Matter fluxes in mountain oases of
Al Jabal Al Akhdar, Oman

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Dedication

To my parents, brother, and sisters

To my wife and our newly born daughter Maryam

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Summary

Since 1970 when Sultan Qaboos bin Said Al Said took over power from this father, agriculture in Oman has undergone major transformations as a consequence of rapid population and economic growth. In this process groundwater extraction has dramatically increased to meet domestic and agricultural needs.

Recently, the agro-ecosystem of ancient mountain oases of Oman have received greater attention as interest has grown to understand the causes of their often millennia old sustainable productivity. Particularly little is known about the carbon (C) and nutrient turnover in these intensive landuse systems. This is partly due to the difficulties to measure such processes in the often remote fields. To fill the existing gap of knowledge, field studies were conducted in five oases at different altitudes of Al Jabal Al Akhdar, the highest agricultural area in Oman, to determine C and nutrient fluxes as well as nutrient use efficiencies for two different cropping systems as affected by temperature, irrigation, and manure quality.

From 2007-2009 representative landuse systems in the mountain oases of Ash Sharayjah (57°39’30” E, 23°04’10” N, 1900 m.a.s.l.), Al’Ayn, (57°39’44” E, 23°04’22” N, 1900 m.a.s.l.), Al’Aqr (57°39’58” E, 23°04’22” N, 1950 m.a.s.l.), Qasha' (57°39’50” E, 23°04’00”N, 1640 m.a.s.l.), and Masayrat ar Ruwajah (57°40’13” E, 23°02’37” N, 1030 m.a.s.l.) were monitored.

Results show that the area occupied with field crops decreased from 2007 to 2009 for all oases, with slight increases from 2008 to 2009 for two oases (Qasha’ and Masayrat ar Ruwajah). In Ash Sharayjah, terrace areas grown with field crops declined from 4.7 ha (32%) in 2007 to 3.1 ha (22%) in 2008 and to 3.0 ha (21%) in 2009. Similarly, the area of field crops decreased steadily in Al’Ayn from 0.9 ha (35.2%) in 2007 to 0.6 ha (25.6%) in 2008 and 0.5 ha (19.8%) in 2009. In contrast, the area dedicated to field crops in Qasha’ and Masayrat ar Ruwajah decreased from 0.9 and 1.6 ha (36.3 and 49.6%) in 2007 to 0.2 and 1.1 ha (5.9 and 34.8%) in 2008. In 2009 it increased again slightly to 0.3 and 1.4 ha (8.5 and 41.3%). In Al’Aqr, the area of field crops slightly increased from 0.3 ha (17.0%) in 2007, to 0.7 ha (39.1%) in 2008, and decreased to 0.5 ha (28.8%) in 2009.

To assess carbon and nutrient fluxes, a soil system balance approach was used for annual and perennial cropping systems. Garlic (*Allium sativum* L.) fields were selected in Ash Sharayjah and Masayrat ar Ruwajah and monitored for two growing seasons (2008/09-2009/10). Pomegranate fields (*Punica garanatum* L.) were selected in

Ash Sharayjah and Qasha' and date palm (*Phoenix dactylifera* L.) plots/stands in Masayrat and monitored for one year (2009/2010). Total balances were determined by calculating the differences between the total amounts of C, N, P, and K in all inputs and outputs such as crop removal at harvest and vertical carbon and nutrient losses. The cumulative leaching losses of mineral N and P were quantified with mixed-bed ion-exchange resin cartridges, while gaseous emissions of CO_2-C, CH_4-C, NH_3-N and N_2O-N were measured using a photo-acoustic infrared multi-gas analyser (INNOVA 1312-5, AirTech Instruments, Ballerup, Denmark).

Goat manure was applied to garlic fields at average rates of 47 and 40 t DM ha^{-1} in Ash Sharayjah and 42 and 37 t DM ha^{-1} at Masayrat during the two growing seasons. Pomegranate trees at Ash Sharayjah and Qasha' received dairy cattle manure at application rates of 66 and 60 t dry matter ha^{-1}, respectively. Annual gaseous C and N emissions clearly reflect the high application rates of manures as well as the variation of air temperature along the altitudinal gradient within the three oases. Annual total C gaseous losses were mainly emitted as CO_2-C, whereas CH_4-C accounted for less than 2% of annual losses. An annual C surplus of 12.5 t ha^{-1} was determined on Ash Sharayjah garlic fields, while a C deficit of -5.5 t ha^{-1} was calculated for Masayrat ar Ruwajah. Annual C surpluses of 16.7, 7.5 and 1.7 t ha^{-1} were obtained for pomegranate and date palm fields at Ash Sharayjah, Qasha' and Masayrat ar Ruwajah, respectively. Due to manure application rates of 78 t DM ha^{-1} $year^{-1}$, date palm fields had the highest total annual N surplus with 1857 kg ha^{-1}. Pomegranate fields at Ash Sharayjah and Qasha' had with 1414 and 1500 kg ha^{-1} also high annual N surpluses compared to garlic fields with 915 kg ha^{-1} at Ash Sharayjah. The removal of K with garlic harvest exceeded its replacement through manure inputs in both Ash Sharayjah and Masayrat ar Ruwajah.

To determine the effects of temperature, irrigation, and manure quality on gaseous N and C emissions, a field study was conducted on maize (*Zea mays* L.) fields in the two mountain oases of Al'Ayn and Masayrat ar Ruwajah. Goat manure was applied in both oases at average rates of 33 and 29 tonnes ha^{-1} and C/N ratios of 18 and 16 in Al'Ayn and Musayrat ar Ruwajah. The higher air temperature in Masayrat ar Ruwajah resulted in higher net emission of all gases throughout the experimental period. Emissions of NH_3-N (118.9 g ha^{-1} h^{-1}) and N_2O-N (184.2 g ha^{-1} h^{-1}) were highest at Al'Ayn during the first day after manure application. Subsequently, these emissions decreased very fast and reflected changes in air temperature rather than soil moisture. In contrast, CO_2-C emissions were very high throughout the entire experimental period averaging 9.2 and 7.7 kg ha^{-1} h^{-1} in Masayrat ar Ruwajah and Al'Ayn, respectively. Emissions of CH_4-C were higher in Masayrat ar Ruwajah and showed a positive correlation with air temperature (r^2=0.647, P<0.001). The higher initial NH_3-N and N_2O-N emissions in Al'Ayn most likely reflected the higher rate of manure application with a higher C/N ratio and total N concentration. In Masayrat ar Ruwajah, the NH_3-N, N_2O-N, CO_2-C, and CH_4-C emissions were enhanced by air temperature (r^2=0.407, P<0.001, r^2=0.367, P<0.001, r^2=0.279, P<0.001, and r^2=0.647, P<0.001, respectively).

The results of this study indicated that water scarcity as a result of low precipitation and an increase in urban water consumption is a major threat to the sustainability of agriculture in these oases. The data also underline the intensive C and nutrient turnover in the man-made irrigated agroecosystems and confirmed the importance of the large manure quantities applied continuously to the terraces as a key factor responsible for sustainable soil productivity. To trace the fate of C and plant nutrients that are released from the large amount of manure applied by oasis farmers, more detailed studies under controlled conditions, using isotope signatures, would be needed.

Zusammenfassung

Seit 1970, als Sultan Qaboos bin Said Al Said die Herrschaft seines Vaters übernahm, hat die Landwirtschaft Omans aufgrund von raschen Zuwächsen der Wirtschaft und Bevölkerung weitreichende Veränderungen erfahren. Die Grundwasserentnahme für häusliche und landwirtschaftliche Zwecke hat in dieser Zeit dramatisch zugenommen .

Dem Agro-Ökosystem Bergoase in Oman wurde jüngst verstärkt Beachtung beigemessen, um die Ursachen der oftmals Jahrtausende alten und nachhaltigen Produktivität besser zu verstehen. Es ist vor allem wenig über den Kohlenstoff- und Nährstoffumsatz in diesem intensiv bewirtschafteten Landnutzungssystem bekannt, was in der Schwierigkeit von Messungen dieser Prozesse in abgelegenen Gebieten begründet liegt. Um diese Wissenslücke zu füllen, wurden Feldstudien in Oasen verschiedener Höhenlagen von Al Jabal Al Akhdar, dem höchsten, landwirtschaftlich genutztem Gebiet Omans, durchgeführt, die darauf abzielten Kohlenstoff- und Nährstoffflüsse als auch Nährstoffnutzungseffizienzen zweier Anbausysteme zu untersuchen, die durch Temperatur, Bewässerung und Düngerqualität beeinflusst werden.

