber system connected to a portable INNOVA photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark). The measurements were conducted always after the irrigation event on bare soil surface between the plants. Irrigation-dependent leaching of nitrogen (N), phosphorus (P) and potassium (K) was assessed by suction plates and mixed-bed ion-exchange resin cartridges. Both, suction plates and resin cartridges, were installed before start of the growing period in a depth of 40 cm. The resin cartridges were unburied and extracted after harvest of the second vegetable crop. Cumulative infiltration as affected by crop specific evapotranspiration during the growing period was calculated with the software Hydrus 1d based on soil physical parameters. The collection of leaching water samples was done simultaneous to the irrigation events while controlling the pressure head with tensiometers.

For 24 months and a total cropping period of 260 days, soil gaseous N emissions averaged 45 kg ha^{-1} (59% NH_3-N, 41% N_2O-N) for MIN, 55 kg N ha^{-1}

(69% NH_3-N, 31% N_2O-N) for ORG1, and 49 kg N ha^{-1} (59% NH_3-N, 41% N_2O-N) for ORG2. Carbon emissions were 6.2 t C ha^{-1} (98% CO_2-C, 2% CH_4-C) for MIN, 9.7 t C ha^{-1} 99% CO_2-C, 1% CH_4-C) for ORG1 and 10.6 t ha^{-1} (98% CO_2-C, 2% CH_4-C) for ORG2.

During the same period, cumulative leaching of nitrogen (NO_3-N, NH_4-N), which was determined with the aid of resins, averaged 30 kg N ha^{-1} for MIN, 10 kg N ha^{-1} for ORG1, and 56 kg N ha^{-1} for ORG2. Leachate data derived from silicon carbide suction plates installed during one growing cycle 2008/9 (130 days) resulted in cumulative leaching on ORG1 and ORG2 plots of respective 37 and 77 kg N (NO_3-N, NH_4-N). A relatively large difference observed in leachate samples between leached total nitrogen (Ntot) compared to mineral nitrogen (Nmin) may represent a relatively large proportion of 36% of leached organically bound nitrogen on total nitrogen in the leachate samples.

Net-balance calculations showed that nutrient surpluses of 361 kg N ha^{-1} and 196 kg P ha^{-1} for radish-carrot and 299 kg N ha^{-1} and 184 kg P ha^{-1} for radish-cauliflower were accompanied by K deficits of -59 kg ha^{-1} and -73 kg ha^{-1} for both cropping systems. Respective (net) carbon balances for MIN, ORG1 and ORG2 plots were -7.3, -3.1, and 1.5 t C ha^{-1} on radish-carrot plots and -5, 1.3 and 4.6 t C ha^{-1} on radish-cauliflower plots.

Deutsche Zusammenfassung

Gasförmige und sickerungsbedingte C- und N- Verluste aus organisch gedüngten und bewässerten Ackerflächen einer Küstenoase im Oman

Einfluß von Düngerqualität und Anbausystem

Es wurden bisher nur wenige experimentelle Untersuchungen zur direkten Applikation von Dung in bewässerten organischen Anbausystemen in den Subtropen durchgeführt. Während Auswirkungen der Dungqualität auf das Pflanzenwachstum für Regionen gemäßigten Klimas relativ gut dokumentiert wurden, sind nur wenige Daten für aride Anbaugebiete in den Tropen und Subtropen vorhanden. Aufgrund dessen wurden die Effekte verschiedener Kohlenstoff/Stickstoff (C/N) Verhältnisse und verschiedener Verhältnisse von strukturellen zu löslichen Kohlenhydraten (NDF/SC) von Dung, der in bewässerten organisch angebauten Gemüsekulturen appliziert wurde, untersucht.

Der Dung stammte von Wasserbüffeln, deren Futter durch C/N-Verhältnisse von 11,0 und 27,2 und Verhältnisse von strukturellen (NDF, z.B. Zellulose, Hemizellulose, Lignin) zu löslichen Kohlenhydraten (SC, z.B. Zucker und Stärke) von 2,1 and 16,1 gekennzeichnet war. Im auf sandigen Böden mit vier Wiederholungen durchgeführten Experiment wurden die aus den oben beschriebenen Futterzusammensetzungen resultierenden zwei Dungvarianten zum einen mit einem C/N-Verhältnis von 19 und einem NDF/SC-Verhältnis von 17 (ORG1) und zum anderen mit einem C/N-Verhältnis von 25 und einem NDF/SC-Verhältnis von 108 (ORG2) verwendet. Als Kontrollbehandlung wurde Mineraldünger (MIN) mit äquivalenten Mengen an mineralischem Stickstoff (N), Phosphor (P) und Kalium (K) appliziert. Der Dung wurde vor der Einarbeitung für sieben Tage luftgetrocknet und zerkleinert. Unterschiede in Phosphor- und Kaliumgehalten des Dungs wurden durch supplementäre Applikation von Mineraldünger ausgeglichen.

Das relevante faktorielle Anbausystem war eine zweijährige Rotation, bestehend aus Rettich (*Raphanus sativus* L.) gefolgt von Blumenkohl (*Brassica oleracea* L. var. *botrytis*) und Karotte (*Daucus carota* subsp. *sativus*). Rettich wurde als erste Kultur gepflanzt, nachdem Anfang Oktober die Umgebungstemperaturen in Sohar auf ein für den Gemüseanbau tolerierbares Niveau gesunken waren. Nach der 40 Tage andauernden Anbauperiode von Rettich wurde eine zweite Dungrate appliziert und für weitere 90 Tage Karotten und Blumenkohl angebaut. Dieselbe Rotationssequenz wurde während der Winterperiode im Oman in den Jahren 2007/8 und 2008/9 wiederholt. Der typische Zeitraum für den Anbau von Gemüsekulturen dauert im Norden des Oman von September bis Mai, da während der restlichen Monate des Jahres ein ökonomisch vertretbarer Anbau von Gemüsekulturen im offenen Feld durch zu hohe Umgebungs- und

Bodentemperaturen verhindert wird. Die Bewässerung des Versuchsfelds mit 46 mm wurde manuell in einer Frequenz von drei Tagen durchführt. Die Höhe der Erträge in den beiden Anbauperioden 2007/8 und 2008/9 variierte stark ($P<0,001$). Obwohl höhere Erträge auf ORG1-Flächen im Vergleich zu ORG2-Flächen während der gesamten experimentellen Periode erkennbar waren, konnten keine statistisch signifikanten Unterschiede festgestellt werden. Eine signifikante Zunahme der Erträge, des Sproßdurchmessers und der Pflanzenhöhe von Blumenkohl ($P<0,001$) sowie der Konzentration von Askorbinsäure in den Wurzeln von Rettich ($P<0,01$) mit erhöhter Verfügbarkeit von N, P und K von ORG2-Flächen über ORG1-Flächen bis hin zur Mineraldünger-Kontrollbehandlung konnte festgestellt werden. Im Gegensatz dazu nahm die Wurzellänge von Karotten von ORG1-Flächen über Mineraldüngerflächen bis hin zu ORG2-Flächen zu ($P<0,001$).

In mehreren Laborexperimenten wurden die Sorptions- und Desorptionseigenschaften der in den oben beschriebenen Feldversuchen für die Bestimmung von Sickerverlusten verwendeten Ionenaustauscherharze (Sorbens) untersucht. Da die Ionenkonzentration und die Infiltrationsrate frei perkolierender Wässer in kultivierten Böden stark variieren kann, war es notwendig, die Auswirkungen dieser Faktoren auf die Wiederfindungsraten des Sorbens zu untersuchen. Gelöste Konzentrationen an Nitrat (41,6 mM NO_3^- und 166,5 mM NO_3^-), Ammonium (63,9 mM NH_4^+ und 256,1 mM NH_4^+), Phosphat (3,5 mM PO_4^{3-} und 13,9 mM PO_4^{3-}) und Kalium (16,1 mM K^+ and 63,9 mM K^+) wurden faktoriell kombiniert und in zwei Flussraten von 5 l in 3 und 9 Stunden auf eine Mischung von Austauscherharzen und Sand appliziert. Sechs Extraktionen mit 1 M NaCl Lösung desorbierten > 90% der zugegebenen Ionen. Mittlere Wiederfindungsraten lagen für Nitrat (NO_3-N) bei 99% (± 6), für Ammonium (NH_4-N) bei 100% (±8) und für Phosphat (PO_4-P) bei 109% (± 6). Die scheinbar hohen Wiederfindungsraten von 151% (±12) für Kalium (K) waren möglicherweise auf eine Kontamination der Austauscherharz-Sand-Mischung zurückzuführen. Die Konzentration der gelösten Ionen hatte keinen Einfluss auf die Wiederfindungsraten der untersuchten Ionen. Die Wiederfindungsrate von Phosphat war abhängig von der Flussrate ($P<0,01$). Die Ergebnisse zeigen, dass die beschriebene Mischung von Ionenaustauscherharzen und Sand durch ein gründliches Reinigungsverfahren vorbehandelt werden muss, um kontaminierende adsorbierte Ionen, die vor allem im benutzten Quartzsand enthalten sind, zu enfernen und eine Quantifizierung von Sickerverlusten von P und K in Böden zu ermöglichen.

Im organischen Anbau bewässerter Gemüsekulturen in heißen und ariden Regionen werden große Wassermengen und hohe Raten von Dung und Kompost appliziert. Es wurde vermutet, dass solche Produktionssysteme in Hinsicht auf den Nährstoffverbrauch ineffizient sind und zu erhöhten Emissionen von Treibhausgasen und Sickerverlusten von Nährstoffen führen. Aufgrund dessen wurden im oben beschriebenen experimentellen organischen Anbausystem über einen Zeitraum von zwei Jahren in der Nähe von Sohar

Gasemissionen von NH_3, N_2O, CO_2 und CH_4 mit einem photoakustischen Infrarot-Multigasmonitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark) und einer damit verbundenen Haube im geschlossenen System gemessen.

In Abhängigkeit von den Bewässerungsraten wurde die Versickerung von Stickstoff (N), Phosphor (P) und Kalium (K) mit Saugplatten und Ionenaustauscherharz-Kartuschen bestimmt. Saugplatten und Harzkartuschen wurden vor Beginn der Anbauperiode in einer Tiefe von 40 cm installiert. Die Harzkartuschen wurden nach Ernte der zweiten Gemüsekultur ausgegraben und extrahiert. Die kumulative Infiltration in Abhängigkeit von pflanzenspezifischen Daten der Evapotranspiration wurde mit Hilfe der Software Hydrus 1d auf der Grundlage bodenphysikalischer Parameter modelliert. Sickerwasserproben wurden während der Bewässerung, bei gleichzeitiger Kontrolle des Vakuumdrucks durch Tensiometer, entnommen.

In zwei Jahre wurden für eine gesamte Anbauperiode von 260 Tagen bodenbürtige kumulative Gasemissionen von 45 kg N ha^{-1} (59% NH_3-N, 41% N_2O-N) für MIN, 55 kg N ha^{-1} (69% NH_3-N, 31% N_2O-N) für ORG1 und 49 kg N ha^{-1} (59% NH_3-N, 41% N_2O-N) für ORG2 gemessen. Emissionen von Kohlenstoff (C) in Form von Kohlenstoffdioxid (CO_2-C) und Methan (CH_4-C) waren 6,2 t C ha^{-1} (98% CO_2-C, 2% CH_4-C) für MIN, 9,7 t C ha^{-1} 99% CO_2-C, 1% CH_4-C) für ORG1 und 10,6 t ha^{-1} (98% CO_2-C, 2% CH_4-C) für ORG2.

Im gleichen Zeitraum lagen die kumulativen, mit Hilfe von Ionenaustauscher-harzen bestimmten Sickerverluste an mineralischem Stickstoff (NO_3-N, NH_4-N) im Mittel bei 30 kg N ha^{-1} für MIN, 10 kg N ha^{-1} für ORG1 und 56 kg N ha^{-1} für ORG2. Die Analyse von Sickerwasserdaten, die mit Siliciumcarbid-Saugplatten während der zweiten experimentellen Anbauperiode 2008/9 (130 Tage) ermittelt wurden, ergab kumulative Sickerverluste auf ORG1- und ORG2-Flächen von jeweils 37 und 77 kg N (NO_3-N, NH_4-N).

Ein relativ großer Unterschied zwischen Gesamtstickstoff (Ntot) und mineralischem Stickstoff repräsentierte wahrscheinlich einen relativ großen Anteil an organisch gebundenem Stickstoff von 36% am Gesamtstickstoff in den Sickerwasserproben.

Die errechneten Nettobilanzen zeigten Überschüsse von 361 kg N ha^{-1} and 196 kg P ha^{-1} für Rettich-Karotte und 299 kg N ha^{-1} und 184 kg P ha^{-1} für Rettich-Blumenkohl, welche von Kalium-Defiziten von -59 kg K ha^{-1} für Rettich-Karotte und -73 kg K ha^{-1} für Rettich-Blumenkohl begleitet waren. Die jeweiligen Kohlenstoff Nettobilanzen auf MIN, ORG1 und ORG2-Flächen lagen bei -7,3, -3,1 und 1,5 t C ha^{-1} für Rettich-Karotte und bei -5, 1,3 und 4,6 t C ha^{-1} für Rettich-Blumenkohl.

Chapter 1

Introduction

Recently organic agriculture is increasing in the Middle East and other subtropical regions (Willer et al., 2010). Frequent wet-dry cycles in the traditionally flood-irrigated fields of these regions have been claimed to cause high nutrient and carbon losses through leaching (Jalali, 2005) and emanation (Dalal et al., 2003; Hans et al., 2005; Scheer et al., 2009). The ecological and economical organic production requires the reduction of these gaseous and leaching losses what is particularly important in organic farming where regulations strongly restrict the use of external inputs. The scarce water resources in arid regions must be used as efficiently as possible while maintaining soil organic C as the crucial determinant of soil productivity (FAO, 1997; Ibrahim, 1999; Norman et al., 1998a, b).

In the here presented study cumulative atmospheric N- and C-losses caused by decomposing organic materials, ammonia release, nitrification and denitrification processes were compared to the measured cumulative leaching losses. Apart from parameters such as moisture and temperature which are often given by agro-ecological conditions, the effects of two buffalo manures with different C/N ratios as compared to an equivalent amount of mineral fertilizer on carbon and nutrient turnover during the growth of irrigated vegetables on the Arabian Peninsula were investigated.

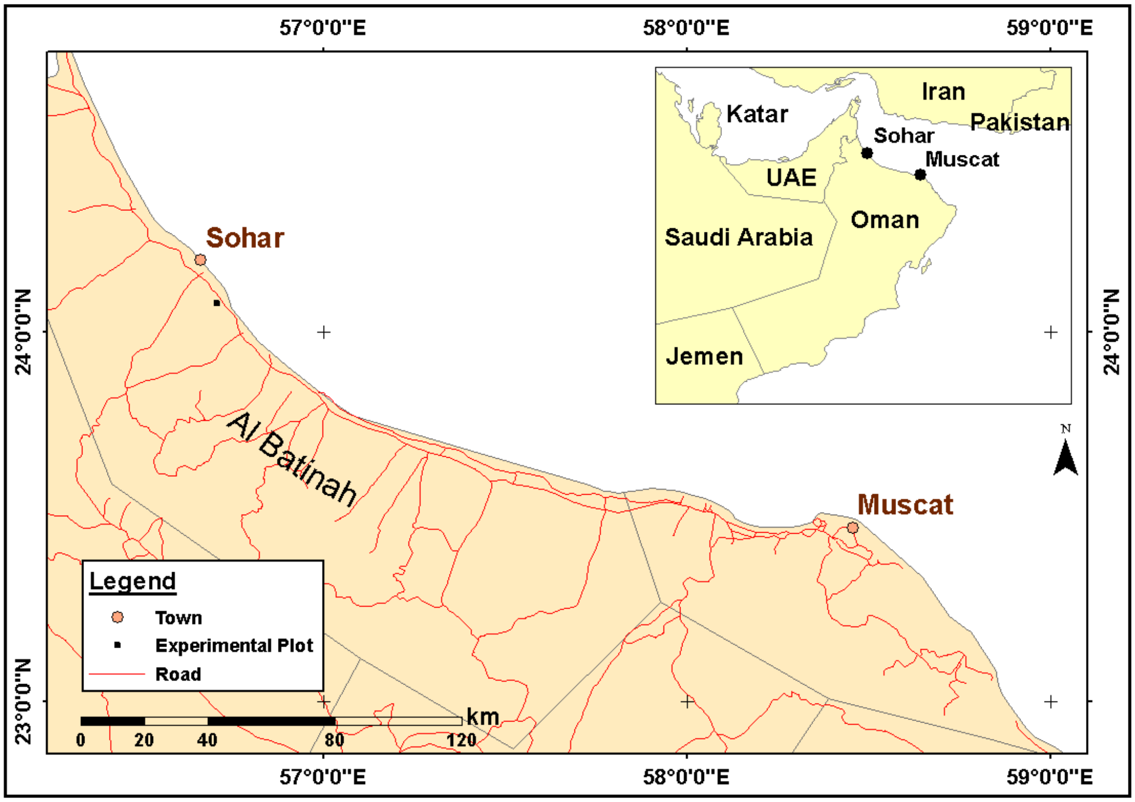
Given year-round irrigation and high temperatures in northern Oman we suspected that matter fluxes on the here cultivated vegetable fields were very large and heavily depended on the continued application of organic matter in the form of manure. Turnover and horizontal and vertical balances of carbon (C), nitrogen (N), phosphorus (P) and potassium (K) were assessed to develop more resource efficient organic cropping systems, to reduce emissions of greenhouse gases (IPCC 1996 and 2007) and to optimize organic production in subtropical hyperarid regions.

The following research hypotheses formed the basis of the here presented study:

Hypothesis 1 (H1):
Gaseous losses of N and C are considerably higher than leaching losses from manure-amended sandy soils under hyperarid climate conditions in Sohar, northern Oman.

Hypothesis 2 (H2):
Crop rotation only marginally affects field-bound C and N releases compared to the quality of incorporated manure.

Hypothesis 3 (H3):
Application of manure of a high C/N ratio & a high ratio of structural to soluble carbohydrates (Neutral detergent fibre / soluble carbohydrate) noticeably reduces atmospheric N losses and the speed of C-transformation.



(A) (B)

Figure 1. Geographic location and images of the experimental plot near Sohar, northern Oman, during cultivation with radish (A) and cauliflower/carrot (B).

The 24 months field experiment was conducted in 2007-2008 and 2008-2009 on a 6 ha private farm in the Batinah plain near Sohar (Oman, 24.2°N, 56.8°E, 4 m a.s.l., Figure 1). The locally prevailing fertile floodplains are irrigated from groundwater aquifers which are fed by winter and rare summer rains in the nearby Hajar Mountains.

Gaseous emissions of nitrogen and carbon were measured with a portable INNOVA photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark) in a closed chamber system (Predotova et al., 2010).

For the measurement of cumulative leaching losses of mineral nitrogen (NO_3-N, NH_4-N) and phosphorus (PO_4-P) mixed-bed ion exchange resins (Lehmann et al., 2001; Lang and Kaupenjohann, 2004; Bischoff, 2007) were used to cover the suspected spatial variability of leachate losses in the experimental plots. Recovery data of NO_3-N, NH_4-N, PO_4-P and K of the used exchange resins as affected by passage rate of solutes, ion concentration in the solution and mode of recovery (concentration of the extractant and number of extractions) were determined. Suction plates were used to measure time-dependent leaching of total amounts of nutrients and dissolved organic carbon (Webster et al., 1993; Siemens et al., 2002 and 2004; Mantovi, 2006) and also to get more knowledge of the proportion of leached organically-bound nitrogen in total nitrogen leaching (Siemens et al., 2002; Van Kessel et al., 2009; Barton et al., 2005).