Von 2007-2009 wurde repräsentative Landnutzungssysteme in den Bergoasen von Ash Sharayjah (57°39'30" E, 23°04'10" N, 1900 NN), Al'Ayn, (57°39'44" E, 23°04'22" N, 1900 NN), Al'Aqr (57°39'58" E, 23°04'22" N, 1950 NN), Qasha' (57°39'50" E, 23°04'00"N, 1640 NN) und Masayrat ar Ruwajah (57°40'13" E, 23°02'37" N, 1030 NN) beobachtet .

Die Ergebnisse zeigen, dass die bestellte Fläche von 2007-2009 für alle Oasen abnahm und für zwei Oasen (Qasha' und Masayrat ar Ruwajah) zwischen 2008 und 2009 leicht zunahm. In Ash Sharayjah nahmen die bestellten Flächen von 4,7 ha (32%) in 2007 auf 3,1 ha (22%) in 2008 und weiter auf 3,0 ha (21%) in 2009 ab. Gleichzeitig verringerte sich die Anbaufläche stetig in Al'Ayn von 0,9 ha (35,2%) auf 0,6 ha (25,6%) bzw. 0,5 ha (19,8%) von 2007 bis 2009. Im Gegensatz dazu nahm die Fläche in Qasha' und Masayrat ar Ruwajah von 0,9 und 1,6 ha (36,3 und 49,6%) in 2007 auf 0,2 und 1,1 ha (5,9 und 34,8%) in 2008 ab und stieg auf 0,3 und 1,4 ha (8,5 und 41,3%) in 2009 an. In der Al'Aqr Oase stieg die Anbaufläche von 0,3 ha (17,0%) in 2007 auf 0,7 ha (39,1%) in 2008 und sank wieder auf 0,5 ha (28,8%) in 2009 ab.

Um die Kohlenstoff- und Nährstoffflüsse zu beurteilen, wurde ein Bodensystembilanzansatz für ein- und mehrjährige Anbausysteme angewandt. In den

Oasen Ash Sharayjah und Masayrat ar Ruwajah wurden Knoblauchfelder (*Allium sativum* L.) ausgewählt und während zweier Anbauperioden (2008/09-2009/10) beobachtet. In Ash Sharayjah und Qasha' wurden Granatapfelfelder (*Punica garanatum* L.), in Masayrat Dattelpalmbestände (*Phoenix dactylifera* L.) ausgewählt und während eines Jahres (2009/10) beobachtet. Die Gesamtbilanzen wurden bestimmt, indem die Unterschiede der Gesamtmenge von C, N, P und K aller Ein- und Austräge, wie Ertragsentfernung bei der Ernte und der vertikale C- und Nährstoffverlust, errechnet wurden. Die kumulativen Auswaschungsverluste von mineralischem N und P wurden mit Mischbett-Ionenaustauscherharzkartuschen quantifiziert, wohingegen Gasemissionen von CO_2-C, CH_4-C, NH_3-N und N_2O-N mit einem photoakustischem Infrarot Multigasanalysegerät (INNOVA 1312-5, AirTech Instruments, Ballerup, Denmark) analysiert wurden.

In den zwei untersuchten Vegetationsperioden wurden auf die Knoblauchfelder von Ash Sharayjah und Masayrat ar Ruwajah im Durchschnitt Ziegendung in Raten von 47 bzw. 40 t Trockensubstanz ha^{-1} und 42 bzw. 37 t Trockensubstanz ha^{-1} angewandt. Granatapfelbäume in Ash Sharayjah und Qasha' erhielten Milchviehdung in Aufwandmengen von 66 bzw. 60 t Trockensubstanz ha^{-1}. Die jährlichen Gasemissionen von C und N reflektieren die hohen Anwendungsraten von Dung sowie die Temperaturunterschiede entlang des Höhengradienten der drei Oasen. Der jährliche C-Verlust durch die Emission wurde größtenteils in Form von CO_2-C emittiert, wohingegen CH_4-C einen Verlust von weniger als 2% ausmachte. Die jährliche C-Bilanz auf Knoblauchfeldern von Ash Sharayjah wies auf einen C-Überschuss von 12,5 t ha^{-1}, wohingegen einen Defizit von 5,5 t ha^{-1} auf Feldern von Masayrat ar Ruwajah erreicht wurde. Jährliche C-Überschüsse von 16,7, 7,5 und 1,7 t ha^{-1} wurden auf Granatapfel- und Dattelpalmpflanzungen von Ash Sharayjah, Qasha' bzw. Masayrat ar Ruwajah gemessen. Aufgrund hoher Dunggaben von 78 t ha^{-1} $Jahr^{-1}$ wiesen Dattelpalmpflanzungen die höchsten gesamt C-Überschusse von 1857 kg N ha^{-1} auf. Granatapfelpflanzungen von Ash Sharayjah und Qasha' wiesen ebenfalls hohe positive N-Bilanzen von 1414 und 1500 kg ha^{-1} im Vergleich zu Knoblauchfeldern in Ash Sharayjah (915 kg N ha^{-1}) auf. Die Entnahme von K mit der Ernte der Knoblauchfelder überstieg die Ausgleichsgabe durch Dung in Ash Sharayjah so wie in Masayrat ar Ruwajah.

Um den Effekt von Temperatur, Bewässerung und Düngerqualität auf die Emission von N und C zu bestimmen, wurde eine Feldstudie auf Maisfeldern (*Zea mays*

L.) in zwei Bergoasen, Al'Ayn und Masayrat ar Ruwajah, durchgeführt. In beiden Oasen wurde Ziegendung mit einer durchschnittlicher Applikationsrate von 33 und 29 t ha^{-1} und einem C/N-Verhältnissen von 18 und 16 in Al'Ayn bzw. Masayrat ar Ruwajah appliziert. Die höheren Lufttemperaturen spiegelten sich in Masayrat ar Ruwajah in höheren Nettoemissionen aller Gase während des gesamten Messzeitraumes wider. Die Emissionen von NH_3-N (118,9 g ha^{-1} h^{-1}) und N_2O-N (184,2 g ha^{-1} h^{-1}) waren in Al'Ayn während des ersten Tages der Düngerapplikation am höchsten. Danach nahmen diese Emissionen sehr stark ab und spiegeln Veränderungen der Lufttemperatur eher als die Veränderungen der Bodenfeuchte wieder. Im Gegensatz dazu waren die CO_2-C Emissionen während des gesamten Experimentzeitraumes mit durchschnittlich 9,2 bzw. 7,7 kg ha^{-1} h^{-1} in Masayrat ar Ruwajah und Al'Ayn sehr hoch. In Masayrat ar Ruwajah waren die CH_4-C-Emissionen höher und positiv mit der Lufttemperatur korreliert (r^2=0.647, P=0.000). Die anfänglich höheren NH_3-N und N_2O-N Emissionen in Al'Ayn spiegeln wahrscheinlich die höheren Raten an Düngerzugaben mit höherem C/N-Verhältnis und N-Gehalt wider. In Masayrat ar Ruwajah wurden die Emissionen von NH_3-N, N_2O-N, CO_2-C und CH_4-C durch höhere Lufttemperaturen (r^2=0,407, P=0,000, r^2=0,367, P=0,000, r^2=0,279, P=0,001 bzw. r^2=0,647, P=0,000) begünstigt.

Die Ergebnisse dieser Studie legen nahe, dass Wasserknappheit aufgrund von geringeren Niederschlägen und erhöhtem städtischen Verbrauch eine große Gefahr für die Nachhaltigkeit dieser Oasen darstellt. Die Daten bestätigen ebenfalls den intensiven C- und Nährstoffumsatz dieses künstlich bewässerten Agro-Ökosystems und bekräftigen die Wichtigkeit der hohen Düngemittelzugabe auf die künstlichen Terrassen als ein Schlüsselelement für nachhaltige Bodenfruchtbarkeit. Um den Verbleib von C und Nährstoffen zu verfolgen, der durch die hohen Düngergaben der Bauern dieser Oasen freigesetzt wird, sind weitere, ausführliche Studien mit Isotopenmarkierung unter kontrollierten Bedingungen nötig.

Chapter 1. General Introduction

1.1 Agriculture in Oman: Challenges for sustainability

Situated in the southeastern part of the Arabian Peninsula, Oman has an arid, hot climate with a mean annual temperature of 18°C in the high mountains and of 28°C in the lowlands, and with maximum daytime temperatures exceeding 40°C, all leading to potential evapotranspiration of >2000 mm (Nagieb et al. 2004; Luedeling and Buerkert 2008). In the country's hyperarid climate with annual rainfall < 100 mm except for the mountain ranges in the North and Dhofar in the South that is influenced by the Indian Summer Monsoon, agriculture is severely limited by the availability of irrigation water that consumes about 80-90% of the renewable fresh groundwater (Norman et al. 1998; Victor and Al-Farsi 2001). Aside from wells, the *Aflaj* system (Arabic: '*aflaj*' is plural of '*falaj*') is the main traditional source of irrigation water in Oman and has been considered the key sustainability factor for agricultural production over the past millennia (Norman et al. 1998; Siebert et al. 2007; Nash and Agius 2011). The *Aflaj* system is classified into three types: the *Dawudi falaj* where a long deep tunnel is excavated from the mother well and conveys water from the deep ground aquifer up to flow at the surface permanently; the *Ghayli falaj* which is fed from the water that has accumulated in the sediments of a *wadi* (valley); and the *Ayni falaj* which is directly fed from natural springs (Siebert et al. 2007). There are more than 4000 active *falaj* systems in Oman (Ghrefat et al. 2011).

The variation of annual precipitation is a major limiting factor of the sustainability of irrigated agriculture in Oman. A study comparing rainfall data collected over the past two decades has reported a negative annual precipitation trend (Kwarteng et al. 2009). Additionally, Omezzine and Zaibet (1998) found that water consumption in Oman exceeds long term recharge. Although the hydrological sustainability of the mountain oases of Al Jabal al Akhdar has been severely threatened over the past 20 years (Luedeling 2007), the high altitude groundwater of Al Jabal Al Akhdar and local infiltration along the wadi channels remain the main sources of water in the alluvial aquifer along the flow paths of *Wadi Mu'aydin* and *Wadi Abyadh* (Matter et al. 2005).

1.2 Mountain oasis agroecosystems

Over the last decade, many efforts have been made to understand the sustainability of the ancient mountain oases of Oman (Buerkert et al. 2005; Siebert et al.

2007; Luedeling and Buerkert 2008; Buerkert et al. 2010; Schlecht et al. 2010; Brinkmann et al. 2011). Agricultural terraces in the high altitude oases are planted with perennial crops such as pomegranate (*Punica garanatum* L.), rose (*Rosa damascene* Mill.), apricot (*Prunus armeniaca* L.), peach (*Prunus persica* L), walnut (*Juglans regia* L.), and annual crops like garlic (*Allium sativum* L.), alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.). The low altitude oases are dominated by perennial date palm (*Phoenix dactylifera* L.), banana (*Musa* AAA), papaya (*Carica papaya* L.), guava (*Psidium guajava* L.), and mango (*Mangifera indica* L.), and annual crops similar to those in other high altitude oases.

Crop and soil management practices as well as environmental parameters are important features in maintaining soil fertility on the man-made, silt-filled terraced fields of these oases. These different agricultural management and land use systems lead to differences in soil texture, structure, and soil organic matter (SOM) dynamics and composition (Nierop et al. 2001).

1.3 Soil organic matter

Soil organic matter (SOM) is the primary source of nutrients in any agro-ecosystem. It plays a very important role in improving soil texture, water holding capacity, and providing energy and nutrients for macro-/microorganisms and plants (Nyberg et al. 2006). It is well known that heterotrophic microbial communities in the soil are responsible for the decomposition and oxidization of SOM whereby organic substances are converted into inorganic ones and consequently nutrients are released and made available to plants (Kimetu et al. 2008). However, this process is affected by the characteristic of SOM, soil properties, macro-/microorganism communities, crop management practices, and environmental factors (Deng and Tabatabai 2000; Burgos et al. 2006). Microbial activity is altered by soil water which lead to the formation of aerobic and anaerobic conditions which affect mineralization pathways and formations (Franzluebbers 1999; De Neve and Hofman 2002; Cannovo et al. 2004).

Nitrogen (N) mineralization is the process by which organic N forms are converted into NH_4^+ and NO_3^- (Benbi and Richter 2002). Ammonification is the first step of N mineralization by which some heterotrophic microorganisms, mainly bacteria and in some cases fungi, hydrolyze proteins and nucleic acids, resulting in the liberation and conversion of amino acids and nitrogenous bases into NH_4^+ (Burger and Jackson 2003). Thereafter, NH_4^+ will undergo a stepwise process called nitrification, in which

Nitrosomonas oxidizes NH_4^+ to NO_2^- and *Nitrobacter* converts the NO_2^- into NO_3^-. According to Kladivko and Keeney (1987), water and temperature affect the rate of N mineralization, but soil pH also has an effect. An increase of soil pH will lead to an increase in N mineralization (Fu et al. 1987). In addition, the presence of plants in soils also stimulates soil N mineralization (Paré et al. 2000). Fisher and Gosz (1986) suggest that plant roots will increase microbial activity and N mineralization by increasing substrate, which may change the C:N ratio in the soil.

1.4 Gaseous emissions of C and N

Recently, gaseous emissions from agricultural soils have received greater attention than in the past due to the rapid rise of greenhouse gases in the atmosphere and their contribution to global warming (Gregorich et al. 2005). As a dynamic biological system, agricultural soils are responsible for approximately one-fifth of global annual emissions of greenhouse gases (Cole et al. 1997; Dobbie and Smith 2001; Velthof et al. 2005; Konda et al. 2008). Therefore, many working groups have started to investigate nutrient dynamics and gaseous losses of C and N in agro-ecosystems (Tucker and Westerman 1989; Grant et al. 2004; Varella et al. 2004; Predotova et al. 2010).

Carbon dioxide (CO_2) emissions from agricultural soils are attributed to root, microbial and faunal respiration and the oxidation of soil organic matter by soil microorganisms. Indeed, respiration is the process by which energy rich molecules such as glucose are oxidized and converted into usable energy for life processes. Although CO_2 emission from agricultural soils reflects biological activity, such as respiration, in the rhizosphere these activities do not reflect the possible abiotic contribution of CO_2 effluxes from the soil. Wichern et al. (2004) suggest that abiotic CO_2 emission from carbonate is mainly stimulated in soils with high carbonate levels and a pH above 8, and West and McBride (2005) maintain that these emissions are only produced by the reaction of $CaCO_3$ with HNO_3, which is formed during nitrification. Methane fluxes in agricultural soils are credited to the anaerobic decomposition of soil organic matter and methanogenic and methanotrophic activities of soil microbes. Conrad (1996) reported a significant relationship between high CH_4 emissions from wetland vegetation with high soil CO_2 concentrations. Total carbon emissions from soils therefore depend on both biotic and abiotic processes.

Nitrogen losses from soil are attributed to volatilization and to microbial activity during the processes of nitrification and denitrification (Bateman and Baggs 2005).

Ammonia (NH_3) and nitrous oxide (N_2O) are the main N forms that escape into the atmosphere from agricultural soil (Kirchmann et al. 1998). Studies suggest that high NH_3 volatilization from soils that have a pH above 7.0 is due to deprotonization of NH_4^+ (Fenn and Kissel 1973; Schlesinger and Peterjohn 1991; Ji and Brune 2006), whereas N_2O emission from agricultural soils is related to anaerobic soil conditions. During the denitrification process, heterotrophic bacteria and fungi reduce NO_3^- and NO_2^- to N_2O, NO or N_2 (Bateman and Baggs 2005). According to Saad and Conrad (1993), the denitrification process is stimulated by high soil water content which leads to anaerobic conditions. Other studies relate high N_2O emission to changes in temperature (Dobbie and Smith 2001). As a result of increasing temperatures and water levels in irrigated soils, microbial activity and respiration is stimulated, leading to greater consumption and depletion of soil oxygen (O_2) which triggers the development of anaerobic sites in such soils (Maag and Vinther 1999). Ruser et al. (2006) found high N_2O emissions as a result of denitrification in soils where water filled ≥70% of soil pore spaces (that is water filled pore space (WFPS) was ≥70%), and N_2 production occurred only at WFPS ≥90%. According to Ciarlo et al. (2007), the greatest N_2O emissions under laboratory conditions occurred at WFPS ≥80%. Although anaerobic denitrification is the main source of N_2O emissions, many studies reveal significant N_2O emissions through aerobic denitrification under conditions where O_2 is not limited (Bateman and Baggs 2005). For example, Patureau et al. (2000) isolated many bacterial strains capable of NO_3 respiration in the presence of O_2 from an ecosystem comprised of a mixture of different environments treated with natural and wastewater.

1.5 Leaching losses of plant nutrients

Application of organic amendments increases soil nutrient levels thereby meeting plant nutrition requirements. However, nutrient losses are expected to increase when soil organic matter is greater than agronomic needs. During the mineralization process, soil microorganisms transform organic compounds into inorganic forms such as NH_4^+, NO_3^-, PO_4^- and K^+. Leaching of such mobile nutrients can have severe environmental impacts. Nevertheless, there are several factors limiting leaching of these nutrients below the rooting zone. Quantity and frequency of irrigation have a significant effect (Zotarelli et al. 2007), and large-scale carbon amendments tend to decrease available soil mineral N and increase microbial biomass (Szili-Kovács et al. 2007). Burger and Jackson (2003) reported on the effectiveness of inducing microbial immobilization of

NH_4^+ and NO_3^- thereby reducing leaching losses through an only gradual release of inorganic N.