Following the introduction (chapter 1) the thesis comprises an analysis of the effects of manure quality on yields and yield components (chapter 2) where also aspects regarding sustainability of the organic vegetable cropping system with direct manure application were addressed. The chapter also comprises results from analysis of leachate samples collected by suction plates. Chapter 3 is focussing on recovery rates of ion exchange resin cartridges used for the assessment of cumulative leaching losses of nutrient ions. The factor effects of passage rate and concentration of applied nutrient solution, concentration of extractant and the required number of extractions on recovery rates were investigated. Horizontal and vertical nutrient and carbon fluxes and calculated balances are presented in the next part of the thesis (chapter 4). The presented results are discussed and conclusions are drawn in chapter 5.

The study was conducted in close cooperation with other members of the DFG research training group 1397 ‘Regulation of Soil Organic Matter and Nutrient Turnover in Organic Agriculture’ at the University of Kassel-Witzenhausen, Germany. Results derived from analysis of chemical and biological reactions and microbial decomposition processes in soils of the experimental site in Sohar, northern Oman, were published by Sandra Hermann (Ludwig et al., 2010) and Nils Rottmann (Rottmann et al., 2010). The outcomes of these studies were useful for the critical interpretation of our own results.

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Chapter 2

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Effects of manure with different C/N ratios on yields, yield components and matter balances of organically grown vegetables on a sandy soil of northern Oman

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Abstract

Little is known about how organic matter quality affects crop production and matter fluxes under irrigated subtropical conditions. To this end river buffalos were fed with two diets characterised by a C/N ratio of 11.0 and 27.2, and a ratio of neutral detergent fibre (NDF, i.e. cellulose, hemicellulose, lignin) / soluble carbohydrates (SC, i.e. sugars and starch) of 2.1 and 16.1, respectively. The diets yielded two manure types with a carbon/nitrogen (C/N) ratio of 19 and a structural/soluble carbohydrate (NDF/SC) ratio of 17 (ORG1) and 25 and 108 (ORG2), respectively. These were split-applied at respective rates of 16 and 12 t ha^{-1} (ORG1) and 22 and 16 t ha^{-1} (ORG2) for two years in a factorial cropping systems experiment consisting of a cropping sequence of radish followed by either cauliflower (radish-cauliflower) or carrot (radish-carrot). The control treatment consisted of an equivalent combination of mineral fertilizers (MIN). Target levels of N, phosphorus (P), and potassium (K) were 590 kg, 251 kg, and 320 kg ha^{-1}, respectively. Despite consistently higher radish yields in ORG1 compared to ORG2 plots, these differences were not significant. Cauliflower yield, stem diameter and plant height ($P<0.001$) as well as the ascorbic acid concentration in radish root ($P<0.01$) increased with higher NPK availability from ORG2 plots to ORG1 and MIN plots, whereas carrot root length increased from MIN plots to ORG1 and ORG2 plots ($P<0.001$). Estimated N and P balances were positive across soil amendments (361 kg N ha^{-1} and 196 kg P ha^{-1} for radish-carrot and 299 kg N ha^{-1} and 184 kg P ha^{-1} for radish-cauliflower), but K balances negative (-59 kg ha^{-1} and -73 kg ha^{-1}). Carbon balances were strongly negative on MIN plots for both cropping systems (-7.3 and -5.0 t C ha^{-1}). The results underline the difficulty of maintaining soil organic C under irrigated subtropical conditions with year-round high temperatures.

Keywords Gaseous C and N emissions; irrigation agriculture; leaching losses; nutrient fluxes

2.1 Introduction

For millennia regular applications of manure at annual rates often exceeding 30 t ha^{-1} allowed to maintain soil C levels in irrigated oasis agriculture of Oman (Wichern et al., 2004; Buerkert et al., 2010), which at altitudes of 700-2000 m asl has been claimed to be a model case for sustainable organic land use management under subtropical conditions (Luedeling et al., 2005; Siebert et al., 2005). The irrigated subtropical lowlands of Oman's Al Batinah region have been cultivated for similar periods of time, however, little experimental data exist (Behera, 2009; Ghosh et al., 2004, Riahi et al., 2009) to assess the sustainability of the vegetable cropping systems dominating there. These data are important as vegetable production in many countries of the Middle East such as on the Arabian Peninsula, Iran, Pakistan, and India heavily relies on irrigation from scarce groundwater resources. These must be used as efficiently as possible while maintaining soil organic C as the crucial determinant of system productivity (FAO 1997, Ibrahim 1999, Norman et al., 1998a, b).

Apart from parameters such as moisture and temperature, which are often given by agro-ecological conditions, the turnover of field-applied manure is also affected by its C/N-ratio and fibre content. They contribute to the nutrient release dynamics, which in turn determines crop growth parameters and final yield (Chadwick et al., 2000; Sørensen et al., 2003; Velthof et al., 2005). A better understanding of these release processes and related matter fluxes is particularly important in organic agriculture where plant nutrient supply largely depends on organic fertilizers and cropping sequence.

In this study we therefore compared the effects of two buffalo manures with different C/N ratios to an equivalent rate of mineral fertilizer on yields, yield components, and matter balances in an irrigated subtropical cropping system with radish, carrot, and cauliflower.

2.2 Materials and methods

2.2.1 Site description

All data were collected during the cool seasons of 2007/8 and 2008/9 on a farm in the coastal Al Batinah plain of northern Oman near Sohar (24.2°N, 56.8°E, 4 m asl). At this location the average annual temperature amounts to 27°C (19 – 33°C monthly range) with a mean yearly relative morning humidity of 80% (66 – 87% monthly range). The average annual precipitation is 102 mm and potential annual evaporation exceeds 2000 mm (WMO 2009). The typical vegetable cultivation period in the Al Batinah plain lasts from September – May, as in the remainder of the year high air- and soil-temperatures prevent economic cultivation of vegetable crops in open fields.

2.2.2 Experimental setting

The experiment was laid out as a two-factorial with four completely randomised replicates (3 soil amendments x 2 cropping systems x 4 replicates = 24 plots). It was repeated in two fields with different cropping history that were randomized independently (2 fields x 24 plots = 48 plots). Plots had a size of 7.0 m x 2.5 m in field 1 and 5.5 m x 2.5 m in field 2. From 2004-2006 before the onset of the experiment, yam (*Dioscorea* L.), bottle gourd (*Lagenaria siceraria* L.), and nigella (*Nigella damascene* L.) were subsequently grown on field 1, while yam, onion (*Allium cepa* L.) and fenugreek (*Trigonella foenum graecum* L.) were cultivated on field 2.

2.2.3 Soil properties

The sandy soil of the experimental plots was a hyperthermic Typic Torrifluvent (US Soil Taxonomy). Its yellowish-brown upper 0.5 m layers contain 82% sand, 16% silt and 2% clay derived from sedimentary rocks of recent fluviatile wadi deposits, that are partly covered by aeolian sand veneers (Al-Farsi et al., 2001). The fine sand and silt fraction represent together 48% of the total soil matrix. The surface soil (0-0.15m) has a bulk density of 1.44 g cm^{-3}, a pH (1:2.5 water) of 7.9, 1.3 g organic C kg^{-1}, 0.6 g total N kg^{-1}, and 35 mg Olson P kg^{-1}.

2.2.4 Treatment description:

Feed composition, production, and processing of buffalo manure

The three soil amendments consisted of two manure treatments and one mineral control treatment (further referred to as 'MIN') comprising equivalent amounts of N, P, and K. The two types of manure originated from river buffalos *(Bubalus bubalis),* breed Nili Ravi, which were fed fodder of different composition (Al-Asfoor et al., 2010). The first diet contained 0.401 kg Rhodes grass hay (*Chloris gayana* Kunth.), 0.392 kg soybean meal (*Glycine max* L.), and 0.207 kg crushed maize (*Zea mays* L.). The second diet contained 0.899 kg Rhodes grass hay, 0.078 g soybean meal, and 0.023 kg wheat bran (*Triticum aestivum* L.). The resulting manures had a C/N ratio of 19 and a NDF/SC ratio of 17 (further referred to as 'ORG1'), and a C/N ratio of 25 and a NDF/SC ratio of 108 (further referred to as 'ORG2').

2.2.5 Soil amendments

During the experimental period 2007/2008 the MIN treatment and both manure treatments contained 135-51-80 kg NPK ha^{-1} for radish (1^{st} rotation phase) and 160-60-80 kg NPK ha^{-1} for cauliflower and carrot (2^{nd} rotation phase), respectively. During the experimental period 2008/2009 nutrient levels were 135-64-80 kg NPK ha^{-1} for radish and 160-75-80 kg NPK ha^{-1} for cauliflower and carrot. This required the application of 16 and 12 t ha^{-1} dry matter of manure ORG1 and 22 and 16 t ha^{-1} of ORG2 in 2007/8 and 2008/9, respectively. Comparability of target NPK levels applied was achieved by two equal applications of $(NH_4)_2SO_4$ (containing 21% N, top-dressed and incorporated) at 15 and 30 days after transplanting (DAT) of radish and cauliflower/carrots, triple superphosphate ($Ca(H_2PO_4)_2$) containing 19.6% P and applied at sowing, and potassium sulphate (K_2SO_4) - containing 41% K and applied at sowing - alone or in combination with the ORG1 and ORG2 manure (Table 1). Radish was cultivated from 02/10/07-07/11/07 and from 22/10/08-30/11/08.

Each year gypsum ($CaSO_4$) was broadcast at 300 kg ha^{-1} to each plot. Manure was rotovated to 0.15 m soil depth after application and irrigated once with 20 mm. Thereafter the crops were irrigated with 46 mm in a frequency of three days. Subsequently, radish var. *'Early Forty Days'* and cauliflower var. *'Spacestar'* were transplanted at a spacing of 0.75 m within row and 0.5 m between rows. Cauliflower was cultivated from 18/11/07-16/02/08 and from 05/12/08-04/03/09. Carrot var. '*Kuroda Improved*' was sown directly in triple rows (consisting of three individual rows spaced 0.1m apart) at a spacing of 0.25 m within row and 0.5 m between triple rows. Plants were thinned to 30 m^{-2} at 20 days after emergence (DAE). Carrot was cultivated from 18/11/2007-19/02/2008 and from 05/12/2008-08/03/2009.

Table 1: Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and organic carbon (C) concentrations (% at 65°C) of two 7 day old manures (ORG1 and ORG2) with different C/N ratios and neutral detergent fibre (NDF, i.e. cellulose, hemicellulose, lignin) / soluble carbohydrates (SC, i.e. sugars and starch) ratios used in an organic crop sequence experiment on a farm near Sohar, northern Oman. Data are averages of two applications in 2007/8 and 2008/9.

Manure type	N	P	K	C	C/N ratio	NDF/SC
ORG1	2.3	0.8	0.5	43.9	19	17
ORG2	1.7	0.7	0.5	42.8	25	108

2.2.6 Plant sampling and analysis

For all crops intermediate sampling occurred only in border rows leaving the central 5.5 m x 1.5 m of each experimental plot in field 1 and the corresponding area in field 2 intact for the estimation of final yield. For radish, ten plants per plot were collected at 18 DAT and final harvest (36 DAT in 2007 and 40 DAT in 2008) to determine root length, root diameter, number of leaves, shoot dry matter, and root yield. For cauliflower, the stem, leaf, and curd portions of three plants were collected at 67 DAT and at 90 DAT (final harvest) to record stem diameter, plant height, average canopy diameter, marketable yield, and total above ground dry matter. For carrot, 20 plants per plot were harvested at 75 and at 94 DAE to determine root length, root diameter, and total dry matter (TDM) of roots and shoots.

2.2.7 Analysis

All plant samples were oven dried to constant weight and ground to 2 mm. They were analysed for total N and C with a CN analyzer (VarioMax® CHN, Elementar Analysensysteme GmbH, Hanau, Germany). Phosphorus was detected colorimetrically (Gericke and Kurmies 1952; Hitachi U-2000 spectrophotometer, Tokyo, Japan) according to the vanado-molybdate method (Gericke et al., 1952). Potassium (K) concentration was determined by flame photometry (Instrument Laboratory 543, Bedford, MA, USA). Ascorbic acid concentration in radish roots and cauliflower curds were determined by HPLC (High performance liquid chromatography, Varian 9010, Sunnyvale, CA, USA) according to the method described by Gökmen et al. (2000).

2.2.8 Horizontal fluxes and total balance calculations of nutrients and carbon

Horizontal (partial) fluxes of N, P, K, and C were calculated by multiplying for the 2-year duration of the experiment all organic and mineral fertilizer inputs for each crop by their concentrations of N, P, K, and C and subtracting from these the N, P, and K removed by the harvested biomass. Resulting partial balance data were expressed as N, P, K, and C per hectare. Total balances for the two growing cycles 2007/8 and 2008/9 were calculated based on horizontal and vertical flux data (see below).

2.2.9 Gaseous losses of C and N

Gaseous C and N fluxes (carbon-dioxide, CO_2-C; methane, CH_4-C; ammonia, NH_3-N; nitrous oxide, N_2O-N) were estimated with a Teflon®-coated PVC cuvette of 0.0078 m^3 volume connected through two (3 mm inner diameter and 0.5 mm wall thickness) Teflon® tubes of 0.30 m length serving as gas inlet and outlet (closed chamber circuit) to a photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark; Buerkert et al., 2010).

To minimize the effects of daily changes in air and soil temperature on gaseous emission readings, readings of gas fluxes were taken in triplicate (three measurements per plot) in six freshly irrigated plots of one of the four replicates that was also used for leaching measurements in field 1. On all plots measurements were conducted during the day time periods 9:30 AM – 11:00 AM, 11 AM – 12:30 AM, 12:30 PM – 2:00 PM. Emanation data in radish were taken at 1, 3, 5, 7, 9, 11, 13, 15, and 17 DAT in 2007/8, and in 2008/9 (as a consequence of data evaluation and to save labour) at 2 and 5 DAT, and 2 days before harvest. In cauliflower and carrot, such data were collected at 2, 4, 6, 8, 10, 12, 35, and 36 (2007/8) and at 2, 4, 35, and 36 (2008/9) DAT and 2 days before harvest (2007/8 and 2008/9). To avoid plant effects on C and N flux measurements, all readings were taken on bare soil surfaces between plants. A more detailed description of the methodological approach is given by Predotova et al. (2010a).

2.2.10 Leaching losses

Cumulative leaching losses of mineral N (Nmin; NO_3-N, NH_4-N) were determined with mixed-bed ion-exchange resin cartridges of 0.11 m diameter and 0.11 m height (Siemens and Kaupenjohann, 2002; Predotova et al., 2010b). These were buried in the soil below the rooting zone at a depth of 0.4 m in all 24 experimental plots (5 cartridges per plot) before the onset of the experiment. The cartridges were filled with pure silica sand of 120 - 700µm (Majan Glass Co., Sohar, Oman) and a mixture of an industrial grade basic anion and cation exchange resin prior to installation according to the guidelines of TerrAquat Consultancy (Stuttgart, Germany), the patent holder of this method. Cartridges were unearthed after the harvest of the second crop in the cropping sequence (total cropping period of 130 days from October 2007 - March 2008 and from October 2008 - March 2009). The resin-sand mixture was removed from the PE-cylinders in four equal layers of which about 60 g each was frozen until analysis.

For ion extraction, according to a modified method of Terr Aquat (30 ± 0.5) g of the mixture were placed into a 250mL plastic bottle to which 100mL of an extractant was added followed by vigorous shaking for 60 minutes; this procedure was repeated eight times for the same sample and extracts pooled. Subsequently, a 25 ml subsample was analyzed for concentrations of nitrate (NO_3-N), ammonia (NH_4-N) and phosphate (PO_4-P) with an ICP-AES (Spectroflame, Spectro GmbH, Kleve, Germany). Cumulative leaching losses per hectare and cultivation period were calculated based on the 95 cm^2 surface area of the resin cartridge. Previous studies had shown that the recovery rates of the resin: sand mixture used in the cartridges varied between 78 and 114% for Nmin and between 96 and 121% for mineral P (PO_4-P; Siegfried et al., 2011).

To compare cumulative leaching data of Nmin from resin cartridges with irrigation event specific measurements of Nmin leaching, and to obtain estimates of leached total N and dissolved organic carbon (DOC), during the 2008/0 cropping cycle four suction plates (Siemens and Kaupenjohann, 2002) were installed at 0.4 m depth in one ORG1 plot and four suction plates in one ORG2 plot, both planted to radish-cauliflower. Given reported differences in adsorption characteristics of such plates (Wessel-Bothe et al., 2000; Peters et al., 2005) we used plates made from silicon carbide that have been found to be low in N adhesion (SiC; UMS GMBH, Munich, Germany). To collect free draining water, the vacuum pressure head was kept at -60 to -100 hPa. During measurements pressure head was adjusted based on readings of mechanical tensiometers at 0.4 m depth (ecoTech Umwelt-Meßsysteme GmbH, Bonn, Germany; Siemens et al., 2004).

To estimate plant root water uptake, seepage, water storage, and cumulative infiltration on the sandy experimental soil, the software Hydrus 1d (Simunek et al., 2008) was used. Input data necessary for Hydrus 1d, particularly of residual water content (Qr), saturated water content (Qs, a parameter related to the inverse of the air entry suction α), a measure of the pore size distribution (N), the saturated hydraulic conductivity (Ks), and an empirical parameter (l) for the soil's physical characteristics according to Van Genuchten (1980) were collected from the plot, in which suction plates were installed. To this end five undisturbed soil samples were taken from 0-0.15 and 0.15-0.30 m depth. Leaching as affected by crop specific evapotranspiration over the growing period was assumed to follow a sigmoidal function (Richards, 1959).

To calculate cumulative suction plate-based leaching of total N, Nmin (NO_3-N, NH_4-N), total P, K, and of DOC per hectare, the calculated amount of seepage was multiplied by the respective concentrations in the water samples. A Dimatec 100® CHN – analyzer (Dimatec Analysentechnik GmbH, Essen, Germany) was used to determine DOC and total N. Nitrate was determined by ion chromatography according to DIN 761, EN ISO 10304 (Deutsche METROHM GmbH & Co. KG, Filderstadt-Plattenhardt, Germany), NH_4-N by a continuous flow analyzer (Alliance Instruments GmbH, Salzburg, Austria), P by spectrophotometry (Hitachi U-2000 spectrophotometer, Tokyo, Japan), and K by flame photometry (Instrumentation Laboratory Co., MA, USA).

2.2.11 Data analysis

All data were subjected to analysis of variance using SPSS 17.0 (Backhaus et al., 2003). Scheffé post-hoc tests were used to identify least significant differences between means. Residuals of some datasets (yield dry matter, yield components, and leaching data) showed deviations from the normal distribution. However, as transformations had only minor effects on the F-values, but made data much harder to present, untransformed data are shown even if in these cases true probabilities may slightly differ from those given.

2.3 Results

2.3.1 Crop yields

Combined analysis of yield data showed no significant effects of manure type on any of the crops, but MIN radish had significantly higher ($P<0.05$) dry matter marketable yield in 2008 compared to respective ORG1 and ORG2 yields (Table 2).