1.6 Research objectives

The present study was conducted in the five mountain oases of Ash Sharayjah (57°39'30" E, 23°04'10" N, 1900 m asl), Al'Ayn, (57°39'44" E, 23°04'22" N, 1900 m asl) and Al'Aqr (57°39'58" E, 23°04'22" N, 1950 m asl) which are located at the top of the large Wadi Mu'aydin watershed at the edge of the Sayq Plateau in the northern Hajar mountains of Oman. Below these three oases lies the oasis of Qasha' (57°39'50" E, 23°04'00"N, 1640 m asl) and the lowest oasis of the watershed is Masayrat ar Ruwajah (57°40'13" E, 23°02'37" N, 1030 m asl).

Research objectives were: (i) to estimate the impact of precipitation and local water demand on land use changes; (ii) to determine the effects of temperature, irrigation cycles, and manure quality on C and nutrient fluxes under different oasis cropping systems; and (iii) to calculate total C and nutrient balances including gaseous and leaching losses of C and N. The above mentioned oases were selected due to their representative character reflecting altitudinal differences in typical oasis agriculture of northern Oman. The following research hypotheses were tested:

1. Variations of annual precipitation as well as the unsustainable exploitation of fresh groundwater affect landuse patterns.
2. Carbon and nutrient turnover rates are faster at low altitude oases due to their higher temperature and shorter irrigation cycles.
3. Under the hot and arid conditions of the study area gaseous losses of N and C are higher than leaching losses.
4. Gaseous N and C emissions vary strongly with air temperature, manure quality, and soil moisture.

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Chapter 2. Effects of changing water availability on landuse in mountain oases of northern Oman[1]

Abstract

In Oman during the last three decades, agricultural water use and groundwater extraction has dramatically increased to meet the needs of a rapidly growing population and major changes in lifestyle. This has triggered agricultural land use changes which have been poorly investigated. The purpose of this study therefore was to examine patterns of short-term land use changes (2007-2009) in the irrigated mountain oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha', and Masayrat ar Ruwajah in the northern Oman Hajar mountains of Al Jabal Al Akhdar. To this end comprehensive GIS-based field surveys were conducted over three years to record changes in terrace use in these five oases in which farmers have traditionally adapted to rain-derived variations in irrigation water supply such as in drought years by leaving agricultural terraces of annual crops uncultivated. Results show that the area occupied with field crops decreased in the year 2009 for all oases. In Ash Sharayjah, terrace areas grown with field crops have declined from 4.7 ha (32.4% of total terrace area) in 2007 to 3.1 ha (21.6%) in 2008 and 3.0 ha (20.5%) in 2009. Similarly, the area proportion of field crops has shrunk in Al'Ayn, Qasha', and Masayrat from 35.2, 36.3, and 49.6% in 2007 to 19.8, 8.5, and 41.31% in 2009, respectively. In Al'Aqr, the area of field crops slightly increased from 0.3 ha (17.0%) in 2007 to 0.7 (39.1%) in 2008, and decreased to 0.5 ha (28.8%) in 2009. During the same period annual dry matter of the indicator crop garlic (*Allium sativum* L.) in Ash Sharayjah varied from 16.3 t ha^{-1} in 2007 to 19.8 t ha^{-1} in 2008 and 18.3 t ha^{-1} in 2009, while the same crop yielded only 0.4, 1.6, and 1.1 t ha^{-1} in Masayrat. In 2009, the total estimated agricultural area of the new town of Sayh Qatanah above the five oases was around 13.5 ha. Our results suggest that scarcity of irrigation water as a result of low precipitation and increased water consumption in the new urban settlements above the five oases may lead to major shifts in the landuse pattern and threaten the sustainability of agriculture in these oases.

Keywords: *Aflaj*; Al Jabal Al Akhdar; irrigation water; nutrient balance; rainfall.

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2.1 Introduction

Given hyperarid conditions and annual rainfall between < 100 mm to 318 mm (Fisher, 1994), agriculture in Oman depends mainly on mountain spring and groundwater irrigation thereby consuming about 80-90% of the country's renewable fresh water resources on 2% of its land surface (Norman et al. 1998; Victor and Al-Farsi 2001; Nagieb et al. 2004). After an analysis of a 27 year rainfall record (1977-2003) from Oman Kwarteng et al. (2009) reported a negative trend in the total amount of annual precipitation which aggravates the findings of a study conducted in the costal Al Batinah plain suggesting that the current level of water consumption exceeds the long term recharge (Omezzine and Zaibet 1998). Variation of annual precipitation is thus a major factor limiting the sustainability of irrigated agriculture (Luedeling et al. 2005).

In recent years, the apparent sustainability of the often millennia-old oasis systems of the northern Omani Hajar mountains has raised considerable scientific interest (Wichern et al., 2004; Luedeling et al. 2005, 2008; Siebert et al. 2007, Golombek et al. 2007). Farmers in these oases irrigate their terraced agricultural area using the ancient *Aflaj* irrigation system which is directly fed by natural springs. The management of the *Aflaj* system (Arabic: '*aflaj*' is plural of '*falaj*') is considered a key factor in the sustainability of agricultural production in Oman (Norman et al. 1998; Siebert et al. 2007; Nash and Agius 2011). In recent decades, these mountain oases have undergone social and economic transformations leading to more pressure on water resources. The rapid growth of the population, changes in people's lifestyle and irrigation of non-agricultural areas for landscaping have (at least outside of the Muscat Metropolitan Area where waste water and desalinized water are increasingly used to sustain plant growth) led to a widespread increase in water demand (Rajmohan et al. 2007). In the oases this can lead to major modifications in land use whose severity largely depends on changes in water flow from the springs. Understanding such farmer managed adaptations in land use and cropping patterns over a time is an interesting research topic as it strongly determines the resilience of oasis agriculture (Alemayehu et al. 2009).

For the oases of the Wadi Muyadin watershed on Al Jabal al Akhdar, a previous study of Luedeling and Buerkert (2008), using data from 1978 to 2005, indicated an expansion of land planted with perennial trees, which leads to a putative increase in water demand. Our study aimed at verifying this trend by studying annual patterns of land use change during the period of 2007 to 2009 in the same mountain oases of Ash

Sharayjah, Al’Ayn, Al’Aqr, Qasha’, and Masayrat ar Ruwajah. We hypothesized that variation of annual precipitation as well as the increasing exploitation of fresh water for residential purposes at the top of the watershed embracing these oases have a direct impact on the variability of irrigation water and subsequent land use.

2.2 Materials and methods

2.2.1 Site description

The study focuses on land use changes in the five major oases of the heavily eroded Wadi Muyadin watershed streching below the rapidly growing town of Sayh Qatanah on the Sayq Plateau: Ash Sharayjah (57°39’30” E, 23°04’10” N, 1900 m asl), Al’Ayn (57°39’44” E, 23°04’22” N, 1900 m asl) and Al’Aqr (57°39’58” E, 23°04’22” N, 1950 m asl) are near the edge of the plateau (Figure 1). Below these three oases lies the oases of Qasha' (57°39’50” E, 23°04’00”N, 1640 m asl) and the lowest oasis of the watershed is Masayrat ar Ruwajah (57°40’13” E, 23°02’37” N, 1030 m asl). The total terraced agricultural area in Ash Sharayjah is about 14.4 ha, while the agricultural area of Al’Ayn and Al’Aqr is about 2.5 and 1.7 ha, respectively. Farmers in the high altitude oases irrigate their terraces from two springs that emerge from the oasis of Al'Ayn, while in the lower oasis of Masayrat (3.3 ha), water is supplied by an irrigation dam. Qasha' contains about 2.6 ha of terraced fields and also obtains its water from one of the springs of Al'Ayn, from where the water flows through a steep channel down to the oasis.

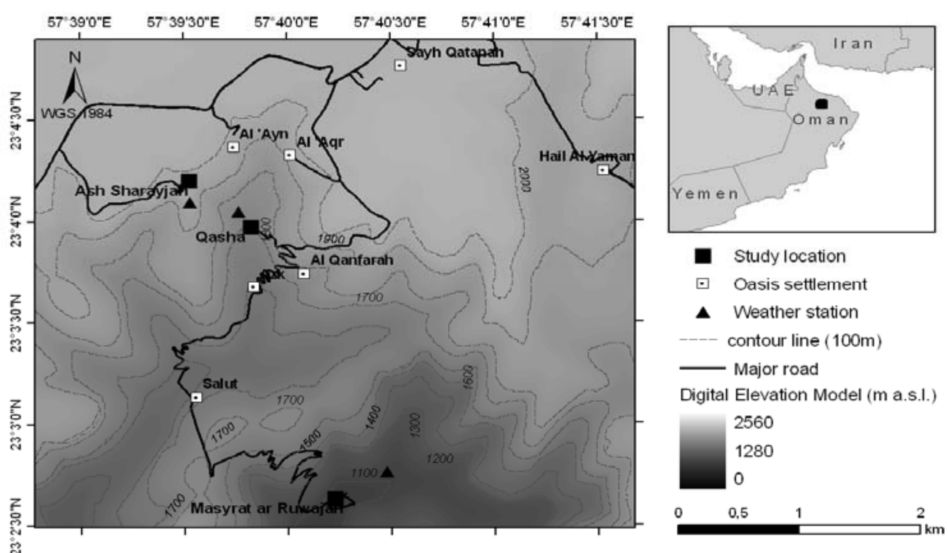
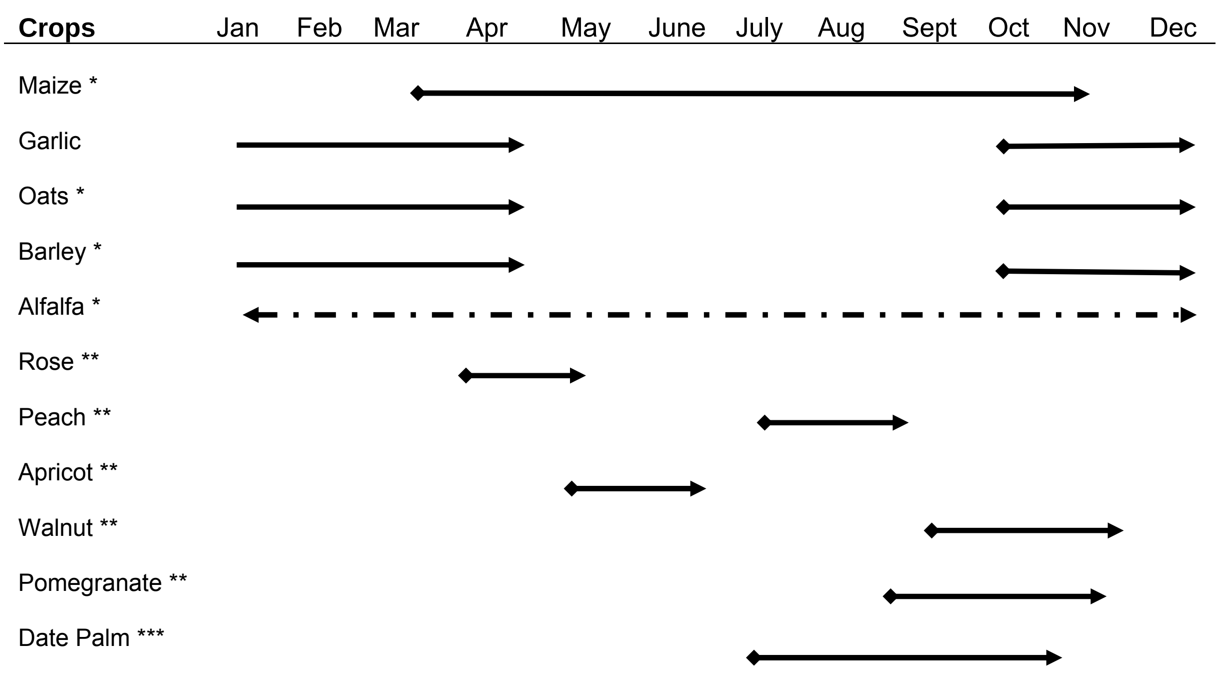


Figure 1. Relief map based on 100 m digital elevation model of Al Jabal Al Akhdar Mountain,

Agricultural terraces in the four high altitude oases are planted with perennial crops such as pomegranate (*Punica garanatum* L.), rose (*Rosa damascene* Mill.), apricot (*Prunus armeniaca* L.), peach (*Prunus persica* L), walnut (*Juglans regia* L.), apple (*Malus domestica* L. Borkh.), plum (*Prunus domestica* L.), pear (*Pyrus communis* L.), fig (*Ficus carica* L.), and grape (*Vitis vinifera* L.), and with annual crops such as garlic (*Allium sativum* L.), alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.).

The low altitude oasis of Masyrat ar Ruwajah is dominated by the typical three storey arrangement of date palm (*Phoenix dactylifera* L.), lime (*Citrus aurantiifolia* L.), sweet lime *(Citrus limettioides* Tan.), bitter orange (*Citrus aurantium* L.), citron (*Citrus medica* Burm.), orange (*Citrus sinensis* Osbeck), lemon (*Citrus lemon* (L.) Burm. f.), banana (*Musa* AAA), papaya (*Carica papaya* L.), guava (*Psidium guajava* L.), mango (*Mangifera indica* L.), and annual crops that are similar to those in the high altitude oases (Table 1).

Table 1. Annual and perennial crops calendar at the oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha', and Masayrat ar Ruwajah, on Al Jabal Al Akhdar, northern Oman.



* Harvested as green animal fodder.

** Grown only in the high altitude oases.

*** Grown only in low land oases.

2.2.2 Irrigation water supply and climatic conditions

Water flow rates of all relevant springs in the watershed were measured using the methodology described by Nagieb et al. (2004). Because of the strong flow rate and difficult topography, the flow of the irrigation water to Ash Sharayjah and Masayrat was estimated by measuring 10 times the speed of a floating device on the main irrigation channel of a known diameter. For the spring fed terraces of Al’Ayn, Al’Aqr and Qasha', measurements were based on a volumetric (barrel) method. To monitor soil moisture as affected by irrigation cycles in one of the six garlic plots at Ash Sharayjah, a soil moisture tension probe was installed at 20 cm depth and connected to a WatchDog® 200 data logger (Spectrum Technologies, Inc., Plainfield, IL, USA) which recorded moisture readings at 30 min intervals. These data enabled us to calculate the beginning of each irrigation cycle on the field and to compute the total number of irrigation cycles and seasonal variations. Watchdog® weather stations (Spectrum Technologies Inc., Plainfield, IL, USA) were placed at representative locations in Ash Sharayjah and Masayrat oases to record climatic data throughout the study period. In Qasha', air temperature was recorded at 30 min intervals throughout the research period using Hobo-Pro® climate loggers (Onset Corp.; Bourne, MA, USA). In addition, climatic data of previous years was collected from the Ministry of Transport and Communications, Directorate General of Civil Aviation and Meteorology, Sultanate of Oman.

2.2.3 Horizontal C and nutrient balances

In garlic fields, horizontal nutrient and carbon balances were determined for two growing seasons (2008/09-2009/10) by calculating the differences between the total amounts of carbon (C), nitrogen (N), phosphorus (P) and potassium (K) in all inputs such as manures, planted garlic cloves, irrigation water, and rainfall, and outputs such as crop removals at harvest. In order to account for the contribution of roots to C balances, total amount of photosynthetic C was estimated by multiplying total harvested DM by a factor of 1.4 based on the assumption that 30% of the total assimilated C was allocated to root DM and exudation (Kuzyakov and Domanski, 2000). To determine C, N, P and K concentration of the crops, three plants were collected as subsamples from each subplot. Samples were oven dried at 60°C, ground (2 mm), and analysed for C, N, P and K. Total C and N were analysed with a thermal conductivity detector (Vario MAX CHN Analyser, Elementar Analysensysteme GmbH, Hanau, Germany). Total P was analyzed after dry-ashing procedure by spectrophotometry (U-2000, Hitachi Ltd, Tokyo, Japan) using the Vanado-Molybdate method, whereas K content was measured by flame photometry (743 AutoCal, Instrumentation Laboratory Co, Lexington, MA, USA). For samples of irrigation water, of which frequency and amounts were determined regularly, dissolved organic carbon (DOC) and total N were determined using a Dimatec 100® CHN-Analyzer (Dimatec Analysentechnik GmbH, Essen, Germany).

2.2.4 Land use changes

All mapping was based on geo-referenced high resolution aerial images taken by a remotely controlled plane (Schaeper and Laemmlein, 2004; Schaeper, 2006) and major ground truthing that led to cadastral maps of the oasis areas (Luedeling et al., 2008). The distribution of land use type per oasis was assessed based on the absolute area (ha) and its percentage of the total oasis area. Agricultural land uses were categorized into five types: (1) abandoned, (2) fallow, (3) trees and crops, (4) only crops and (5) only trees. Changes in field crop area were assessed separately for major crops. In order to calculate changes on annual yields of indicator crops, six garlic fields were selected in Ash Sharayjah and Masayrat as a winter crop and monitored for two growing seasons (2008/09-2009/10). Similarly, six maize (*Zea mays* L.) fields were selected in the same oases during the summer season of 2009. In order to calculate total fresh yield per area, yields of three subplots of 1 m^2 size were determined for each field.