Total dry matter yields of cauliflower and carrot were consistently higher in ORG1 plots than in ORG2 and MIN ones (Table 3), but these differences were not statistically significant. During the first growing cycle marketable cauliflower yields were with 1.6 t ha^{-1} highest in MIN plots followed by those in ORG2 and ORG1 plots. During the second cropping cycle cauliflower yields were with 1.4 t ha^{-1} highest on MIN and ORG1 plots followed by those of ORG2 plots (Table 3). During both cropping cycles marketable carrot yields were highest in ORG1 plots and lowest in MIN plots.

Overall TDM and marketable yield of radish significantly increased by 60% and 115% from the first cropping cycle 2007/8 to the second cycle 2008/9 (Table 2). For carrot and cauliflower, in contrast, respective decreases in TDM and marketable yields amounted to 43% and 41% (carrot) and 35% and 11% (cauliflower).

Table 2: Effects of soil amendments (A), year of cropping cycle (Y) and the combined effect (A x Y) on total dry matter (TDM) yield and marketable yield of radish, carrot and cauliflower in an organic field experiment conducted near Sohar, northern Oman (2007-2009). Data show means with one standard error of the difference (sed).

Crop	Year	TDM yield (kg ha^{-1})	sed		*F*-Probability
Radish	2007/8	1630	147	A	<0.001
	2008/9	2630		Y	<0.001
				AxY	<0.010
Carrot	2007/8	230	180	A	0.123
	2008/9	1210		Y	<0.001
				AxY	0.461
Cauliflower	2007/8	5310	494	A	0.149
	2008/9	3430		Y	<0.001
				AxY	0.152
Crop	**Year**	**Marketable yield (kg ha^{-1})**	**sed**		***F*-Probability**
Radish	2007/8	590	69	A	<0.05
	2008/9	1270		Y	<0.001
				AxY	<0.010
Carrot	2007/8	1360	120	A	0.146
	2008/9	810		Y	<0.001
				AxY	0.351
Cauliflower	2007/8	1410	175	A	0.386
	2008/9	1260		Y	0.278
				AxY	0.344

Table 3: Yield dry matter data of a two-year cropping systems experiment near Sohar, northern Oman (2007-2009). Data show means with one standard error of the mean.

Crop	Year	Amendment*	Plant biomass					
			Market yield	Total dry matter	Storage of mineral nutrients & carbon			
					Roots & shoots			
					N	P	K	C
			kg DM ha^{-1}		kg ha^{-1}			
Radish	2007	MIN	610 (34)	1,700 (95)	45 (7)	12 (1)	78 (7)	615 (22)
		ORG1	620 (39)	1,730 (108)	54 (4)	15 (1)	85 (5)	681 (26)
		ORG2	530 (25)	1,450 (68)	38 (5)	14 (2)	76 (3)	567 (51)
Carrot	2007/8	MIN	1,390 (136)	2,080 (179)	22 (3)	7 (1)	66 (9)	742 (109)
		ORG1	1,540 (111)	2,390 (201)	27 (6)	9 (2)	74 (18)	876 (123)
		ORG2	1,170 (161)	1,900 (227)	23 (2)	8 (1)	62 (6)	725 (64)
Cauliflower	2007/8	MIN	1,580 (208)	6,230 (559)*	118 (15)	29 (3)	190 (32)	2,950 (349)
		ORG1	1,230 (205)	4,420 (757)*	111 (21)	29 (6)	187 (46)	2,362 (399)
		ORG2	1,420 (97)	5,270 (521)*	103 (10)	32 (4)	204 (46)	2,470 (259)
Radish	2008	MIN	1,590 (85)	3,290 (161)	69 (6)	16 (3)	166 (10)	1,146 (100)
		ORG1	1,130 (100)	2,310 (203)	62 (11)	18 (2)	126 (26)	1,071 (116)
		ORG2	1,080 (90)	2,250 (191)	60 (6)	16 (2)	140 (22)	988 (97)
Carrot	2008/9	MIN	710 (82)	1,010 (100)	13 (2)	5 (1)	40 (6)	447 (66)
		ORG1	910 (104)	1,380 (170)	24 (5)	9 (1)	58 (10)	660 (93)
		ORG2	820 (109)	1,250 (179)	19 (3)	8 (1)	58 (12)	604 (102)
Cauliflower	2008/9	MIN	1,360 (165)	3,490 (167)*	77 (3)	16 (1)	109 (4)	1,379 (60)
		ORG1	1,360 (115)	3,780 (289)*	96 (10)	21 (2)	128 (14)	1,500 (122)
		ORG2	1,050 (218)	3,390 (473)*	73 (10)	19 (3)	112 (15)	1,341 (176)

* ORG1 denotes an application of manure with an average C/N ratio of 19 and a neutral detergent fibre / soluble carbohydrate (NDF/SC) ratio of 17, ORG2 an application of manure with an average C/N ratio of 25 and a NDF/SC ratio of 108, and MIN a mineral fertilizer application with equivalent rates of N, P and K.

2.3.2 Plant growth parameters

In both years average length of radish roots at harvest was with 214 mm (±3.4) similar across soil amendments. Radish root diameter was with 25 mm (±0.3) larger in 2008/9 than in 2007/8 with 17 mm (±0.4; $P<0.001$). For carrots in both years, average root length was with 200 mm (±7) highest on ORG2 plots followed by 175 mm (±3) on MIN plots and 173 mm (±4) on ORG1 plots ($P<0.001$). The diameter of carrot roots was with 33 mm (±0.4) similar across amendments. In both years, stem diameter of cauliflower at 70 DAT with respective 13 mm (±0.3, ORG2), 14 mm (±0.3, ORG1), and 15 mm (±0.4, MIN) increased with the availability of N and P from ORG2 and ORG1 to MIN ($P<0.001$). Plant height of cauliflower increased with 347 mm (±57), 355 mm (±50), and 411 mm (±85) from ORG1 plots over ORG2 plots to MIN plots ($P<0.001$).

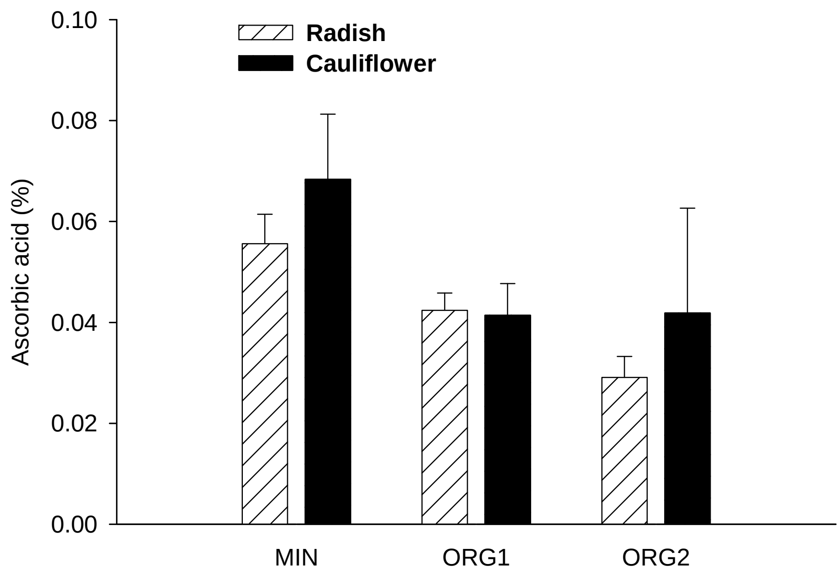

Figure 1: Ascorbic acid concentrations in radish root dry matter and cauliflower curd dry matter harvested in an organic crop sequence experiment with different soil amendments (a NKP mineral fertilizer control, MIN; manure with a C/N ratio of 19 and a NDF/SC ratio of 17, ORG1; and manure with a C/N ratio of 25 and a NDF/SC ratio of 108, ORG2) conducted near Sohar, northern Oman. Vertical bars represent one standard error of the mean (n=8) for radish and cauliflower, respectively. Different letters above the bars indicate significant differences between means ($P<0.01$).

2.3.3 Nutrient uptake and C storage in plants

For radish and cauliflower, N, P, and K uptake was highest on ORG1 plots followed by MIN and ORG2 plots, while for carrot nutrient uptake and C storage of the plants was highest on ORG1 plots followed by ORG2 and MIN plots. However, none of these differences were significant. Reflecting DM increases, uptake of N, K, and total C storage in radish and cauliflower was significantly higher in the second cropping cycle than in the first one ($P<0.01$), whereas nutrient uptake of carrots tended to decrease during the same period.

Across both years and all treatments, nutrient uptake in the harvested shoot DM averaged 57, 15, and 109 kg N, P, and K, respectively. This was accompanied by a C storage of 1,173 kg ha^{-1}. Respective data for root yields were 55, 15, 112, and 844 kg ha^{-1} for radish and 21, 8, 60, and 676 kg ha^{-1} for carrot.

Ascorbic acid concentrations in radish roots were significantly higher on MIN plots than on ORG2 plots, but were not significantly different from those obtained on ORG1 plots ($P<0.01$). The same sequence was also observed in cauliflower curds, but here numerical differences were not significant (Figure 1).

2.3.4 Horizontal and vertical matter fluxes

2.3.4.1 Horizontal fluxes

Horizontal flux calculations over the total experimental period 2007-2009 yielded regardless of the amendment net N balances of over 400 kg ha^{-1} for radish-carrot and around 350 kg ha^{-1} for radish-cauliflower, respectively. Net P balances averaged 200 kg ha^{-1} and 190 kg ha^{-1}. Horizontal balances of K, in contrast, were strongly negative for both cropping systems (Table 4).

2.3.4.2 Vertical fluxes

During the 260 cropping days of the four cropping periods in the two experimental cropping cycles, estimated amendment dependent emanation was 45 – 55 kg N ha^{-1} and 6.2 - 10.6 t C ha^{-1} (Siegfried et al., 2011). Carbon emissions were significantly higher in the second than the first cropping cycle ($P<0.001$).

The modelled water flux calculations indicated the much larger role of seepage compared to evaporation on the sandy soils of our experiment (Table 5). Across both cropping systems resin-derived Nmin leaching averaged 30 kg ha^{-1} for MIN, 10 kg ha^{-1} for ORG1 and 56 kg ha^{-1} for ORG2 ($P<0.05$). Cumulative PO_4-P leaching amounted to 9, 6, and 10 kg ha^{-1} ($P<0.001$). Leaching losses were significantly higher ($P<0.05$ for N and $P<0.001$ for P) in the second than in the first cropping cycle.

Estimates of Nmin derived from SiC suction plates in radish-cauliflower for 2008/9 were regardless of manure type several-fold larger than those from extracted resins (Figure 2). The suction plate data also indicate that substantial amounts of N were leached as organic N (16 kg ha^{-1} $year^{-1}$ from ORG1 and 52 kg N ha^{-1} $year^{-1}$ from ORG2, calculated as total N minus Nmin) and that large amounts of DOC moved with the irrigation water through the profile (Figure 2).

Table 4: Horizontal balance with inputs and outputs for two cropping systems radish-carrot and radish-cauliflower and three soil amendments MIN, ORG1 and ORG2 for a 2-year experimental period 2007-2009 in Sohar, northern Oman (MIN – mineral fertilizer, ORG1 – manure low C/N and NDF/SC, ORG2 – manure high C/N and NDF/SC). Positive numbers listed in the table indicate gains, negative ones losses.

Year		Input			Output						Horizontal balance					
					Radish - Carrot			Radish - Cauliflower			Radish - Carrot			Radish - Cauliflower		
		MIN	ORG1	ORG2	MIN	ORG1	ORG2	MIN	ORG1	ORG2	MIN	ORG1	ORG2	MIN	ORG1	ORG2
2007/8		kg ha^{-1} 130 days^{-1}														
	N	295	295	295	-76	-80	-79	-139	-109	-121	219	215	216	156	186	174
	P	112	112	112	-25	-27	-26	-36	-31	-39	87	85	86	76	81	73
	K	160	160	160	-246	-162	-171	-219	-155	-214	-86	-2	-11	-59	5	-54
	C	0	4,929	7,894	0	0	0	0	0	0	0	4,929	7,894	0	4,929	7,894
2008/9		kg ha^{-1} 130 days^{-1}														
	N	295	295	295	-74	-75	-78	-102	-120	-93	221	220	217	193	175	202
	P	139	139	139	-21	-26	-24	-24	-31	-26	118	113	115	115	108	113
	K	160	160	160	-207	-189	-161	-212	-216	-164	-47	-29	-1	-52	-56	-4
	C	0	3,832	5,840	0	0	0	0	0	0	0	3,832	5,840	0	3,832	5,840
2007 -		kg ha^{-1} 260 days^{-1}														
2009	N	590	590	590	-150	-155	-157	-241	-229	-214	440	435	433	349	361	376
	P	251	251	251	-46	-53	-50	-60	-62	-65	205	198	201	191	189	186
	K	320	320	320	-453	-351	-332	-431	-371	-378	-133	-31	-12	-111	-51	-58
	C	0	8,761	13,734	0	0	0	0	0	0	0	8,761	13,734	0	8,761	13,734

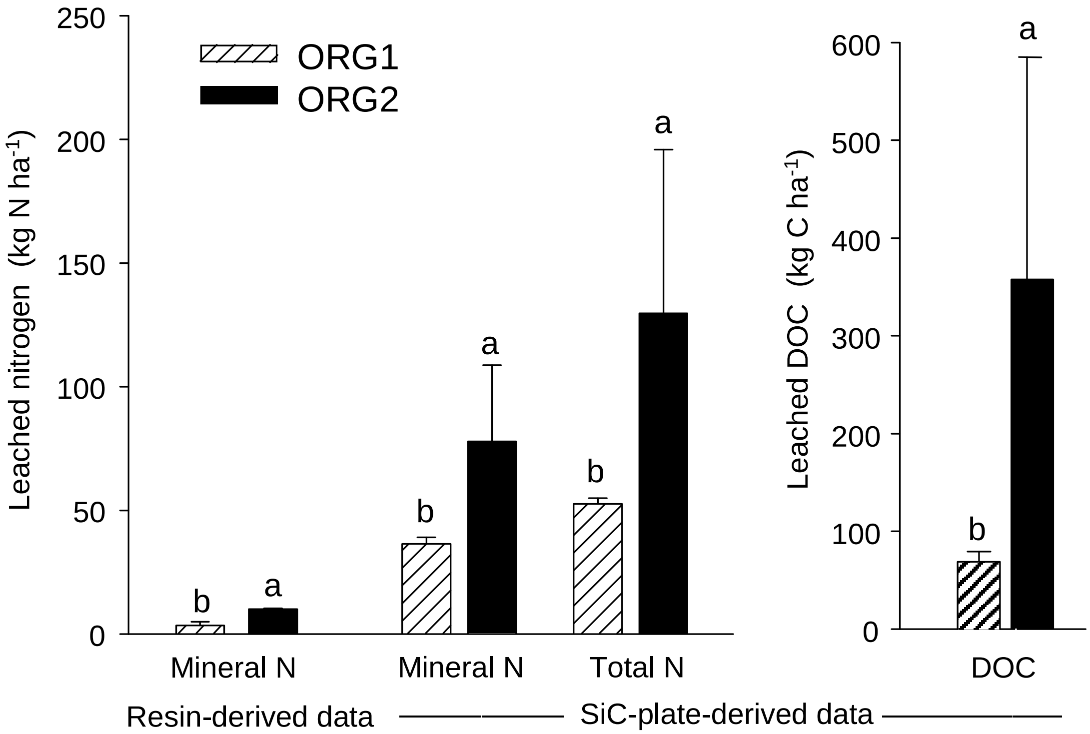

Figure 2: Leaching losses of mineral nitrogen (NO_3-N und NH_4-N) derived from resin cartridges and mineral N, total N, and dissolved organic carbon (DOC) derived from suctions plate made from silicon carbide (SiC) in an organic cropping systems experiment with radish-cauliflower conducted near Sohar, northern Oman. For SiC plate based values the calculated amount of seepage (Table 5) was multiplied by the respective concentrations in the water samples. Data were collected under manure of a C/N ratio of 19 and a NDF/SC ratio of 17 (ORG1) and manure with a C/N ratio of 25 and a NDF/SC ratio of 108 (ORG2). Vertical bars represent one standard error of the mean (Resin cartridges, n=5; SiC plates, n=4), respectively, and different letters above the bars indicate significant differences between means (P<0.01).

Table 5: Cumulative infiltration (irrigation), seepage (bottom flux) and plant root water uptake as modelled by Hydrus 1d (Qr = residual water content, Qs = saturated water content, α= parameter related to the inverse of the air entry suction, N = parameter characterising the pore size distribution, Ks = saturated hydraulic conductivity, l = empirical parameter) in an irrigated sandy experimental soil near Sohar, northern Oman.

	Soil (without plants) (mm)	Radish (adult plants) (mm)	Cauliflower (adult plants) (mm)
Cumulative root water uptake		10.4	10.4
Seepage	30.2	29.0	29.0
Water storage	11.7	7.4	7.4
Evaporation	4.3	0.1	0.1
Cumulative infiltration	45.8	45.8	45.8

Hydraulic parameters (van Genuchten 1980)

Qr	Qs	α	N	Ks	l
0.045	0.43	0.145	2.68	1200	0.5

2.3.5 Total balances

Based on the bi-annual resin-derived leaching data total balances of N and P, and horizontal balances of K on radish-carrot plots were 329, 190, and -96 kg ha^{-1} for MIN, 318, 182, and -98 kg ha^{-1} for ORG1, and 337, 197, and -67 kg ha^{-1} for ORG2. For this cropping sequence, respective C balances for MIN, ORG1, and ORG2 plots amounted to -7.3, -3.1, and 1.5 t ha^{-1} (Siegfried et al., 2011). Net balances of N, P, and K on radish-cauliflower plots were 228, 174, and -225 kg ha^{-1} for MIN, 202, 160, and -207 kg ha^{-1} for ORG1, and 232, 163 and -203 kg ha^{-1} for ORG2. For this cropping system, C balances amounted to -5, 1.3, and 4.6 t ha^{-1} for MIN, ORG1, and ORG2 plots. For individual crops, C balances were in both cropping cycles most negative in carrot, except for the MIN and ORG1 treatment in 2007/8 (Figure 3).

While NPK balances were not significantly affected by the soil amendments, differences in C balances were ($P<0.05$). There also were significant effects of cropping system on total balances of N ($P<0.001$), P ($P<0.001$), and K ($P<0.05$). Carbon balances significantly differed between cropping cycles ($P<0.05$).

If the SiC suction plate data of total N leaching were used instead, N balances would be substantially lower but still highly positive across treatments (data not shown). In this case C balances would also be substantially affected by the apparently large amounts of DOC moving from the heavily manured plots through the sandy soils.

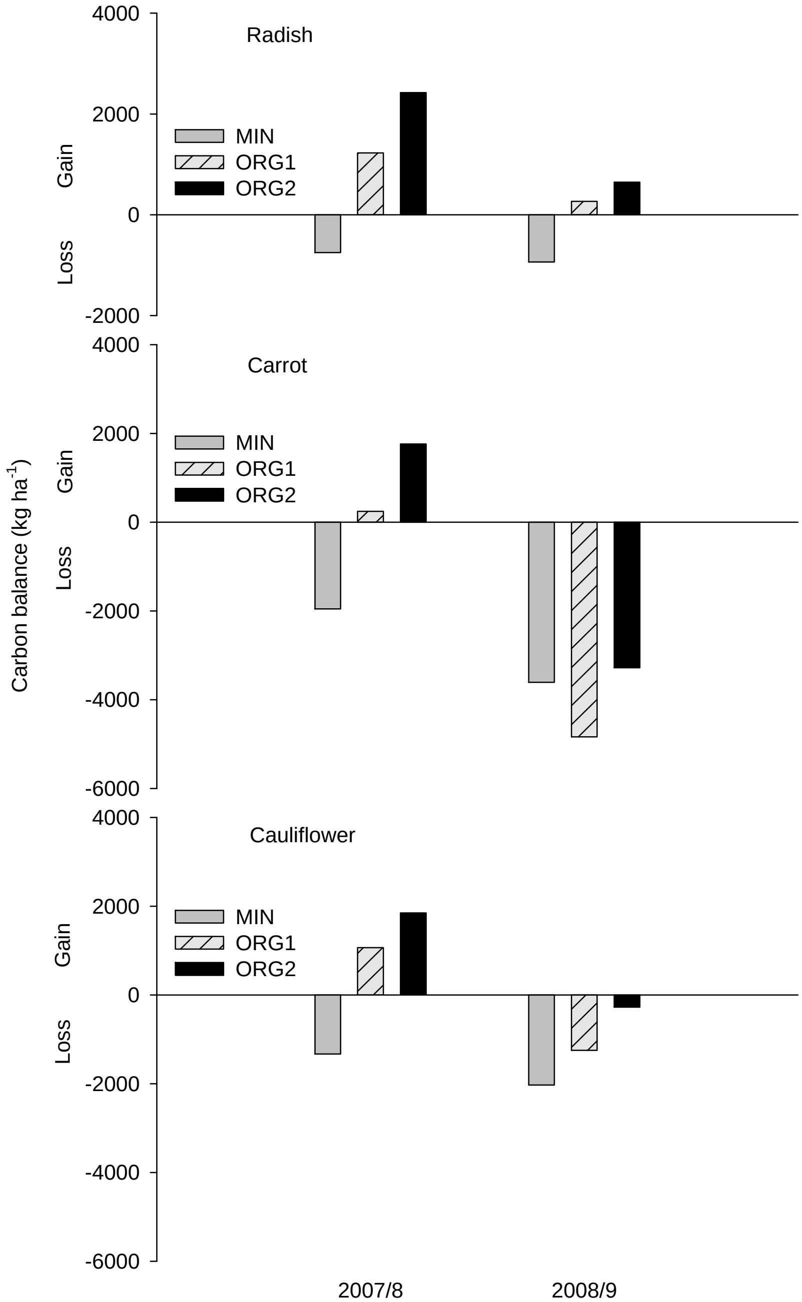

Figure 3: Carbon balances for radish (40 days cropping period), carrot and cauliflower (90 days cropping period) in an organic crop sequence experiment with different soil amendments (a NKP mineral fertilizer control, MIN; manure with a C/N ratio of 19 and a NDF/SC ratio of 17, ORG1; and manure with a C/N ratio of 25 and a NDF/SC ratio of 108, ORG2) conducted near Sohar, northern Oman in 2007/8 and 2008/9. Vertical bars represent net C balances for the different soil amendments and years of cropping.

2.4 Discussion

In contrast to our expectations, over the two year duration of our experiment, the application of organic manures with different C/N and NDF/SC ratios did not significantly affect marketable yield and yield components of irrigated radish, carrot or cauliflower. Nevertheless, during the two cropping cycles higher availability of N, P, and K from MIN plots tended to enhance crop growth compared ORG1 and ORG2 plots. This confirms similar results of Chadwick et al. (2000) and Magdoff et al. (2000). For some of the yield components, these differences were significant. This was also the case for the ascorbic acid concentrations of radish and cauliflower that despite of higher yields were highest for MIN (Figure 1). This contradicts results of Warman (1997) who found no differences between organically grown radish and cauliflower compared to those cultivated conventionally with mineral fertilizers and of Asami et al. (2003) who reported higher ascorbic acid concentrations in three organically grown crop species. Between-year variability in ambient temperature may have had larger effects on yield and yield components than the type of manure applied.

The observed higher C emissions (CO_2-C, CH_4-C) during the second cropping cycle compared to the first one may have been due to temporarily higher average ambient temperatures during the vegetation period October 2008 - March 2009 (16-32°C) than during October 2007 - March 2008 (13-29°C).

The removal of shoot and root residues after the first harvest of the three vegetable crops 2007/8 certainly contributed to negative or lowered C balances for the second growing cycle (Figure 3). In organic cropping systems plant residues typically are left in the field and finally incorporated into the soil to partially compensate for losses of plant nutrients and C.

Even if lacking field replications preclude statistical comparison of differences between resin-derived and SiC plate-derived Nmin, total N and DOC data, the results suggest that both methods can not be directly compared. For resin cartridges solute flow interruptions at the phase break from soil to resins may lead to an underestimation of leaching, whereas an elevated suction pressure may lead to an overestimation of leached nutrients and DOC for suction plates. This certainly merits further research in a replicated field experiment and under controlled conditions.

The negative C balances observed in our study raise questions with regard to the rates of manure applied to sustain the described irrigated organic vegetable cropping sequence in the year-round hot lowlands of northern Oman. In view of the recent consumer-driven area increase of organic farming in the Middle East and South Asia (Willer et al., 2010) with their relatively large areas of irrigated farming on drylands, efforts to retard the turnover of organic C should be given more attention. This is of particular importance in the coastal lowland farming systems of Oman where the role of organic matter in soil water storage and related water use efficiency can hardly be overemphasized (Norman et al., 1998b).

The apparent large positive N balances, in contrast, may in the long term lead to increased leaching and emanation losses as any built-up of soil organic matter is unlikely under the described turnover conditions. In this context composting of manure instead of its direct application, with additives such as tannins that are known to slow down mineralization (Somda and Powell 1998; Lorenz et al., 2000), may merit further investigation. On the other side any delay in N mobilization may hamper vegetable growth and final yield which depending on manure prices would be economically hard to accept in commercial organic farming.

2.5 Conclusions

The lack of consistent effects of different manure types on crop yields may have been largely due to the temperature and soil moisture related rapid turnover of the applied organic substrates that were also reflected in large N and C emanation. While the applied amounts of manure led to net surpluses of N and P during the second cropping cycle, C balances were positive for both manure treatments in the first, but negative and inconsistent in the second cropping cycle, leading to a likely depletion of soil C stocks. Under the subtropical conditions of our study area this questions the sustainability of irrigated cropping systems, in which all crop residues are removed, and in which manures are used directly at the described application rates. Our data call for further research to develop practices aiming at a lower turnover of C originating from manure as well as of soil born C. On the sandy soils of our study area this may also lead to decreased leaching of organically bound N and P.

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Chapter 3

Submitted to Communications in Soil Science and Plant Analysis

Sorption and desorption characteristics of ion exchange resins to estimate leaching losses in the field

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Abstract

Laboratory experiments were conducted to determine sorption and desorption properties of ion exchange resins. Dissolved nitrate (41.6 mM NO_3^- and 166.5 mM NO_3^-), ammonium (63.9 mM NH_4^+ and 256.1 mM NH_4^+), phosphate (3.5 mM PO_4^{3-} and 13.9 mM PO_4^{3-}) and potassium (16.11 mM K^+ and 63.94 mM K^+) were factorially combined and added at flow rates of 5 l at 3 and 9 hrs to an exchange resin:sand mixture. Six extractions with 1 M NaCl desorbed > 90% of the added ions. For nitrate (NO_3-N) apparent recovery rates averaged 99% (± 6), for ammonium (NH_4-N) 100% (±8) and for phosphate (PO_4-P) 109% (± 6). Apparent recovery rates of potassium (K) were with 151% (±12) erroneously high and likely reflected contamination of the exchange resin:sand mixture. Ion concentration of the solution did not affect recovery rates of any of the studied ions, but PO_4-P recovery depended on flow rate (P<0.01).

Keywords: Nutrient flows; Ion recovery rate; Vertical flux rate

3.1 Introduction

Previous laboratory studies and field investigations (Schnabel 1983; Hart et al., 1984; Wyland et al., 1993; Skogley and Dobermann 1996; Kjonaas 1999; Langlois et al., 2003 Hartmann et al., 2003, Lang et al., 2004) showed that mixed bed cation-anion exchange resins can be used to determine cumulative leaching losses of plant nutrients, heavy metals and ionic organic compounds. However, given different experimental layouts and technical approaches with a variety of exchange resins and containers, conclusions about apparent recovery rates are difficult to draw. While Schnabel (1983) found that 99% of added nitrogen (N) was adsorbed by ion exchange resins, Wyland and Jackson (1993) reported a 85% average recovery rate of nitrate (NO_3^-) added to resin bags. Bischoff (1999) reports for his setup recovery rates of chloride tracers around 92%, but recovery data of NO_3-N, NH_4-N, PO_4-P and K as affected by passage rate of solutes, ion concentration in the solution and mode of recovery (concentration of the extractant and number of extractions) remain unknown. This study therefore aimed at filling these gaps of knowledge.

3.2 Materials and Methods

The following procedure was used to determine the background concentrations of N, P and K in the sorbent: 2 x 4 samples of 30 g pure silica sand were extracted eight times with 0.5 M and 1 M NaCl. Extracts 1-8 of each sample were pooled and duplicates of 25 ml were analysed for NO_3-N, NH_4-N, PO_4-P and K by ICP-AES. The concentrations of the nutrients found in the blank extractions of the used silica sand were subtracted from the total recovered amounts of ions to calculate apparent recovery rates of the sorbent.

3.2.1 Effects of solute concentration, flow rate and pre-treatment of exchange resins

In all our studies a homogenous mixture (thereafter referred to as ‘sorbent’) of strong basic and acid ion exchange resins (Rohm & Haas, Frankfurt, Germany) combined with silica sand filled into a PVC cartridge of 110 mm diameter and 110 mm height was used (Bischoff et al., 1999). The used ratio of the components in the sorbent was 1:1:1.5 for the study on effects of solute concentration, flow rate and pre-treatment on ion recovery rates, 1:1:3 for the study on the number of required resin extractions, and 1:1:2 for the study on the effects of the NaCl concentration of the extractant.

To prepare standard solutions with defined N, P and K concentrations 3.33 and 13.31 g of NH_4NO_3 and 0.60 and 2.41 g of K_2HPO_4 (both anhydrous extra pure; Merck GmbH, Darmstadt, Germany) equivalent to 20% and 80% of the anion and 13% and 52% of the respective cation exchange capacity of the sorbent were dissolved in 5 l of deionised water. The sorption capacities were calculated based on the producer information for the resins. We choose a 4:1 ratio of NH_4NO_3 *versus* K_2HPO_4 to simulate the likely dominance of N in soil leaching experiments.

Each ion solution was drip-applied with a peristaltic pump (Model 505 S, Watson-Marlow Limited, Falmouth, UK) at two flow rates (5 l in 3 hours and 5 liters in 9 hours) to five cartridges (replicates) holding 925 g (moist weight) of the sorbent (Figure 1).

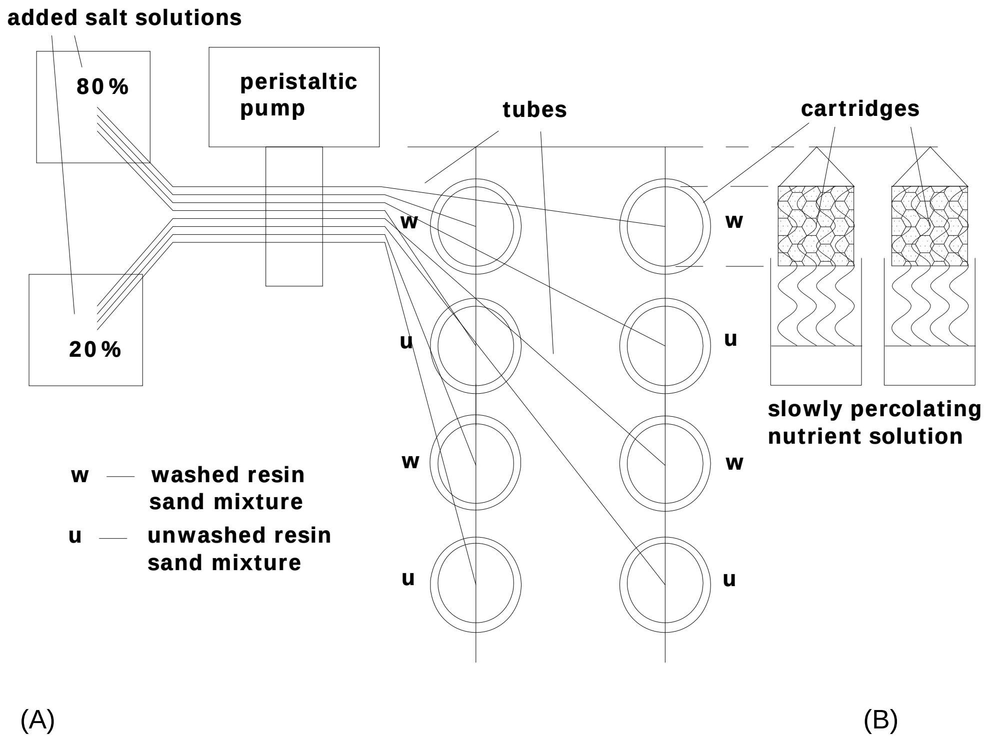

Figure 1: Diagram showing (A) the application of two different nutrient solutions reaching 80 and 20 % of the sorption capacity of the ion exchange resins: sand mixture (sorbent) and (B) the nutrient solution flow through the cartridges filled by the sorbent and collection of the leachate in glass containers below the cartridges.

To examine the effects of pre-treatment of the sorbent on ion recovery rates, the former was washed with 1 M NaCl and subsequently dried at 25 °C for 24 hours. The recovery rates obtained from such pre-treated sorbents were compared to those of an unwashed control mixture. After application of the standard solutions, the 40 resin cartridges were emptied and ions extracted six times by vigorously shaking duplicates of 30 g sorbent with 100 ml 0.5 M NaCl (99.8% NaCl; Roth GmbH + Co. KG, Karlsruhe, Germany) for 60 minutes. Solutions from both replicates were pooled for each of the six extractions and frozen at -20°C until analysis of desorbed NO_3-N, NH_4-N, PO_4-P and K by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, Spectroflame, Spectro GmbH, Kleve, Germany). To calculate apparent recovery rates, the quantities of recovered N, P and K in the extracts were compared to the added quantities whereby remaining ion concentrations in the leaching solutions also collected during the experiment were accounted for.

3.2.2 Effects of the number of resin extractions on apparent ion recovery

To study the effect of the number of resin extractions 4.16, 8.32 and 16.64 g of NH_4NO_3 and 0.75, 1.51 and 3.02 g of K_2HPO_4 representing 25%, 50% and 100% of the manufacturer provided adsorption capacity of the sorbent for anions and 16.25%, 32.5% and 65% for cations were dissolved in 5 l of deionised water and applied at a flow rate of 5 l h^{-1} in quadruplicate to resin-filled cartridges. Subsequently, 30 g of the sorbent in each cartridge was extracted eight times by shaking with 100 ml 1 M NaCl for 60 minutes. Duplicate samples of 25 ml of each extract were analysed for NO_3-N, NH_4-N, PO_4-P and K as above to determine the amount of desorbed solutes per extraction.

3.2.3 Effect of the concentration of the extractant

For this experiment 6.3 g of KNO_3, 6.66 g NH_4NO_3 and 2.36 g $NH_4H_2PO_4$ were dissolved in 5 l of distilled water and trickled to six cartridges with a volumetric cation-, anion-exchange resin and sand mixture of 1:1:2 over a period of 24h. The ion load represented 42% of the potential cation and 80% of the potential anion capacity of the mixture. In three of the cartridges four samples of the sorbent (15 ± 0.05 g) were extracted with 100 ml 0.5 M NaCl and in the remaining three cartridges with 100 ml 1 M NaCl. The extraction was repeated eight times and the extracts 1-4, 5-6 and 7-8 were pooled together. From each pooled sample, 50 ml sub-samples were taken in duplicate, frozen till analyzed for NO_3-N, NH_4-N, PO_4-P and K as above by ICP-MS. Additionally, dry matter of the sorbent at 65°C was estimated from four 10 g (± 0.5 g) subsamples.

All data were subjected by ANOVA analysis of factor effects on ion recovery using SPSS 17.0 (Backhaus et al., 2003).

3.3 Results

In blank samples of the anion resin 11 mg NO_3-N l^{-1}, 2 mg PO_4-P l^{-1} and 21 mg K l^{-1} were found while 2 mg PO_4-P l^{-1} and 70 mg K l^{-1} was found in the cation resin. The background contamination in the silica sand was 18 mg PO_4-P l^{-1} and 625 mg K l^{-1}.

The apparent total recovery rates from the sorbent averaged 107-112% (unwashed sorbent) and 78-88% (washed sorbent) for N at the low saturation of the sorption capacity and 101-103% (unwashed sorbent) and 93-114% (washed sorbent) at the high sorption saturation (Table 1). For P respective averages at low and high saturation were 106% and 107% for the unwashed and 96% and 121% for the washed sorbent. For K the respective average recovery at the low and high saturation was 169% and 156% for the unwashed sorbent and 130% and 147% for the washed sorbent.

Flow rate significantly affected the recovery of PO_4-P ($P<0.01$; Figure 2). At a flow rate of 5 l per 3 h^{-1}, apparent PO_4-P recovery rate averaged 93% (±7, n=20), while it reached 124% (±9, n=20) at 5 l per 9 h^{-1}. Pre-treatment of the sorbent, in contrast, had no significant effect on apparent recovery rates, except for K^+ in combination with flow rate ($P<0.05$; n=40). Statistically significant interactions also occurred for solute concentration by flow rate with respect to the recovery of NH_4-N ($P<0.05$; n=40), PO_4-P ($P<0.05$; n=40) and K ($P<0.01$; n=40).

Our data also showed that six extractions with 1 M NaCl allowed to recover >90% of NO_3-N, NH_4-N, PO_4-P and K from the sorbent (Figure 3). The comparison of the two NaCl extractant concentrations revealed that the use of 0.5 M NaCl allowed the extraction of 96% of the NO_3-N, 100% of the NH_4-N, 106% of the PO_4-P, but only 90% of the K that was extracted by the 1 M NaCl extractant.

Table 1: Fate of nitrogen (NO_3-N and NH_4-N), phosphorus (PO_4-P) and potassium (K) added at two solute concentrations representing two saturations of the resin adsorption capacity across two flow rates in an ion recovery experiment with a 1:1:1.5 mixture of anion-cation exchange resins and silica sand. Data represent means with standard errors (n=10).