2.2.5 Estimation of new agricultural areas at Sayh Qatanah

To calculate the total new irrigated agricultural areas of Sayh Qatanah, Google satellite images were used (Imagery date: 19/03/2009, GeoEye-1). Agricultural areas were classified into five categories: (i) larger areas comprising military and other governmental buildings, mosques, and hotels, (ii) houses with intensive, (iii) medium, (iv) small scale backyard agriculture, and (v) Sha'biah housing blocks where green areas are smaller than around other houses. The size of larger areas was measured using the area calculator of Free Map Tools (http://www.freemaptools.com/area-calculator.htm), while houses were counted into the previously mentioned categories and multiplied by the average agricultural area for each category.

2.2.6 Statistical analysis

Data were statistically analyzed with SPSS version 17.0 (SPSS Inc., Chicago, USA), while graphs were made with Sigma Plot 10.0. Differences between the two growing seasons were tested with paired t-tests at $P < 0.05$. Data of which residuals were not normally distributed were log-transformed before statistical analysis.

2.3 Results

2.3.1 Climatic conditions and irrigation water supply

Average ambient air temperature was 19.6 ^oC at Ash Sharayjah, 21.0 ^oC at Qasha', and 24.7 ^oC at Masayrat (Figure 2). In the years 2008 and 2009, annual rainfall was below the 312 mm long-term average (Brinkmann et al. 2011). During the three study years annual rainfall varied widely. In 2008 and 2009, precipitation totaled 90 and 205 mm at Ash Sharayjah and 31 and 224 at Masayrat, while in 2010 more rainfall events occurred and annual precipitation totaled 639 and 379 mm at Ash Sharayjah and Masayrat, respectively (Figure 4).

Overall flow rates of irrigation water were substantially higher in 2007 than in 2008 and 2009 (Figure 5), even if in each year high flow rates were measured immediately after rainfall events. The high water flow rates in 2007 and 2010 reflected heavy precipitation events which occurred as a result of summer cyclones and storms (Figure 5). In all cases, spring flow rates quickly deceased only a few months after such heavy summer rainfall events.

From March to November 2009 water flow rates were substantially higher at Masayrat than at Ash Sharayjah. Throughout 2009 the average amount of irrigation water supplied to the cultivated area (annual and perennial) of Ash Sharayjah was 17,453 $m^3\ ha^{-1}\ year^{-1}$, whereas the oases of Al'Ayn, Al'Aqr, Qasha' received an average of 23,959 $m^3\ ha^{-1}\ year^{-1}$, and irrigated cropland in Masayrat 57,231 $m^3\ ha^{-1}\ year^{-1}$. Soil moisture measurements conducted in the garlic field in Ash Sharayjah showed 15 irrigation events with intervals of 5 – 17 days in 2008 (surface soil moisture varied from 14 – 134 kPa), while 13 events were recorded in 2009 with soil moisture tension varying from 20 – 200 kPa (Figure 6).

In Ash Sharayjah, a linear regression analysis revealed that precipitation significantly (r^2=0.31, P=0.006) enhanced water flow rate from the spring.

2.3.2 Horizontal C and nutrient balances

In Ash Sharayjah, the application of goat manure to garlic fields decreased from 47 t DM ha^{-1} during the growing season 2008/2009 to 40 t DM ha^{-1} in 2009/2010.

Similarly, goat manure was applied to garlic fields in Masayrat at an average application rate of 42 and 37 t DM ha^{-1} during the two years growing seasons. Consequently, average annual inputs of C and N from manure decreased in the year 2009/2010 (Table 4). Although our data indicated significant difference of P and K partial balance between the two growing seasons (*P*=0.037), annual average C and nutrient exported with garlic yield during the two seasons were not significantly different in both oases (P>0.05).

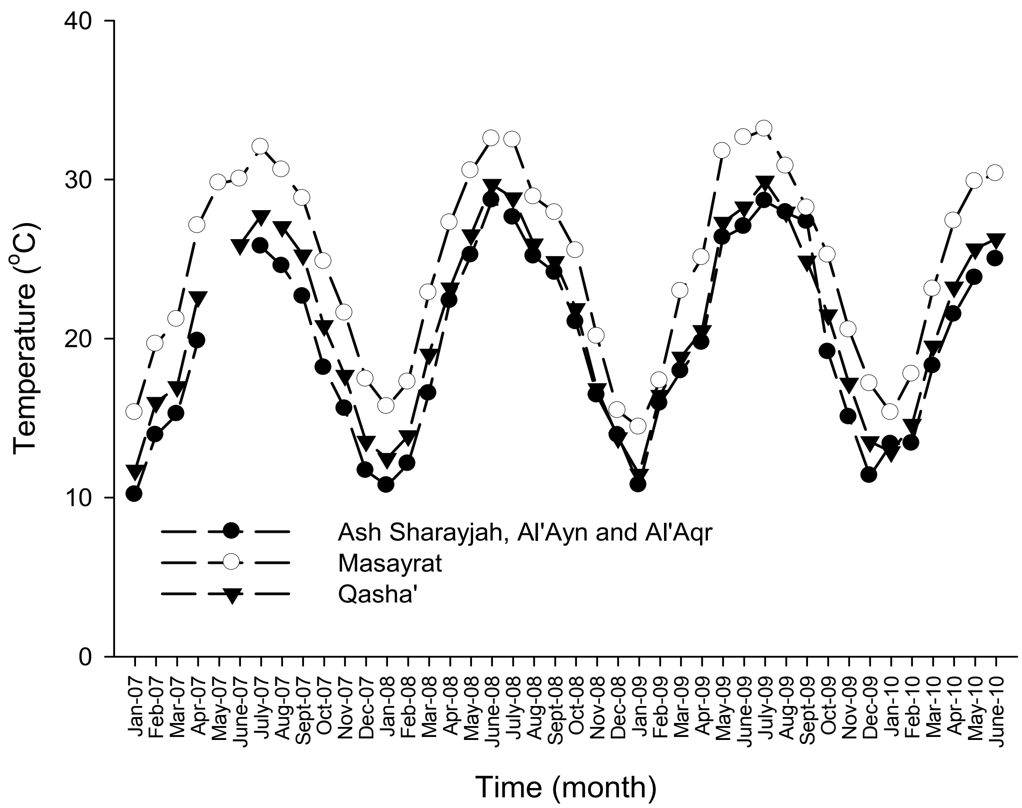


Figure 2. Mean monthly air temperatures recorded at the oases of Ash Sharayjah, Al'Ayn, Al'Aqr Qasha', and Masayrat ar Ruwajah in northern Oman during the research period (January 2007-June 2010).