Saturation capacity Anion/ Cation	Pre-treatment	Nutrient	Total added	Leachate		Total extracted		Recovery rate
			mg	mg	stderr	mg	stderr	%
20%/13%	unwashed	NO_3-N	583	0.0	0.00	653	103	112
		NH_4-N	583	0.7	0.20	621	101	107
		PO_4-P	110	0.0	0.03	117	18	106
		K	270	0.7	0.11	457	74	169
	washed	NO_3-N	583	0.0	0.00	510	50	88
		NH_4-N	583	0.3	0.18	456	49	78
		PO_4-P	110	0.1	0.06	106	14	96
		K	270	0.8	0.15	350	54	130
80%/52%	unwashed	NO_3-N	2,330	1.0	0.88	2,405	219	103
		NH_4-N	2,330	1.8	0.27	2357	258	101
		PO_4-P	430	14.1	7.58	459	42	107
		K	1,090	3.5	0.48	1,704	280	156
	washed	NO_3-N	2,330	3.9	0.87	2,174	118	93
		NH_4-N	2,330	2.8	0.68	2,647	527	114
		PO_4-P	430	14.7	4.40	522	55	121
		K	1,090	3.8	0.23	1,606	245	147

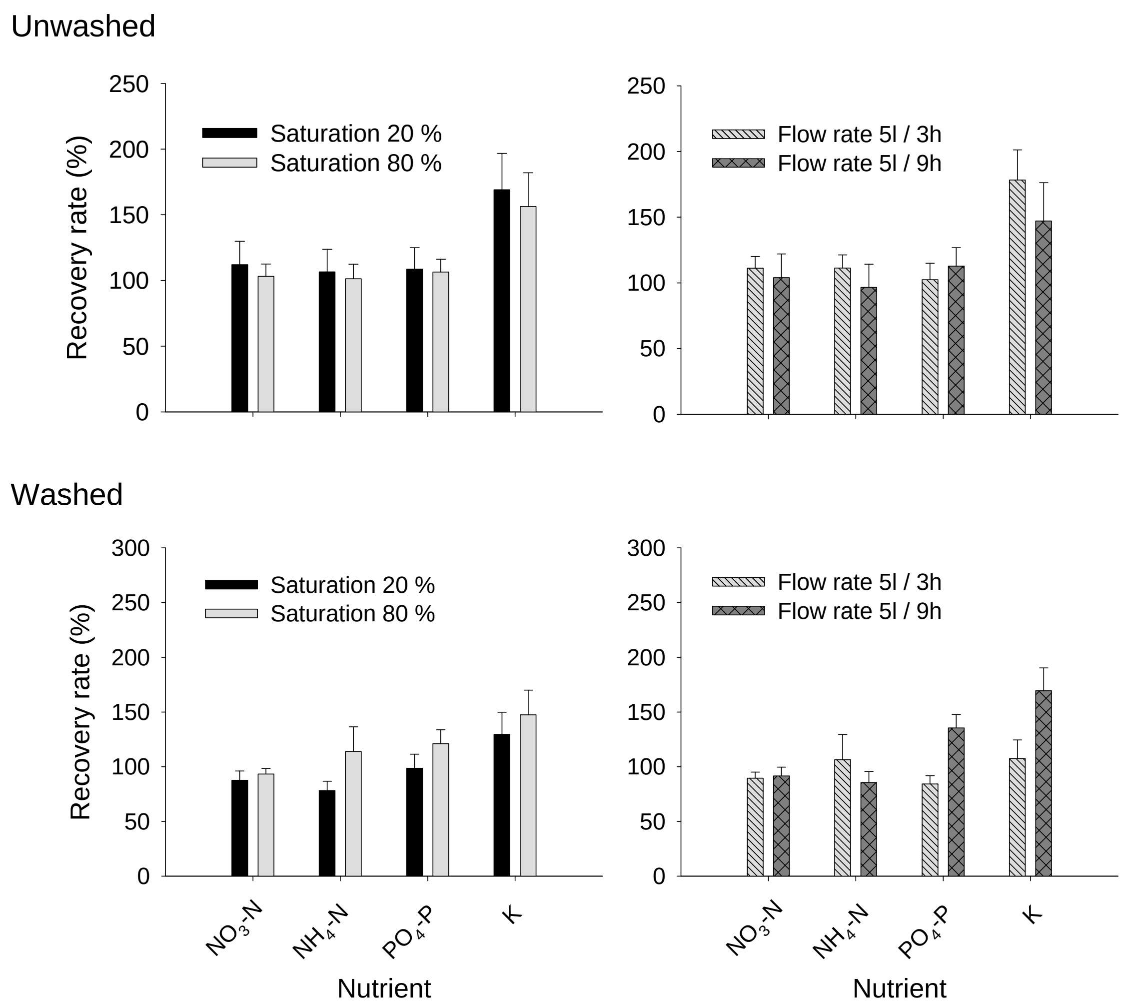

Figure 2: Effects of solute concentration leading to different saturations of the sorbent solution, flow rate and pre-treatment of the sorbent on recovery rates of an ion exchange resin – silica sand mixture used to adsorb ions from a percolating nutrient solution. Bars represent means with one standard error (n=10).

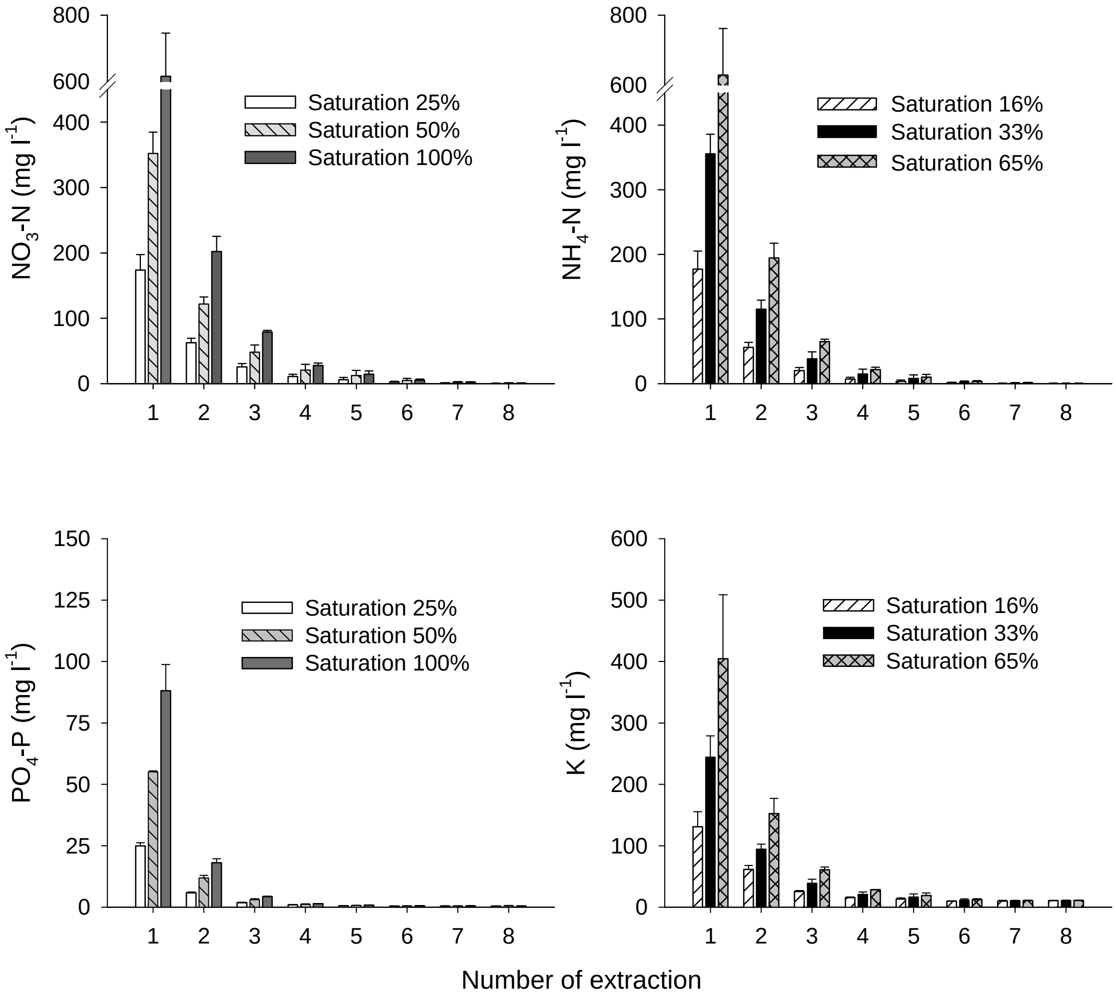

Figure 3: Concentration of NO_3-N, NH_4-N, PO_4-P and K in each of eight extractions of an ion exchange resin – silica sand mixture used to adsorb ions from three percolating nutrient solutions representing different saturations of the sorbent. The extractant consisted of a 1 M NaCl solution. Bars present means with one standard error (n=4).

3.4 Discussion

Low concentrations of nutrients in the leachates and high apparent recovery rates for N and P suggest that the resin exchange method allows reliable estimates for both nutrients in percolating water. The excessively high apparent recovery rates of K, however, are due to the high K concentrations in the blank extractions of the sorbents, particularly the silica sand and the cation resin samples that led to erroneous values. This makes the ion exchange resin method unsuitable for the quantitative estimation of K fluxes in water based percolating solutes unless major efforts allow to extract all excess K from the sorbent during conditioning. A similar need of proper resin pre-treatment of ion exchange resin sand mixtures has been reported by Thiffault et al. (2000).

At both flow rates the homogeneous application of the percolating nutrient solution ensured an almost complete adsorption of NO_3-N, NH_4-N and K as < 0.3% of the total applied amounts of these nutrients were found in the leachate leaving the cartridge. Only at the high saturation capacity the 3.3% of applied total PO_4-P concentrations found in the leachate indicated the possibility of errors (Table 1).

Our finding that six extractions extracted >90% of the N, P and K ions from the sorbent supports similar results obtained by Predotova et al. (2010) in field based leaching experiments and data of Kjonaas et al. (1999). The latter authors concluded that five extractions with 2 M KCl removed nearly 100% of resin-adsorbed N. However, the number of extractions needed may vary with environmental conditions, solute composition (in particular the presence of organically bound ions) and amount and composition of suspended clay in the soil solution. It should therefore be checked prior to the extraction of larger sample sets (Mamo et al., 2004).

3.5 Conclusions

For the quantification of leaching losses of P and K from soils the ion exchange resin - sand mixture are to be pre-treated by a thorough cleaning procedure to remove adsorbed contaminating ions particularly from the quartz sand used. Repeated thorough washing of the quartz sand and the exchange resins with 1 M NaCl followed by abundant rinsing with deionized water should eliminate most of the unwanted K.

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Chapter 4

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Nutrient and carbon balances in organic vegetable production on an irrigated, sandy soil in northern Oman

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Abstract

Our understanding of nutrient and carbon (C) fluxes in irrigated organic cropping systems of subtropical regions is limited. Therefore leaching of mineral nitrogen (N) and phosphorus (P), gaseous emissions of NH_3, N_2O, CO_2 and CH_4, and total matter balances were measured over 24 months comprising a total cropping period of 260 days in an organic cropping systems experiment near Sohar (Oman). The experiment on an irrigated sandy soil with four replications comprised two manure types (ORG1 and ORG2) characterised by respective carbon/nitrogen (C/N) ratios of 19 and 25 and neutral detergent fibre (NDF) / soluble carbohydrates (SC) ratios of 17 and 108. A mineral fertilizer (MIN) treatment with equivalent levels of mineral N, P and potassium (K) served as a control. The three treatments were factorially combined with a cropping sequence comprising radish (*Raphanus sativus* L.) followed by cauliflower (*Brassica oleracea* L. var. *botrytis*) or carrot (*Daucus carota* subsp. *sativus*). Over the 24 months experimental period gaseous N emissions averaged 45 kg ha^{-1} (59% NH_3-N, 41% N_2O-N) for MIN, 55 kg N ha^{-1} (69% NH_3-N, 31% N_2O-N) for ORG1, and 49 kg N ha^{-1} (59% NH_3-N, 41% N_2O-N) for ORG2. Carbon losses were 6.2 t ha^{-1} (98% CO_2-C, 2% CH_4-C) for MIN, 9.7 t C ha^{-1} (99% CO_2-C, 1% CH_4-C) for ORG1, and 10.6 t ha^{-1} (98% CO_2-C, 2% CH_4-C) for ORG2. Exchange resin-based cumulative leaching of mineral N amounted to 30 kg ha^{-1} for MIN, 10 kg ha^{-1} for ORG1, and 56 kg ha^{-1} for ORG2. Apparent surpluses of 361 kg N ha^{-1} and 196 kg P ha^{-1} for radish-carrot and 299 kg N ha^{-1} and 184 kg P ha^{-1} for radish-cauliflower were accompanied by K deficits of -59 kg ha^{-1} and -73 kg ha^{-1}, respectively, for both cropping systems. Net C balances for MIN, ORG1, and ORG2 plots were -7.3, -3.1, and 1.5 t C ha^{-1} for radish-carrot and -5.0, 1.3, and 4.6 t C ha^{-1} for radish-cauliflower. The results underline the difficulty to maintain soil C levels in intensively cultivated, irrigated (sub)tropical soils.

Key words**:** Carbon turnover; Gaseous losses; Matter fluxes; Nitrogen leaching; Nutrient cycling

4.1 Introduction

With an average annual precipitation of 55 mm and a potential evapotranspiration exceeding 2000 mm agriculture in northern Oman completely depends on irrigation (FAO, 1997; Norman et al., 1998). However, the country's irrigated area covers only 0.2% of the total land surface of which 57% is in the Batinah plain. Besides date palm (*Phoenix dactylifera* L.), banana (*Musa* ssp.), alfalfa (*Medicago sativa* L.) and wheat (*Triticum* ssp.), which represent the main traditional crops of the country (60,330 ha), vegetables are grown on a considerable part (5,700 ha) of the cultivated area in the lowlands (FAO, 1997). Given year-round irrigation and high temperatures, we suspected that turnover of soil organic matter on such lowland vegetable fields was very large and heavily depended on the continued application of organic matter such as animal manure. This should be particularly the case under the self-imposed input constraints of organic agriculture as practised on sandy soils in the Batinah Plain of northern Oman (Willer and Kilcher, 2010). There nutrient and carbon losses through leaching (Jalali, 2005) and emanation (Hans et al., 2005; Buerkert et al., 2010) were suspected to be high and may question the sustainability of such systems.

It is well known that volatilization of N and C from manure can be reduced by its immediate incorporation into the surface soil after application and by dietary adjustments such as a modification of the C/N or the NDF/ SC ratio in the feed (Velthof et al., 2003; Gerard et al., 2005). This study therefore aimed at determining N, P, and K fluxes and turnover rates of organic C in a locally practised organic cropping sequence amended with manure from two different feed qualities.

4.2 Materials and Methods

4.2.1 Research site and experimental setup

A 24-months field experiment was conducted in 2007-2008 and 2008-2009 on a 6 ha private farm in the coastal plains of the Batinah Plain near the city of Sohar in northern Oman (24.2°N, 56.8°E, 4 m a.s.l.). The locally prevailing floodplains are irrigated from groundwater aquifers which are fed by winter and rare summer rains in the nearby Hajar Mountains. The prevailing coarse loamy, mixed, hyperthermic Typic Torrifluvent soils are derived from recent fluviatile wadi-deposits that have a gravel-rich subsoil and are partly covered by aeolian sand veneers (Al-Farsi et al., 2001; Table 1). The 82% sand, 16% silt, and 2% clay in the brown coloured and slightly alkaline upper 50 cm of the fine sand and silt fraction represent 48% of total particles and have a bulk density of 1.44 g cm^{-3}.

The 3 x 2 completely randomized factorial experiment used for our studies had four replications and thus comprised 24 plots. Soil amendments applied were two organic manure treatments (ORG1, ORG2) and one mineral fertilizer control (MIN) that contained the same amounts of N, P and K as in the manure treatments (Table 2). The manures were characterized by a C/N ratio of 19 with a NDF/SC ratio of 17 (ORG1) and a C/N ratio of 25 with a NDF/SC ratio of 108 (ORG2). Both manures originated from water buffaloes *(Bubalus bubalis),* breed Nilli Ravi, which were fed two diets characterised by a C/N ratio of 11.0 and 27.2, and a NDF/SC ratio of 2.1 and 16.1, respectively.

Table 1: Soil physical and chemical properties (0-15 cm) at the research site near Sohar, northern Oman before the onset of the organic soil amendment by cropping sequence experiment in 2007.

Sand	Silt	Clay	Bulk density
	%		g cm^{-3}
82	16	2	1.44

pH	C_{org}	N_{tot}	P_{Olsen}	K	Ca	Mg	Fe	B	Na	Mn	Cu	Zn
	-------- % -------		----- ppm -----		------------ % ------------			------------------- ppm ------------------				
7.9	1.3	0.06	35	560	1.7	1.2	1	8	718	360	13	27

Prior to soil application both manures were air-dried to constant weight for seven days and analysed for their concentrations of N, P, K, and organic C (C_{org}). Comparability of target NPK levels applied was achieved by two equal applications of $(NH_4)_2SO_4$ (containing 21% N, top-dressed and incorporated) at 15 and 30 days after transplanting, DAT, of radish and cauliflower/carrots), triple superphosphate ($Ca(H_2PO_4)_2$) containing 19.6% P and applied at sowing, and potassium sulphate (K_2SO_4) - containing 41% K and applied at sowing. These were applied alone (MIN) or as minor supplements to ORG1 or ORG2 manure.

Table 2: Nutrient concentrations of air-dried manure with a C/N ratio of 19 and a NDF/SC ratio of 17 (ORG1), a C/N ratio of 25 and a NDF/SC ratio of 108 (ORG2), and amounts of manure and mineral fertilizer equivalents (MIN) applied in an organic soil amendment by cropping systems experiment near Sohar, northern Oman in 2007-2008 and 2008-2009.

Period	**Amendment**	**Moisture**	**N**	**P**	**K**	**Quantity applied** Target N (kg ha^{-1})	
						135	160
		%	— % DM —			kg ha^{-1}	kg ha^{-1}
2007/8	ORG1	5.55	2.01	0.69	0.63	7,105	8,421
2007/8	ORG2	6.16	1.47	0.56	0.53	9,782	11,594
2008/9	ORG1	9.21	2.58	0.84	0.36	5,717	6,775
2008/9	ORG2	9.22	1.98	0.93	0.48	7,447	8,826

Supplemental application of fertilizer combined with ORG1 and ORG2

Period	**Amendment**	**— Radish —**		**— Carrot/Cauliflower —**	
		TSP*	K_2SO_4	TSP	K_2SO_4
		kg ha^{-1}			
		Target P (51 kg ha^{-1})	Target K (80 kg ha^{-1})	Target P (60 kg ha^{-1})	Target K (80 kg ha^{-1})
2007/8	ORG1	24	92	26	73
2007/8	ORG2	-	76	-	54
		Target P (64 kg ha^{-1})	Target K (80 kg ha^{-1})	Target P (75 kg ha^{-1})	Target K (80 kg ha^{-1})
2008/9	ORG1	104	150	119	141
2008/9	ORG2	6	116	-	101

Application of fertilizer (control, MIN)

Period	**Amendment**	**Crop**	**— Mineral fertilizer —**		
			N as $(NH_4)_2SO_4$	P as TSP	K as K_2SO_4
			kg ha^{-1}		
2007/8	MIN	Radish	135	51	80
2007/8	MIN	Carrot/Cauliflower	160	60	80
2008/9	MIN	Radish	135	64	80
2008/9	MIN	Carrot/Cauliflower	160	75	80

* TSP = Triple Superphosphate

The three soil amendments contained during the first experimental year (2007-2008) 135 kg N ha^{-1}, 51 kg P ha^{-1}, and 80 kg K ha^{-1} for the first crop and 160 kg N ha^{-1}, 60 kg P ha^{-1}, and 80 kg K ha^{-1} for the second crop of the season. During the second experimental year (2008-2009) N, P, and K applications were 135, 64, and 80 kg ha^{-1} for the first crop and 160, 75, and 80 kg ha^{-1} for the second crop. The entire manure quantity was surface applied and rototilled to 0.15 m three days before transplanting. Application of N as $(NH_4)_2SO_4$ in the control treatment was split into two equal amounts that were incorporated before and after transplanting of crops. To exclude differences in applied Ca as a source of error, gypsum ($CaSO_4$) was applied at 300 kg ha^{-1} on all plots to each crop. Prior to transplanting all plots were flood-irrigated once with 20 mm and afterwards with 46 mm every three days.

In both years the cropping sequence consisted of radish (*Raphanus sativus*) planted on all experimental plots from 02/10/2007-07/11/2007 and from 22/10/2008-30/11/2008 followed by either cauliflower (*Brassica oleracea var. botrytis*, cultivated from 18/11/2007-16/02/2008 and from 05/12/2008-04/03/2009) or carrot (*Daucus carota* subsp. *sativus*, cultivated from 18/11/2007-19/02/2008 and from 05/12/2008-08/03/2009). Plot size was 7 m by 2.5 m and planting density was 350,000 plants ha^{-1} for radish, 40,000 plants ha^{-1} for cauliflower, and 600,000 plants ha^{-1} for carrot.

4.2.2 Flux measurements

4.2.2.1 Horizontal fluxes

Horizontal fluxes of nutrient and carbon were calculated based on amounts and nutrient concentrations of fertilizers and manure DM applied as inputs. From these respective data of nutrient uptake in DM yields of each crop harvested during the two cropping sequences were subtracted as outputs. Horizontal C balances on MIN plots were set to zero.

4.2.2.2 Leaching

Cumulative leaching losses were determined with mixed-bed ion-exchange resin PVC-cartridges of 0.11 m diameter and 0.11 m height (Siemens and Kaupenjohann, 2004; Predotova et al., 2010b). The cartridges were filled with pure silica sand of 120 - 700µm (Majan Glass Co., Sohar, Oman) and a mixture of an industrial grade basic anion and cation exchange resin. Before the onset of the experiment, cartridges were installed according to the guidelines of TerrAquat Consultancy (Stuttgart, Germany), the patent holder of this method, below the crops' rooting zone at a depth of 0.4 m in all 24 experimental plots (5 cartridges per plot). Cartridges were unearthed after the harvest of the second crop in the sequence (total cropping period of 130 days from October 2007-March 2008 and from October 2008-March 2009). The resin-sand mixture was removed from the cylinders and divided in four equal layers of which about 60 g each were frozen until analysis. Subsequently, a subsample of 30 g of resin was extracted 8 times with 100 ml of 0.5 M NaCl by vigorous shaking for 60 minutes. Subsequently, 25 ml samples were analyzed for concentrations of nitrate (NO_3-N), ammonia (NH_4-N), and phosphate (PO_4-P) with an ICP-AES (Spectroflame, Spectro GmbH, Kleve, Germany). Cumulative leaching losses per hectare and cultivation period were calculated based on the 95 cm^2 surface area of a resin cartridge. Previous studies had shown that the recovery rates of the used resin:sand mixture used in the cartridges varied from 78-114% for mineral nitrogen (NO_3-N, NH_4-N) and from 96-121% for mineral phosphorus (PO_4-P).

4.2.2.3 Gaseous emissions

Fluxes of ammonia (NH_3-N), nitrous oxide (N_2O-N), carbon-dioxide (CO_2-C), and methane (CH_4-C) were estimated with a closed chamber system (Figure 1). The Teflon®-coated cuvette (0.3 m diameter and 0.11 m height (Hans et al., 2005; Predotova et al., 2010a) was fitted air-tight to a 0.3 m wide and 0.06 m high PVC ring pressed 0.05 m deep into the soil surface. The cuvette was equipped with a digital thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany) for continuous monitoring of internal air humidity and temperature. Carbon and N fluxes were measured with a portable INNOVA photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark) which was connected by two 1 m long Teflon® tubes (in- and outflow) to the cuvette. Simultaneously to the gas measurements soil moisture at 0.06 m depth was determined with a TDR-probe connected to a tension-humidity meter (INFIELD 7, UMS GmbH, Muenchen, Germany) and soil temperature with a digital thermometer (Carl ROTH GmbH+Co, Karlsruhe, Germany). A Watchdog® weather station (Spectrum Technologies Inc., Plainfield, IL, USA) was used to record air temperature, humidity, wind speed, wind direction, irradiation and precipitation as well as soil moisture and temperature at 0.4 m depth near the field border in 30 min intervals. The gas-monitor was set to compensate for cross-interference of gases and water vapour with NH_3, N_2O, CO_2, and CH_4 and at a sample integration time of 5 s. Detection limits were 200 µg kg^{-1} for NH_3, 30 µg kg^{-1} for N_2O, 13 mg kg^{-1} for CO_2, and 400 µg kg^{-1} for CH_4.

To minimize effects of rising temperatures on gas fluxes, during each measurement day readings were taken in triplicate (three measurements per plot) in six freshly irrigated plots of one of the four replicates that was also used for leaching measurements. On these six plots measurements were conducted during 9:30 AM – 11:00 AM, 11:00 AM – 12:30 AM, 12:30 PM – 2:00 PM to minimize the effect of diurnal changes in air and soil temperature on gaseous emissions. For radish, measurements were taken at 1, 3, 5, 7, 9, 11, 13, 15 and 17 DAT in 2007/8 and at 2, 5 DAT and 2 days before harvest in 2008/9. For cauliflower and carrot, measurements were taken at 2, 4, 6, 8, 10, 12, 35, 36 (2007/8) and 2, 4, 35, 36 (2008/9) DAT and during two days before harvest (2007/8 and 2008/9). To avoid plant effects on C and N flux measurements, all readings were taken between the plants on the bare soil surface.

Equation 1 was used to calculate the flux rate of the measured gases whereby the gas concentration at the beginning of the emission period (c_{G1}) was subtracted from the concentration at the end of the emission period (c_{G2}) and divided by the interval length (t_E) during which the chamber remained closed on the soil surface.

$$E_G = \left[\left(\frac{c_{G2} \times V_{CH} \times 298.15 \times \frac{3600}{t_E} \times \frac{1}{A_{CH}}}{(V_{NG} \times 1000000) \times (273.15 + T_{CH2})}\right) - \left(\frac{c_{G1} \times V_{CH} \times 298.15 \times \frac{3600}{t_E} \times \frac{1}{A_{CH}}}{(V_{NG} \times 1000000) \times (273.15 + T_{CH1})}\right)\right] \times m_G$$

E_G – Gaseous emission (mg h^{-1} m^{-2})

c_{G1} – Gas concentration at the start of emission (ppm)

c_{G2} – Gas concentration at the end of emission (ppm)

T_{CH1} – Air temperature inside the closed chamber at the start of emission (°C)

T_{CH2} – Air temperature inside the closed chamber at the end of emission (°C)

V_{NG} – Volume of the normalised gas (0.02445 m^3)

V_{CH} – Chamber volume (0.00838 m^3)

t_E – Time period of emission (sec)

A_{CH} – Base area of the chamber (0.07022 m^2)

m_G – Molar mass of the measured gas (g mol^{-1}) (Equation 1)

To estimate treatment effects on cumulative C and N emissions, flux rates measured during one measurement period (October/November) for radish and three measurement periods (December, January, and February/March for cauliflower and carrot) were averaged and multiplied by the length of the cultivation period of the respective crop.

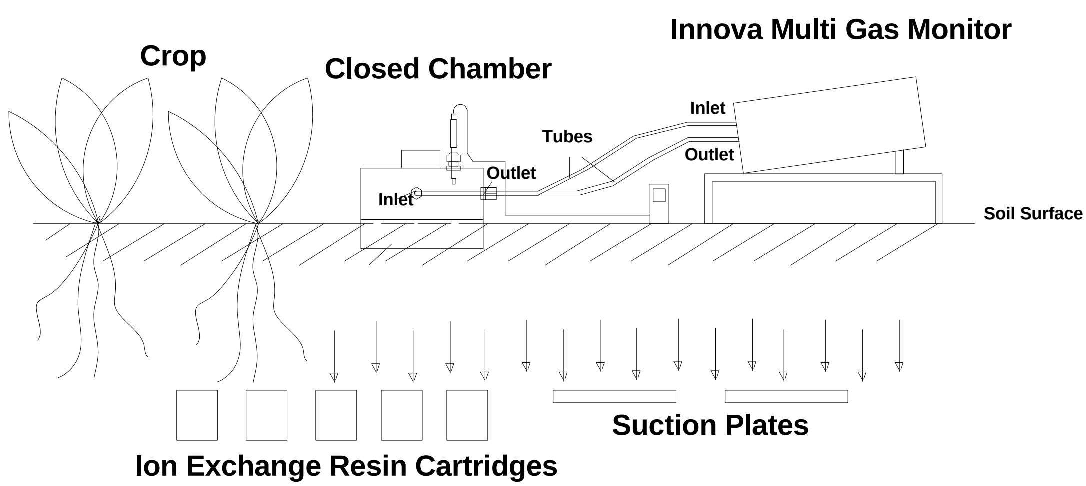

Figure 1: Setup to measure nitrogen (N) and phosphorus (P) leaching losses and gaseous carbon (C) and nitrogen (N) fluxes in an organic soil amendment by cropping systems experiment near Sohar, northern Oman.

4.2.3 Matter balances

Horizontal and vertical fluxes were combined to calculate a total balance for the entire experimental period 2007-2009. Thereby outputs due to gaseous emissions, leaching rates, and harvest removal (applicable to N, P, K, but not C) were subtracted from inputs of mineral and organic fertilizer application for each soil amendment (MIN, ORG1, ORG2), cropping system (radish-carrot, radish cauliflower), and the two cropping cycles (2007/8 and 2008/9).

4.2.4 Data analysis

Treatment effects on cumulative gaseous emissions and leaching were analysed by ANOVA using SPSS 17.0 and means were separated by the Scheffé post-hoc test at $P<0.05$ (Backhaus et al., 2003).

Examination of ANOVA residuals of the leaching data obtained from mixed-bed ion-exchange resins indicated deviations from the normal distribution. As these could not be effectively removed by data transformation, respective F-values are only approximate.

4.3 Results

4.3.1 Horizontal fluxes

Manure dry matter inputs amounted to 28 t ha^{-1} (8.76 t Corg ha^{-1}; ORG1) and 38 t ha^{-1} (13.73 t Corg ha^{-1}; ORG2). These were split-applied at 16 and 12 t ha^{-1} (ORG1) and 22 and 16 t ha^{-1} (ORG2) for 2007/8 and 2008/9, respectively, to the two-year cropping sequence of radish-cauliflower or radish-carrot (Table 2). The inputs contained a total of 590 kg N, 251 kg P, 320 kg K, and equivalent amounts of mineral fertilizers (MIN, Figure 2). These were accompanied by outputs for radish-carrots of 150, 155, and 157 kg N ha^{-1}; 46, 53, and 50 kg P ha^{-1}; and 453, 351, and 332 kg K ha^{-1} on MIN, ORG1, and ORG2 plots, respectively. Outputs for radish-cauliflower on respective MIN, ORG1 and ORG2 plots were 241, 229, and 214 kg N ha^{-1}; 60, 62, and 65 kg P ha^{-1}; and 431, 371, and 378 kg K ha^{-1} (Table 3, Figure 2).

For both cropping systems bi-annual horizontal N balances were positive regardless of amendment type but by 91, 74, and 57 kg larger for radish-carrot than for radish-cauliflower (Table 3). Similar differences in positive balances were noted for P. In contrast, K balances on MIN, ORG1, and ORG2 plots were with -133, -31, and -12 kg ha^{-1} for radish-carrot and -111, -51, and -58 kg ha^{-1} for radish-cauliflower consistently negative. Horizontal C balances across cropping systems were with 9 and 14 t ha^{-1} positive on ORG1 and ORG2 plots (Table 3).

Table 3: Horizontal balance with inputs and outputs for two cropping systems radish-carrot and radish-cauliflower and three soil amendments MIN, ORG1 and ORG2 for a 2-year experimental period 2007-2009 in Sohar, northern Oman (MIN – mineral fertilizer, ORG1 – manure low C/N and NDF/SC, ORG2 – manure high C/N and NDF/SC). Positive numbers listed in the table indicate gains, negative ones losses.

Year		Input			Output						Horizontal balance					
					Radish - Carrot			Radish - Cauliflower			Radish - Carrot			Radish - Cauliflower		
		MIN	ORG1	ORG2	MIN	ORG1	ORG2	MIN	ORG1	ORG2	MIN	ORG1	ORG2	MIN	ORG1	ORG2
2007/8		kg ha^{-1} 130 $days^{-1}$														
	N	295	295	295	-76	-80	-79	-139	-109	-121	219	215	216	156	186	174
	P	112	112	112	-25	-27	-26	-36	-31	-39	87	85	86	76	81	73
	K	160	160	160	-246	-162	-171	-219	-155	-214	-86	-2	-11	-59	5	-54
	C	0	4,929	7,894	0	0	0	0	0	0	0	4,929	7,894	0	4,929	7,894
2008/9		kg ha^{-1} 130 $days^{-1}$														
	N	295	295	295	-74	-75	-78	-102	-120	-93	221	220	217	193	175	202
	P	139	139	139	-21	-26	-24	-24	-31	-26	118	113	115	115	108	113
	K	160	160	160	-207	-189	-161	-212	-216	-164	-47	-29	-1	-52	-56	-4
	C	0	3,832	5,840	0	0	0	0	0	0	0	3,832	5,840	0	3,832	5,840
2007 -		kg ha^{-1} 260 $days^{-1}$														
2009	N	590	590	590	-150	-155	-157	-241	-229	-214	440	435	433	349	361	376
	P	251	251	251	-46	-53	-50	-60	-62	-65	205	198	201	191	189	186
	K	320	320	320	-453	-351	-332	-431	-371	-378	-133	-31	-12	-111	-51	-58
	C	0	8,761	13,734	0	0	0	0	0	0	0	8,761	13,734	0	8,761	13,734

4.3.2 Vertical fluxes

4.3.2.1 Cumulative leaching losses

Over the 2-year experimental period with a total cropping period of 260 days soil amendments led to significant differences in resin-based leaching losses of mineral N. These amounted to 30 kg ha^{-1} for MIN, 10 kg ha^{-1} for ORG1, and 56 kg N ha^{-1} for ORG2 ($P<0.05$). Cumulative PO_4-P leaching was 9 kg P ha^{-1} for the control treatment MIN, 6 kg P ha^{-1} for ORG1, and 10 kg P ha^{-1} for ORG2 (Table 4, Figure 2).

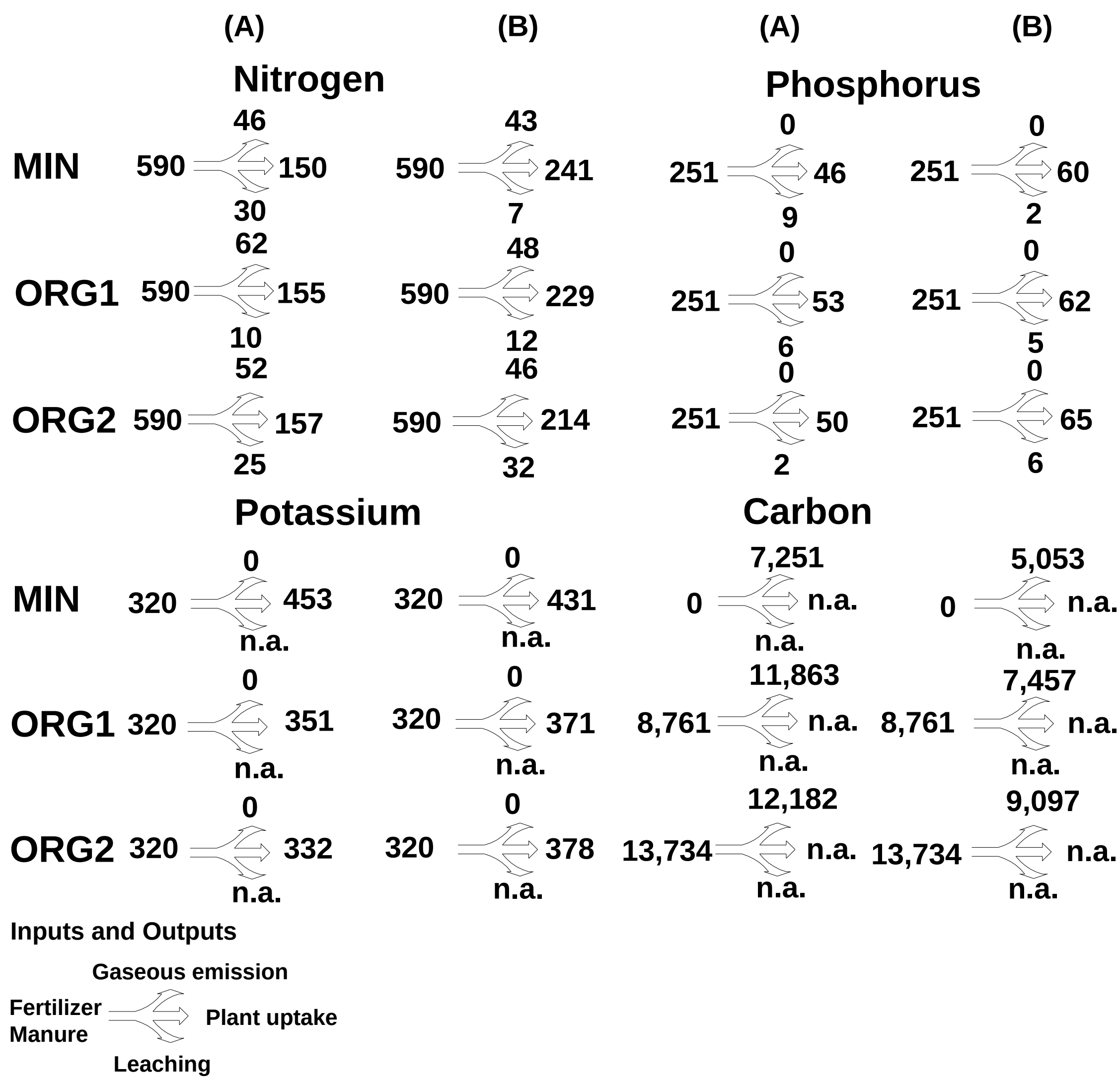

Figure 2: Fluxes of nitrogen, phosphorus, potassium and carbon in the cropping systems radish followed by carrot (A) and radish followed by cauliflower (B) for three different soil amendments (two manure types - ORG1 and ORG2, and equivalent mineral fertilizers – MIN) in kg ha^{-1} 24 month^{-1} and a cropping period: 260 days near Sohar, northern Oman.

4.3.2.2 Gaseous emissions

During the 260 day experimental period total gaseous N emissions of the four cropping cycles averaged 45 kg ha^{-1} (70% NH_3-N, 30% N_2O-N) in MIN plots, 55 kg N ha^{-1} (80% NH_3-N, 20% N_2O-N) in ORG1, and 49 kg N ha^{-1} (70% NH_3-N, 30% N_2O-N) in ORG2 plots. Carbon emissions during the same period amounted to 6.2 t C ha^{-1} (98% CO_2-C, 2% CH_4-C) for MIN, 9.7 t C ha^{-1} (98% CO_2-C, 2% CH_4-C) for ORG1, and 10.6 t ha^{-1} (98% CO_2-C, 2% CH_4-C) for ORG2 (Figure 2 and 3, Table 5).

In radish, the application of ORG2 led compared with MIN to a significant increase of 54% in CO_2-C emissions in 2007 ($P< 0.001$, n=27) and to a 121% increase in 2008 ($P<0.01$, n=27). The application of ORG1 led to 110% higher NH_3-N emissions ($P<0.05$, n=27) compared to MIN and 133% higher NH_3-N emissions compared to ORG2 ($p<0.05$, n=27) in 2008/9 (Figure 3).