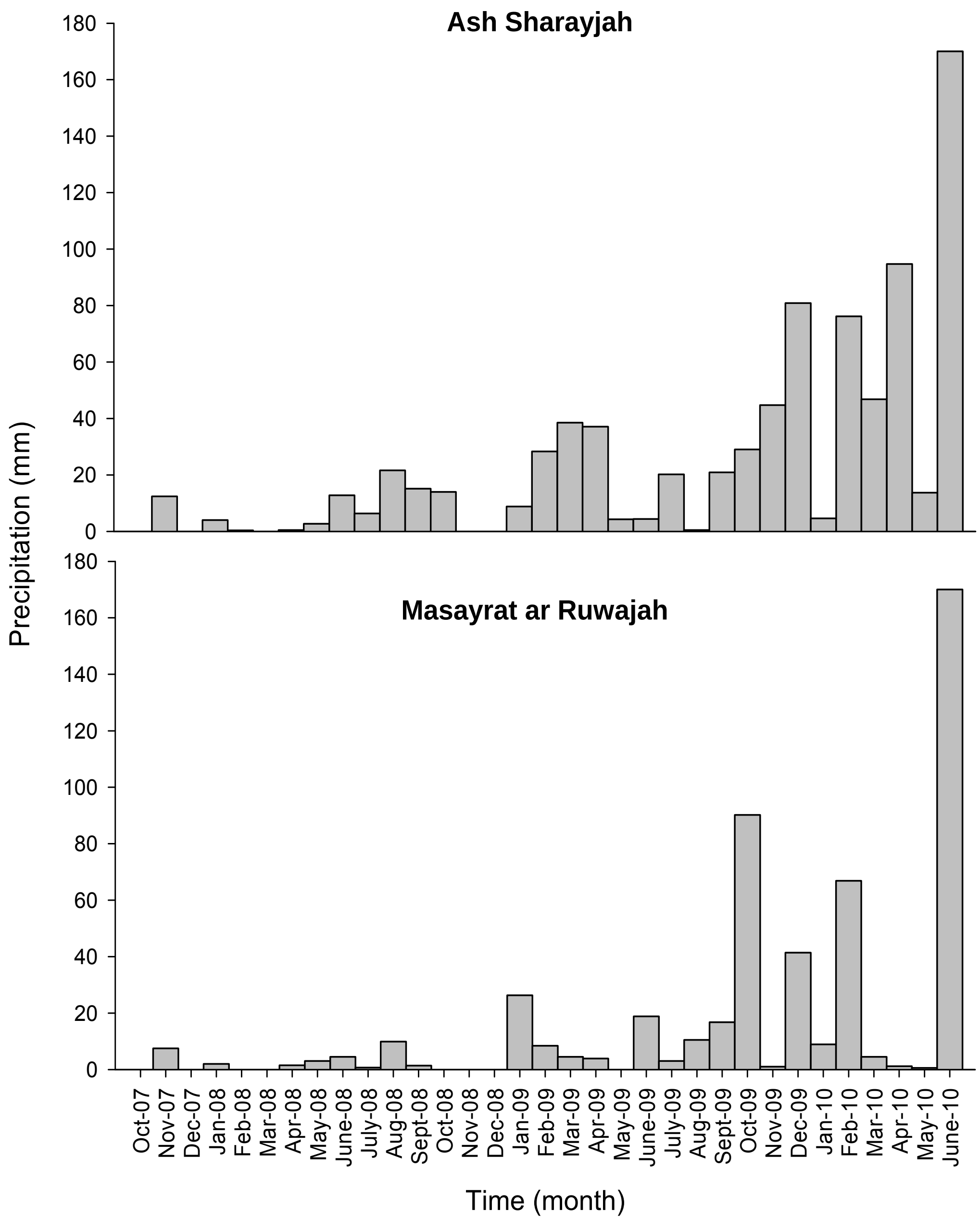


Figure 3. Average monthly rainfall (mm) recorded at the oases of Ash Sharayjah and Masayrat ar Ruwajah in northern Oman from October 2007 to June 2010.

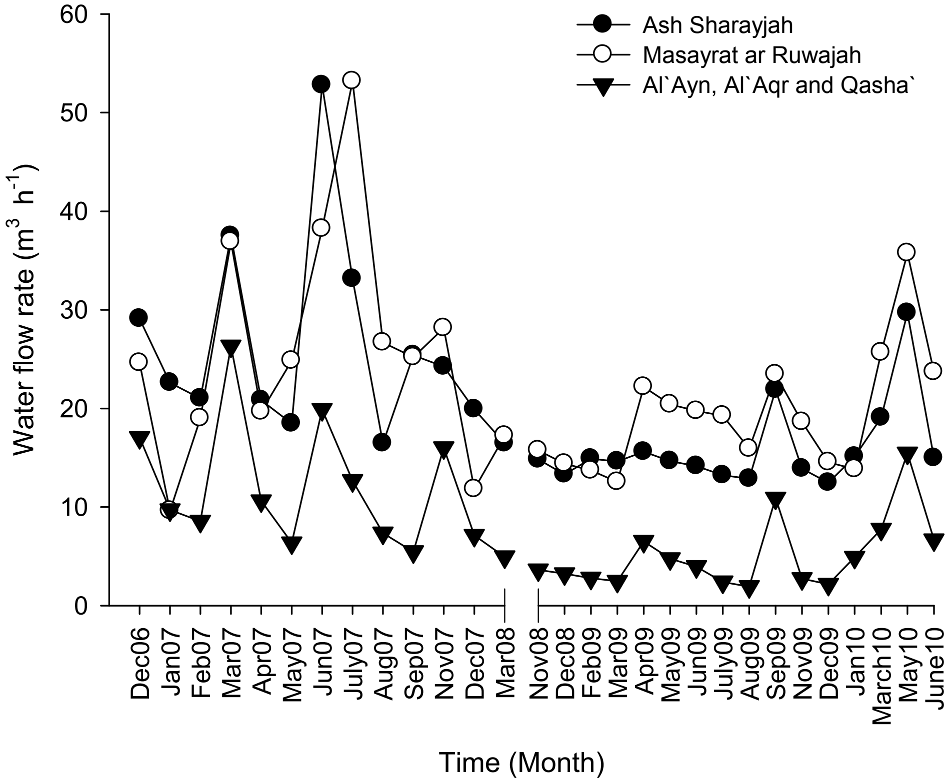


Figure 4. Water flow rate from springs supplying oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha', and Masayrat ar Ruwajah in Wadi Muaydin, northern Oman.

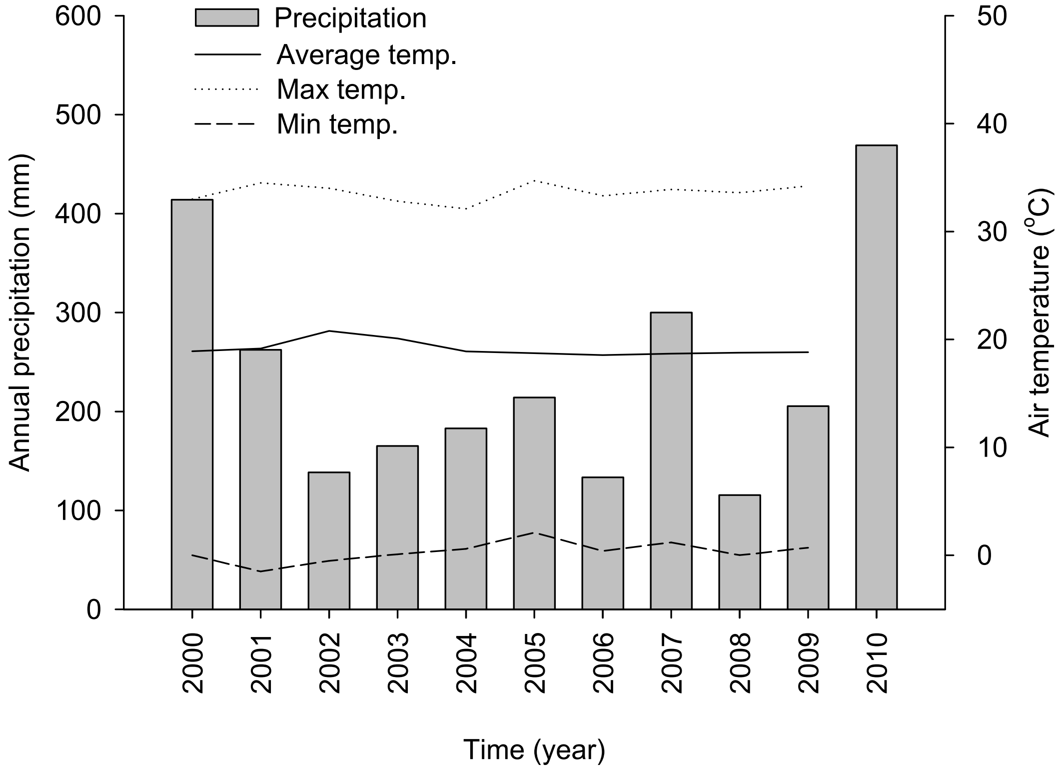


Figure 5. Annual precipitation, average, maximum, and minimum air temperature from 2001 to 2010 at Sayh Qatanah, Al Jabal al Akhdar, northern Oman. (Source: Ministry of Transport and communications, Directorate General of Civil Aviation and Meteorology, Sultanate of Oman).

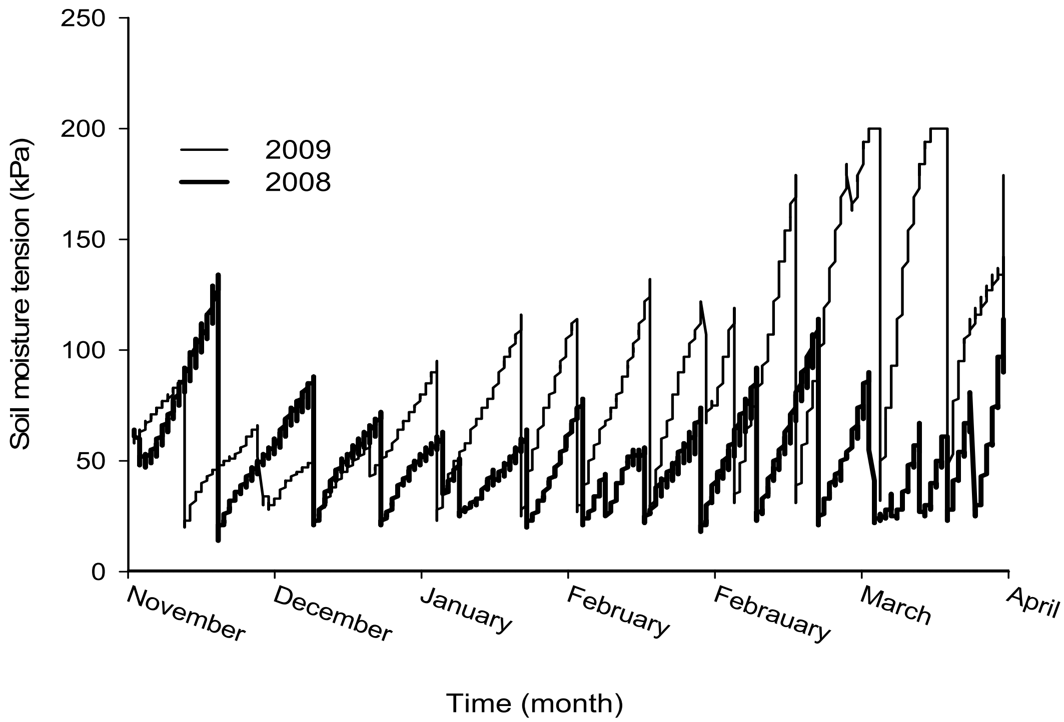


Figure 6. Soil moisture tension curve under garlic fields grown in two seasons (2008 / 2009) in the oasis of Ash Sharayjah, Wadi Muaydin, northern Oman.