Carrot plots in turn had 34% higher CO_2-C emissions on ORG2 plots compared to MIN ($P<0.05$, n=72) and 30% higher CO_2-C emissions on ORG1 plots compared to MIN plots in 2007/8. During the growing period of carrot in 2008/9 the emissions of CO_2-C on ORG1 plots were 93% higher than those on MIN plots ($p<0.05$, n=108). For carrot there were no significant effects of soil amendments on NH_3-N, N_2O-N and CH_4-C.

Cauliflower ORG2 plots had 91% higher CO_2-C emissions than MIN plots ($P<0.001$, n=72) in 2007/8. During the same growing period 47% higher CO_2-C emissions were detected on ORG2 plots compared to ORG1 plots ($P<0.01$, n=72). For the second cauliflower growing period in 2008/9 average cumulative CO_2-C emissions were 70% higher on ORG2 plots compared to MIN and 66% higher on ORG1 plots compared to MIN. During the second growing period of cauliflower in 2008/9, however, differences between manure types and the MIN treatment were not significant ($P=0.087$, n=54).

Across treatments and years gaseous N and C emissions tended to be higher in carrot than in cauliflower (Figure 4). For both crops CO_2-C emissions were 2-fold higher in the second than in the first cropping cycle (Figure 3). Flux rates of NH_3-N and CH_4-C were similar throughout both years. For carrot and cauliflower NH_3-N emissions were highest at the onset of the season, soon after fertilizer application, while N_2O-N and CO_2-C emissions increased towards the end of the growing cycle. Emissions of NH_3-N, N_2O-N, CO_2-C and CH_4-C were 29%, 11%, 60% and 37%, respectively, higher from carrots than from cauliflower plots (NH_3-N, $P<0.01$; CO_2-C, $P<0.001$). Average CO_2-C emissions in radish, carrot and cauliflower plots were respectively 40%, 151% and 69%, and N_2O-N emissions in radish, carrot and cauliflower plots 4%, 74% and 59%, respectively, higher during the second than during the first growing period. This year-effect may reflect differences in ambient temperatures conditions and soil water content in 2008/9 compared to 2007/8 (Figure 5).

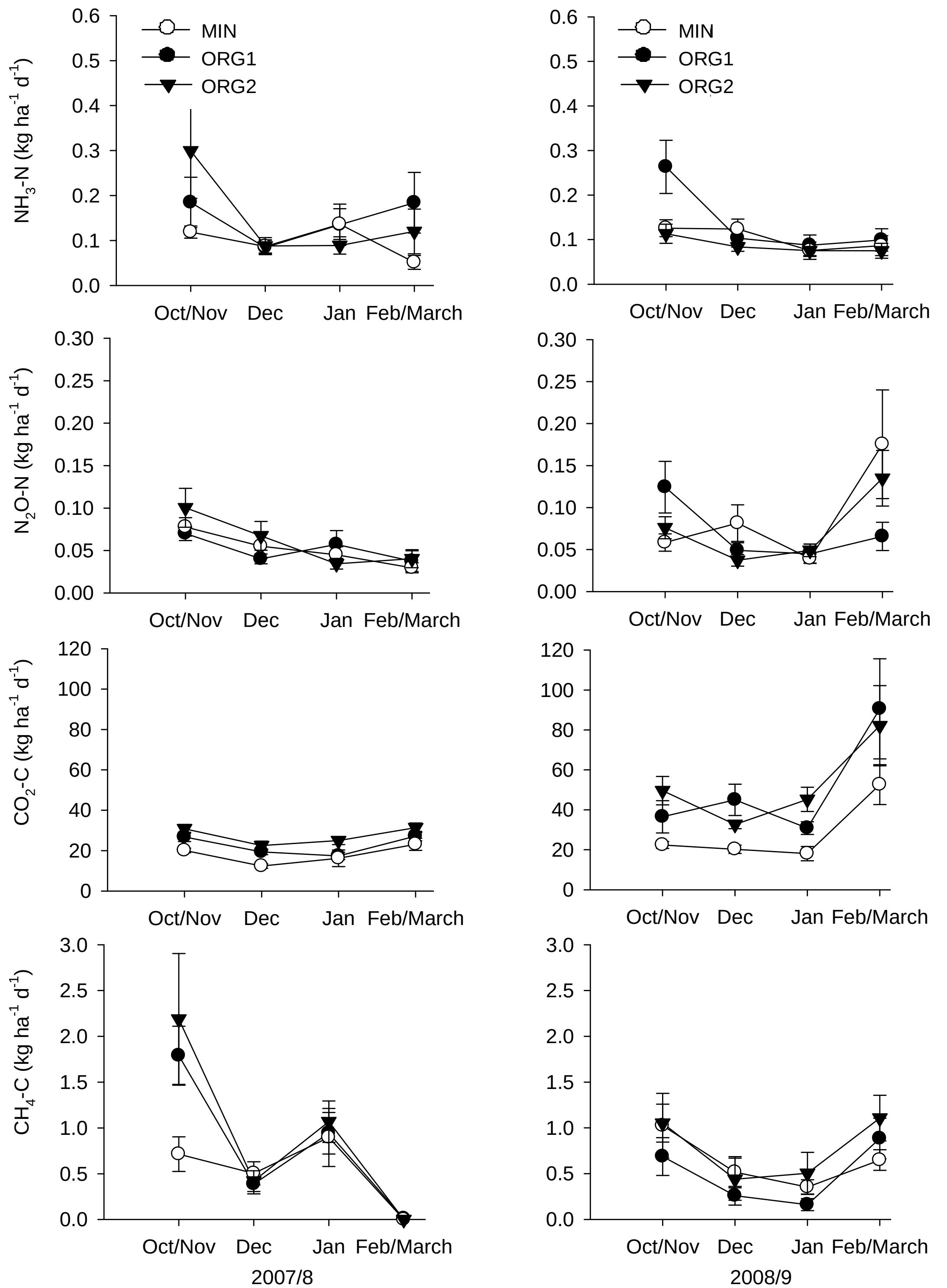

Figure 3: Emission rates of NH_3-N, N_2O-N, CO_2-C and CH_4-C during the cropping season for three soil amendments near Sohar, northern Oman, in 2007/8 and 2008/9. MIN – mineral fertilizer, ORG1 – manure low C/N and NDF/SC, ORG2 – manure high C/N and NDF/SC). Data represent means with one standard error of the mean.

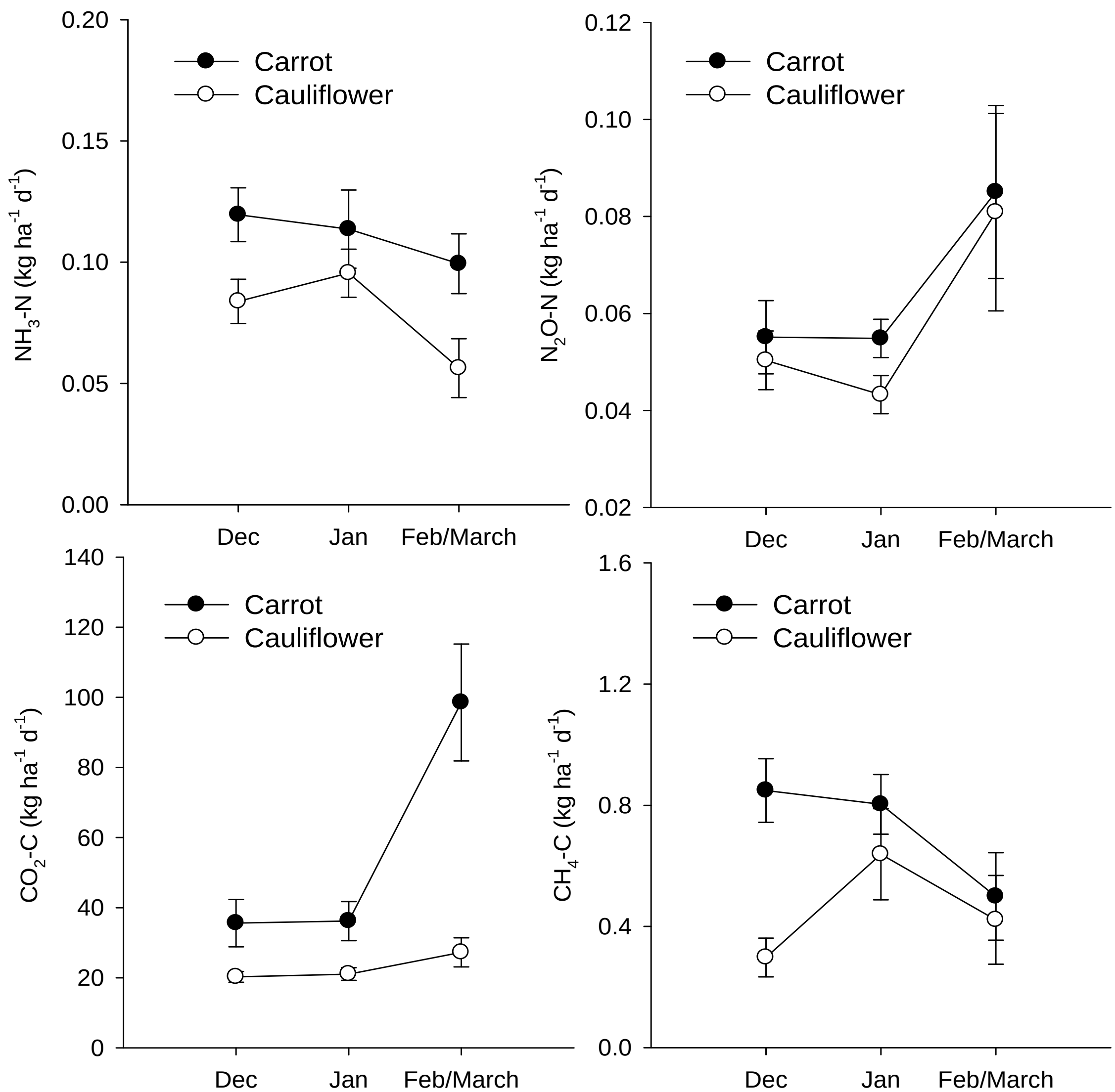

Figure 4: Emission rates of NH_3-N, N_2O-N CO_2-C and CH_4-C on plots planted with carrots and cauliflower in Sohar, northern Oman. Data represent means with one standard error of the mean.

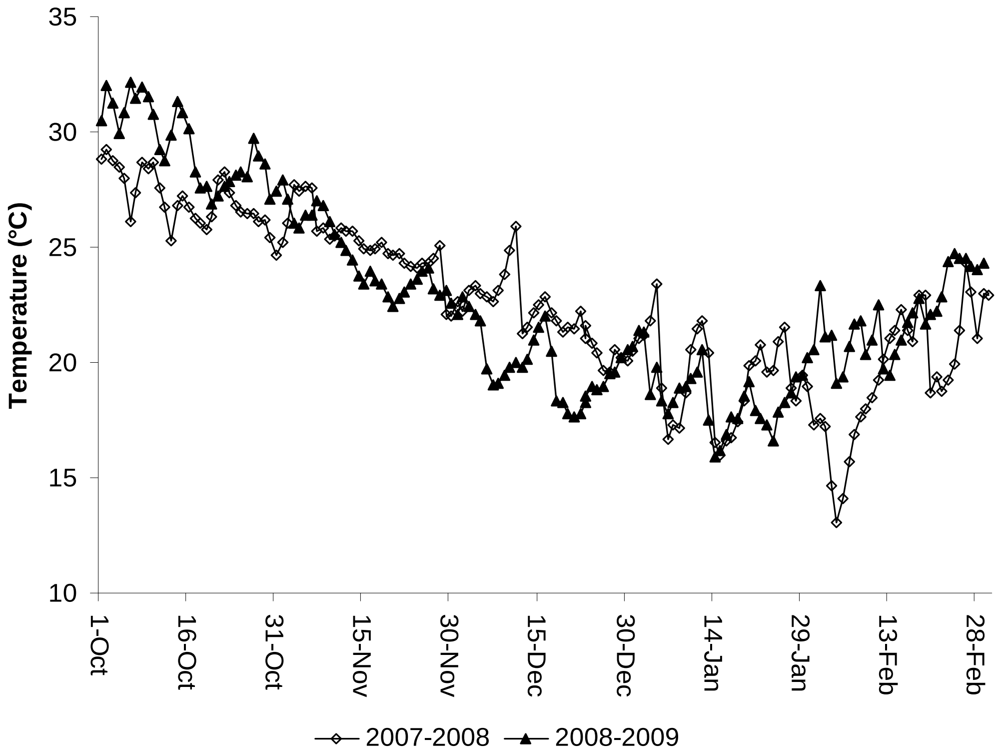

Figure 5: Average ambient daily temperature during the cultivation periods 2007/8 and 2008/9 of the organic cropping systems experiment near Sohar, northern Oman.

Table 4: Cumulative leaching losses of mineral nitrogen (N) and phosphorus (P) from irrigated sandy soils determined by mixed-bed ion exchange resins near Sohar, northern Oman. Data represent means with one standard error.

	Cumulative leaching 2007-2008		**Cumulative leaching 2008-2009**	
	Mineral N	**Mineral P**	**Mineral N**	**Mineral P**
Fertilizer	kg ha^{-1} yr^{-1}			
MIN	7.6 (± 1.2)	1.2 (± 0.4)	21.9 (± 9.4)	7.7 (± 4.3)
ORG1	5.8 (± 0.5)	2.1 (± 0.8)	3.9 (± 1.1)	3.5 (± 0.4)
ORG2	13.0 (± 2.3)	2.1 (± 0.8)	43.1 (± 12.4)	8.3 (± 1.9)
Cropping system				
Radish-carrot	7.7 (± 0.6)	0.9 (± 0.1)	9.9 (± 4.7)	4.5 (± 1.0)
Radish-cauliflower	13.0 (± 2.3)	2.1 (± 0.8)	43.1 (± 12.4)	8.3 (± 1.9)
Average	8.5 (± 0.7)	1.6 (± 0.3)	19.7 (± 4.3)	6.0 (± 1.2)

4.3.3 Total balances

Total balances of N, P, and K on radish-carrot plots were 364, 196, and -96 kg ha^{-1} on MIN plots, 363, 192, and -98 kg ha^{-1} on ORG1 plots, and 356, 199, and -67 kg ha^{-1} on ORG2 plots. For this cropping system, C balances amounted to -7.3, -3.1, and 1.5 t ha^{-1} for MIN, ORG1, and ORG2 plots, respectively. For radish-cauliflower balances followed the same pattern (Table 5). Differences between NPK balance data for the soil amendments MIN, ORG1 and ORG2 were not significant. For the latter cropping sequence C balances amounted to -5.1, 1.3, and 4.6 t ha^{-1} for MIN, ORG1, and ORG2 plots, respectively (Table 5).

Total balances of N, P, and K were unaffected by soil amendments, however, the latter significantly altered C balances ($P<0.001$, Figures 6 and 7). The cropping system, in contrast, significantly affected total balances of N, P, K, and C ($P<0.001$ for N, $P<0.001$ for P, $P<0.05$ for K and $P<0.001$ for C). The P balance was 41% more positive in the first than the second cropping cycle while total C balances became severely negative only in 2008/9 ($P<0.001$ for P and C). Net balances of N and K were similar for both experimental periods (Figures 6 and 7).

4.4 Discussion

Gaseous N losses were much larger than respective leaching values of mineral N (Table 5). Radish-cauliflower with manure of low C/N and fibre ratio (ORG1) was most efficient in terms of added N (Campbell et al., 1995). On ORG1 plots gaseous N losses in radish-cauliflower were 23% lower than in radish-carrot but C emanation was four-fold higher (Table 5). Gaseous C losses were even higher and N losses lower for ORG2. Tendencies of higher yields on ORG1 plots for some of the crops during parts of the rotation cycle were inconsistent. Nitrogen uptake in radish-cauliflower tended to be highest on MIN plots followed by ORG1 and ORG2 plots. This confirms results of Chadwick et al. (2000) showing increases in plant N uptake with manure mineralization, but this was not evident in radish-carrot. The latter could have been due to higher gaseous and leaching losses on these plots (Table 5; Figure 2, 4) which may have been prevented amendment effects on yield and nutrient uptake of carrots.

The negative C balances in MIN plots and in ORG1-amended radish-carrot were mainly the consequence of the high CO_2-C emissions from the irrigated soils (Table 5, Figure 2) which reflect a mixture of root respiration, decomposition of plant residues and soil organic matter as described for temperate forest soils by Sakata et al. (2007) and for soils of Omani mountain oases by Wichern et al. (2004). Unfortunately, within the scope of this study we could not determine the relative contribution of these components. While N and P balances were positive for all treatments the negative K balances were surprising, but leaf analyses did not indicate deficiency in any of the crops (Benton Jones, 2003).

The higher resin-derived cumulative leaching losses of mineral N in ORG2 compared to ORG1 plots contradicted our expectation the C/N ratio of manure largely determines its turnover dynamics (Chadwick et al., 2000; Sørensen et al., 2003; Velthof et al., 2005). It may, however, well be that higher plant uptake in

ORG1 plots (N demand) may have led to lower leaching losses on ORG1 as compared to ORG2 plots. In any case it should be underlined that our approach tends to heavily underestimate N leaching losses as the resin-technique does not allow to account for leached organic-N forms. These may reach on sandy cropped soils up to 21% of total leached N (Siemens and Kaupenjohann, 2002; van Kessel et al., 2009). Barton et al. (2005) reported that in soils irrigated with 2300 mm of domestic effluents even up to 87% of total N could be organic N.

Gaseous C emanation (CO_2-C and CH_4-C fluxes) was significantly higher on ORG2 than on MIN plots. It also tended to be higher on ORG1 plots, although this difference was not significant. The high C emissions on manured plots likely reflected the effects of added substrate of high turnover under the high soil moisture and temperature conditions of irrigated agriculture in Oman (Figure 2; Hans et al., 2005; Paustian et al., 2000).

In contrast to our expectations and data of Canh et al. (1998) and Velthof et al. (2003) even the large differences in the C/N and NDF/SC ratio of the two manures applied in this study did not significantly affect N emission. Differences may have been masked by soil heterogeneity (Stark 1994; Huisman et al., 1997; Velthof et al., 2003), such as spatial differences in soil water content, and microbial activities. Higher N and C emission rates on carrots compared to cauliflower plots ($P<0.05$, Figure 4) led to overall higher gaseous N losses and may be the result of lower N uptake in carrot compared to cauliflower (Table 5; Figure 4).

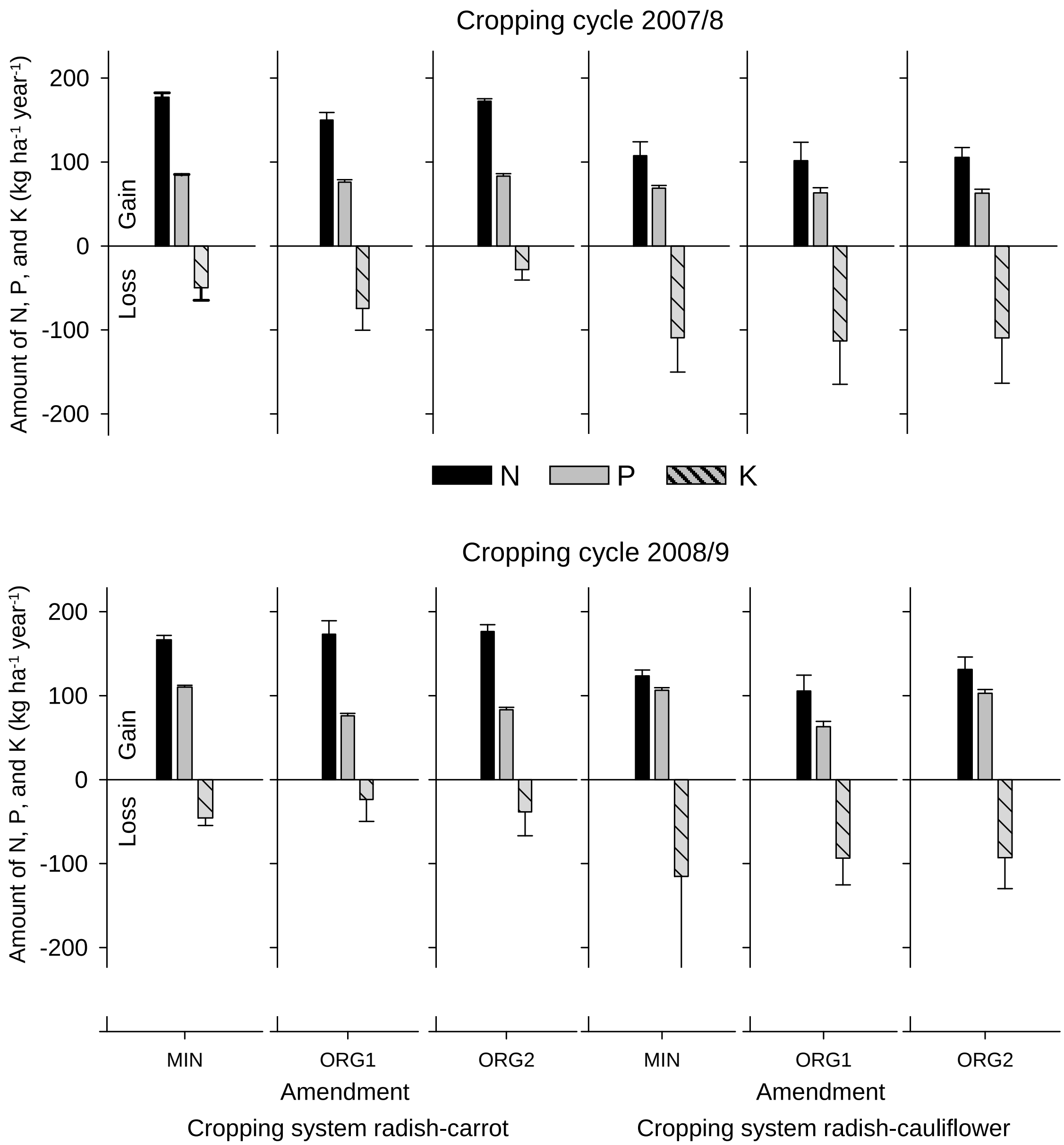

Figure 6: Nutrient balances for the organic cropping systems radish-carrot and radish-cauliflower during the two cropping cycles 2007/8 and 2008/ with cropping periods of 130 days each. Those lasted from September 2007 – March 2008 and from September 2008 – March 2009. ORG1 and ORG2 refer to two types of manure and MIN to an equivalent mineral fertilizer rate. Bars represent means with one standard error.

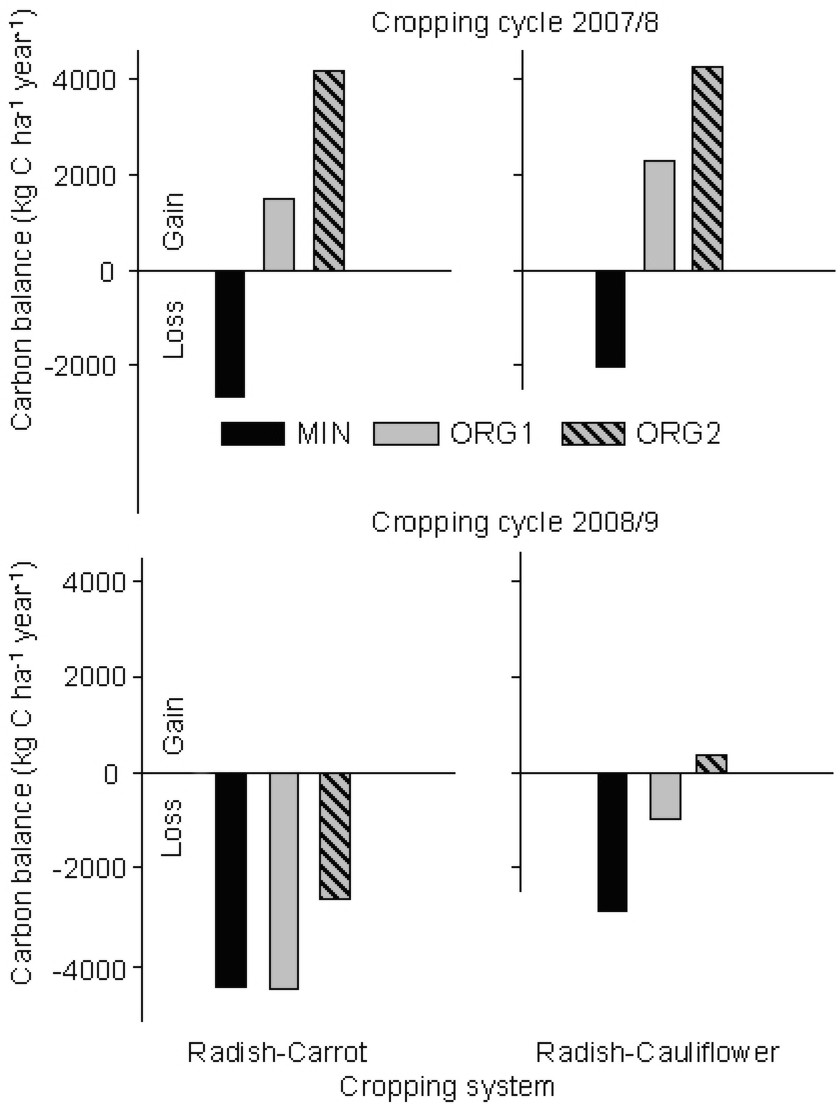

Figure 7: Carbon balances for the organic cropping systems radish-carrot and radish-cauliflower during the two cropping cycles 2007/8 and 2008/8 with cropping periods of 130 days each. Those lasted from September 2007 – March 2008 and from September 2008 – March 2009. ORG1 and ORG2 refer to two types of manure and MIN to an equivalent mineral fertilizer rate.

Table 5: Total balance of nitrogen (N), phosphorus (P), potassium (K) and carbon (C) for the bi-annual experimental period 2007-2009 showing inputs and outputs (kg ha^{-1} 24 $month^{-1}$, cropping period 2 x 130 days = 260 days) of an organic soil amendment by cropping systems experiment near Sohar, northern Oman. Positive numbers listed in the table indicate gains, negative ones losses. Soil amendments were manure with a low C/N and NDF/SC ratio (ORG1), manure with a high C/N and NDF/SC ratio (ORG2), and a mineral fertilizer equivalent (MIN).

	Total net balance (kg ha^{-1} 24 $month^{-1}$)							
	N	P	K	C	N	P	K	C
Cropping system	Radish followed by carrot				Radish followed by cauliflower			
Amendment	MIN							
Fertilizer	590	251	320	0	590	251	320	0
Emissions	-46			-7,251	-43			-5,053
Leaching	-30	-9			-7	-2		
Crop uptake	-150	-46	-453		-241	-60	-431	
Balance	364	196	-133	-7,251	299	188	-111	-5,053
Amendment	ORG1							
Fertilizer	590	251	320	8,761	590	251	320	8,761
Emissions	-62			-1,863	-48			-7,457
Leaching	-10	-6			-12	-5		
Crop uptake	-155	-53	-351		-229	-62	-371	
Balance	363	192	-31	-3,102	301	184	-51	1,304
Amendment	ORG2							
Fertilizer	590	251	320	13,734	590	251	320	13,734
Emissions	-52			-2,182	-46			-9,097
Leaching	-25	-2			-32	-6		
Crop uptake	-157	-50	-332		-214	-65	-378	
Balance	356	199	-12	1,552	298	180	-58	4,637

4.5 Conclusions

Under the arid subtropical climate conditions of Oman cultivation of irrigated vegetables is accompanied by a very fast turnover and subsequent high C and N volatilization. The results of the study show that the sustainable cultivation of organic vegetables on the prevailing sandy soils may require even larger inputs of C in the form of manure, compost, and crop residues and also of K than used in our study. Across soil amendments and cropping systems volatilization was the main pathway of C and N losses. Future research should emphasize the search for management options on how to effectively decrease the turnover of added organic matter.

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Chapter 5

General discussion and conclusions

5 .1 General discussion

5.1.1 Effects of manure with different C/N ratios on organically grown vegetables

In contrast to our expectations stated in our second hypothesis (H2) different C/N and NDF/SC ratios of manure did not significantly affect marketable yield and yield components of irrigated radish, carrot or cauliflower. The variability of ambient temperatures between years may have had larger effect on organically grown vegetables than the quality of manure. Nevertheless, during the two cropping cycles higher availability of N, P, and K from MIN plots, compared to the low C/N and low NDF/SC (ORG1) and the high C/N and high NDF/SC (ORG2) plots tended to enhance crop growth confirming results of Chadwick et al. (2000), Lampkin (1990) and Magdoff et al. (2000). For some of the yield components (e.g. ascorbic acid concentration) effects of these differences were significant.

The turnover of C and N could not effectively be retarded by direct application of manure of high C/N and NDF/SC contradicting our third hypothesis (H3). High temperatures and following elevated gaseous emissions of carbon (C) led to a depletion of C-stocks in the soil during our field study. The removal of plant residues, which was not quantified during the here presented research, may have also contributed to negative or lowered C balances. In a sustainable organic cropping system plant residues would have been left in the field and be again incorporated into the soil to partially compensate for losses of nutrients and carbon.

5.1.2 Gaseous losses from irrigated sandy subtropical soils

Gaseous C and N losses were found to be larger than respective leaching values what confirms our first hypothesis (H1). For the radish-cauliflower cropping system, respective volatilization losses on ORG1 plots of N and C were reduced by 23% and 37% compared to radish-carrot.

The analysis of gaseous emission data showed significantly higher carbon (CO_2-C, CH_4-C) emissions on ORG2 plots compared to the control (MIN). Carbon emissions tended also to be higher on ORG1 plots as compared to the MIN plots, although this difference was not significant. The high C emissions on organically amended plots likely reflected the high input of manure as this substrate has been shown previously to have a particularly high turnover under the high soil moisture and temperature conditions of irrigated agriculture in Oman (Hans et al., 2005; Paustian et al., 2000).

In contrast to our expectations and data of Canh et al. (1998) and Velthof et al. (2003) even the large differences in the C/N and fibre content ratio of the two manures applied in this study did not significantly affect emission rates of N. Differences may have been masked by soil heterogeneity (Stark, 1994; Huisman et al., 1997; Velthof et al., 2003), such as spatial differences in soil water content, and microbial activities. Higher NH_3-N emission rates on carrots compared to cauliflower plots ($P<0.05$) resulted in higher cumulative emission of N in the radish-carrot compared to the radish-cauliflower cropping system. This may be the result of lower N uptake in carrot compared to cauliflower.

The gaseous emissions were measured with a portable INNOVA photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark) in a closed chamber system allowing multiple measurements to cover the high spatial and temporal variability of emissions from the soil surface (Hans et al., 2005; Predotova et al., 2010, Paustian et al., 2000). While the setup seemed to be very practical, some questions arise regarding the measurement time period in the closed chamber, adhesion of gas molecules to the walls of the gas chambers and daily temperature dependent fluctuation of emissions discussed in detail by Predotova et al. (2010). In our study the cumulative emission was calculated by averaging the flux rates determined during one measurement period (October/November) for radish and three measurement periods (December, January and February/March for cauliflower and carrot) and multiplying by the length of the cultivation period of the respective crop. Future extrapolations of cumulative emissions from organically fertilized soils could be improved by higher frequency of measurement periods to better cover temporal variations of emissions during the cropping period.

5.1.3 Leaching losses from irrigated soils measured with mixed-bed ion exchange resin cartridges and suction plates

Under laboratory conditions low concentrations of nutrients in the leachates and high apparent recovery rates for N and P suggest that the resin exchange method (Bischoff et al., 1999; Bischoff, 2007) allows reliable estimates for both nutrients in percolating water. The excessively high apparent recovery rates of K, however, are due to the high K concentrations in the blank extractions of the sorbents, particularly the silica sand and the cation resin samples that led to erroneous values. This makes the ion exchange resin method unsuitable for the quantitative estimation of K fluxes in water based percolating solutes unless major efforts allow the extraction of all excess K from the sorbent during conditioning. A similar need of proper resin pre-treatment of ion exchange resin sand mixtures has been reported by Thiffault et al. (2000).

At our experimental site near Sohar, northern Oman, the installation of ion exchange resins seemed to be a suitable and simple method for the measurement of leaching losses. The cartridges containing the sorbent mixture could be installed at relatively high number (n=40 per soil amendment) without the use of large financial and technical resources. The high number of installed cartridges was intended to overcome the suspected high spatial variability of preferential flow. The continuously changing water tension in irrigated soils with short consecutive wetting and drying cycles is to our knowledge not affecting sorption properties of the sorbent mixture in the cartridges while it poses difficulties for the technical operation of tension controlled soil solution sampling methods (e.g. suction plates).

Suction plates were installed during our experiment to measure time dependent leaching of total amounts of nutrients and dissolved organic carbon (Webster et al., 1993; Siemens et al., 2002 and 2004; Mantovi 2006) and also to get more knowledge of the proportion of leached organically bound nitrogen on total nitrogen leaching (Siemens et al., 2002; Van Kessel et al., 2009; Barton et al., 2005). After completion of the experiment we were able to compare the results of the exchange resin method and suction plates.

The cumulative leaching values for Nmin determined by suction plates and subsequent modelling with Hydrus 1d by far exceeded the estimates of leached Nmin determined by mixed-bed ion exchange resins. This difference may be attributable to the effect of suction pressure head on the surrounding soil water leading to increased concentrations in the leachate samples as compared to the zero tension method of mixed-bed ion exchange resins (Magid et al., 1993). Our own results showed that almost the total amounts of NO_3-N, NH_4-N and PO_4-P applied under laboratory conditions were recovered from the mixed-bed ion exchange resins (Siegfried et al., 2010).

The difference of Ntot and Nmin concentrations found in leachate samples represented a relatively large share of organically bound nitrogen averaging 36% that is also reported for temperate sandy soils (6-21%) by Siemens et al. (2002) and for soils irrigated with domestic effluent (69-87%) by Barton et al. (2005). According to this result it seems questionable whether the exchange resins where able to account for all of the leached nitrogen under organically amended soils in our study.

5.1.4 Nutrient and carbon balances of organically fertilized subtropical soils

The total balance for nitrogen calculated from horizontal and vertical fluxes was positive for all the treatments and the two cropping systems during two experimental periods from October 2007 till March 2008 and from October 2008 till March 2009 while net balances of carbon (C) were negative for MIN plots across cropping systems and positive for ORG1 and ORG2 except for ORG1 on radish-carrot plots.

The negative or depleted net C balances were largely caused by the elevated CO_2-C emissions from irrigated organically and conventionally amended soils. While positive net balances were calculated for N and P, the negative or depleted net C-balances reflect the very high turnover rates of organic C under irrigation and high ambient temperature. For K negative net balances were calculated but analysis of potassium concentrations in leaves did not show deficiencies of potassium in any of the crops (Benton Jones 2003).

The decrease of net C balances of radish, carrot and cauliflower observed during the field study reflect a depletion of C stocks in the second period of the experiment that was likely caused by increasing temperatures at constantly high irrigation rates and following elevated gaseous losses of carbon (C). The removal of plant residues after the first harvest of the three vegetable crops 2007/8 also contributed to negative or lowered C balances for the second growing cycle. In a sustainable organic cropping system plant residues would have been left in the field and be again incorporated into the soil to partially compensate for losses of nutrients and carbon.

The negative C balances observed in our study raise questions with regard to the rates of manure applied to sustain the described irrigated organic vegetable production system in the year-round hot lowlands of northern Oman. In view of the recent consumer-driven area increase of organic farming in the Middle East and South Asia (Willer et al., 2010), the retarded turnover of organic C should be given more attention. This is of utmost importance in the coastal lowland farming systems of Oman where the role of organic matter in soil water storage and related water use efficiency can hardly be overemphasized (Norman et al., 1998).

The balance calculations were based on measurements of horizontal and vertical fluxes in organic vegetable cropping systems. Potential fluxes which were not accounted for are possible emissions of N_2 and NO (Butterbach-Bahl et al., 2004; Mosier and Parkin, 2007). These speculative losses would lead to less positive balances of N. Another source of error could be the crop residues left unintentionally in the experimental field. These root residues which were not accounted for in the balance would lead to higher horizontal fluxes of plant nutrient uptake.

5.2 Conclusions

The lack of consistent effects of different manure types on crop yields may have been largely due to the temperature and soil moisture related high turnover of the applied organic substrates that also led to large gaseous N and C emissions. While the applied amounts of manure led to net surpluses of N and P, during the second rotation cycle, C balances were positive for manure treatments in the first, but negative and inconsistent in the second rotation cycle reflecting a depletion of soil C stocks. This raises questions about the sustainability of irrigated cropping systems, in which all crop residues are removed, and in which manures would be used directly at the described application rates under the hyperarid conditions of our study area, and it also calls for further research to develop practices aiming at a lower turnover of C originating from manure and of C existing in the soil.

For the quantification of leaching losses of P and K from soils the ion exchange resin - sand mixture are to be pre-treated by a thorough cleaning procedure to remove adsorbed contaminating ions particularly from the quartz sand used. Repeated thorough washing of the quartz sand and the exchange resins with 1 M NaCl followed by abundant rinsing with deionized water should eliminate most of the unwanted K. The exchange resin method seemed to be appropriate for mineral nutrient leaching measurements while some questions arise whether this method is also applicable for the detection of high proportions of organically bound nutrients in leachate of manure amended soils.

The results of the study showed that under extreme climatic conditions on irrigated sandy soils organic cultivation of vegetables is limited in the first instance by the carbon content of applied manure and soil and in the second instance by the amount of applied N, P and K. Across soil amendments and cropping systems gaseous emissions were found to be the main pathway of nitrogen and carbon losses from irrigated sandy soils in Sohar, northern Oman. Future research should further emphasize on reduction of greenhouse gas emissions and leaching losses for the development of sustainable organic cropping systems in Oman and other hyperarid tropical countries.

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Affidavit

I assure that this dissertation was written independently and without non-permissible help and that I used no sources other than those specified in the dissertation. All quotations that have been extracted from published or unpublished sources have been marked as such. No part of this work has been used in other PhD processes.

Hiermit versichere ich, dass ich die vorliegende Dissertation selbständig und ohne unerlaubte Hilfe angefertigt und keine anderen als die in der Dissertation angegebenen Hilfsmittel benutzt habe. Alle Stellen, die aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht. Kein Teil dieser Arbeit ist in einem anderen Promotionsverfahren verwendet worden.

Witzenhausen, 22.09.2010 Konrad Siegfried

List of publications

Articles in peer-reviewed journals (currently under review)

Siegfried, K., Vazhacharickal, P.J., Predotova, M. and Buerkert, A. Sorption and desorption characteristics of ion exchange resins to estimate leaching losses in the field. Communications in Soil Science and Plant Analysis (submitted 13.8.2010).

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