2.3.3 Land use changes

Mixed fields (trees and crops) occupied 4.5, 0.9, 0.4, 0.8, and 1.3 ha (31.5, 37.2, 24.4, 29.1, and 38.1%) in 2007 and 2.8, 0.4, 0.6, 0.2, and 1.3 ha (19.7, 14.5, 33.6, 8.8, and 40.8%) in 2009 of the total areas of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha', and Masayrat, respectively. Meanwhile, in Ash Sharayjah the area of terraces with only trees increased from 1.8 ha (12.7%) of the total area in 2007 to 4.8 ha (33.5%) in 2008 and 24.1 ha (8.3%) in 2009. Similarly, in Masayrat, fields with only trees occupied less than 0.9 ha (26.8 %) in 2007, 1.2 ha (36.3%) in 2008, and 1.1 ha (36.2%) in 2009.

In contrast, in Ash Sharayjah, the area of terraces grown to field crops (barley *Hordeum vulgare* L., garlic, maize and oat *Avena sativa* L., alfalfa *Medicago sativa* L. other fodder crops and small amounts of vegetables) decreased gradually from from 4.7 ha (32.4%) in 2007 to 3.1 ha (21.6%) in 2008 and 3.0 ha (20.5%) in 2009 (Table 2).

Annual dry matter yield and C, N, P and K exported with garlic and maize crops (Table 3) were extrapolated for the total growing area in Ash Sharayjah and Masayrat ar Ruwajah. In Ash Sharayjah, the garlic fields totaled around one hectare throughout the research period resulting in a total annual dry matter yield of 16.3 t in 2007, compared to 19.8 t in 2008, and 18.3 t in 2009. Meanwhile, garlic fields in Masayrat occupied only 230, 890 and 600 m^2 and produced total annual dry matter yields of 0.4, 1.6, and 1.1 t during the years 2007, 2008, and 2009, respectively (Figure 7). In summer, maize was grown as a fodder crop and harvested within 40-50 days. This allowed 4-5 cropping cycles in the high altitude oasis and 5-6 cropping cycles in Masayrat and total annual maize dry matter yields in Ash Sharayjah of 86.0, 21.5, 80.5 t $year^{-1}$, whereas they were 30.0, 20.4, 32.4 t $year^{-1}$ in Masayrat for 2007, 2008 and 2009, respectively.

2.3.4 New agricultural area of Sayh Qatanah

In 2009, the total estimated irrigated agricultural area of the sprawling new urban settlement of Sayh Qatanah amounted to 13.5 ha. Around 8.4 ha (61%) of this area consisted of backyard house gardens, while 2.8 ha (20.7%) and 2.3 ha (17.1%) were newly established gardens in the Military camp and governmental buildings, respectively.

Table 2. Land use changes of annual crops grown at the oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha', and Masayrat ar Ruwajah, Wadi Muaydin, northern Oman, from 2007-2009.

Oases	**Crops**	**2007** Area (m^2)	%	**2008** Area (m^2)	%	**2009** Area (m^2)	%
Ash Sharayjah	Alfalfa	135	0.3	180	0.6	0	0.0
	Barley	17985	38.7	4980	16.0	3113	10.6
	Garlic	8694	18.7	10571	34.1	9769	33.2
	Maize	13860	29.8	3449	11.1	12987	44.1
	Oats	4243	9.1	11607	37.4	3324	11.2
	Other fodders	1147	2.5	195	0.6	70	0.2
	Vegetables	415	0.9	64	0.2	202	0.7
	Total area	**46479**	**100.0**	**31046**	**100.0**	**29465**	**100.0**
Oasis area	14.36 ha	**32.4%**		**21.6%**		**20.5%**	
Al'Ayn	Alfalfa	887	10.0	458	7.1	297	5.96
	Barley	3096	34.9	327	5.1	843	16.89
	Garlic	1591	17.9	978	15.2	1161	23.28
	Maize	238	2.7	2405	37.2	1809	36.27
	Oats	2655	29.9	2097	32.6	878	17.60
	Other fodders	307	3.5	113	1.8	0	0.00
	Vegetables	99	1.1	62	1.0	0	0.00
	Total area	**8873**	**100.0**	**6440**	**100.0**	**4988**	**100.0**
Oasis area	2.52 ha	**35.2%**		**25.6%**		**19.8%**	
Al'Aqr	Alfalfa	62	2.1	42	0.6	0	0.0
	Barley	455	16.0	738	11.3	2091	43.3
	Garlic	585	20.5	2499	38.0	645	13.4
	Maize	66	2.3	1850	28.1	615	12.7
	Oats	1684	59.1	1447	22.0	1470	30.4
	Other fodders	0	0.0	0	0.0	0	0.0
	Vegetables	0	0.0	0	0.0	11	0.2
	Total area	**2852**	**100.0**	**6576**	**100.0**	**4832**	**100.0**
Oasis area	1.68 ha	**17.0%**		**39.1%**		**28.8%**	
Qasha'	Alfalfa	0	0.0	0	0.0	0	0.0
	Barley	1533	16.5	23	1.5	62	2.9
	Garlic	1369	14.7	886	58.3	0	0.0
	Maize	3953	42.6	187	12.3	1629	75.3
	Oats	1210	13.0	12	0.8	0	0.0
	Other fodders	623	6.7	200	13.1	345	15.9
	Vegetables	598	6.5	214	14.1	128	5.9
	Total area	**9286**	**100.0**	**1522**	**100.0**	**2164**	**100.0**
Oasis area	2.56 ha	**36.3%**		**5.9%**		**8.5%**	
Masayrat	Alfalfa	911	5.6	601	5.2	51	0.4
	Barley	976	6.0	223	2.0	0	0.0
	Garlic	232	1.4	889	7.8	598	4.4
	Maize	5333	32.8	3607	31.6	5710	42.1
	Oats	2271	14.0	1287	11.2	274	2.0
	Other fodders	6245	38.4	4402	38.5	6851	50.6
	Vegetables	304	1.8	417	3.7	67	0.5
	Total area	**16272**	**100.0**	**11426**	**100.0**	**13551**	**100.0**
Oasis area	3.28 ha	**49.6%**		**34.8%**		**41.3%**	

Table 3. Average dry matter yield of garlic and maize in the oases of Ash Sharayjah (Sh) and Masayrat (Ma), Wadi Muaydin, northern Oman, 2008-2009.

Crop	Oases	Average Yield	C	N	P	K
		t DM ha^{-1}	------------------------------%------------------------------			
Garlic	Sh	18.679	43.6	2.9	0.5	4.0
	Ma	17.946	43.7	2.8	0.7	4.0
Maize	Sh	12.383	44.8	2.2	0.3	2.2
	Ma	9.429	44.6	1.8	0.4	1.5

2.4 Discussion

Our data show that farmers adapt to changes in rainfall and subsequent spring flow by adjusting their area planted to field crops, whereby timing and quantity of precipitation play a major role. When evaluating the groundwater recharge caused by the tropical cyclone Gonu, which hit Oman in 2007, Abdalla and Al-Abri (2010) found that frequent precipitation events cause more significant groundwater recharge than a single major cyclonic event, because the lower surface run-off during the former leads to a more efficient infiltration.

In our study winter precipitation had a direct impact on garlic cultivation by maintaining desirable water supply during the period before harvesting. Consequently, farmers diverted the water available in winter to growing garlic, and thus water scarcity first affected areas planted to barley and oats. Water scarcity effects were particularly severe in Qasha' resulting in a major reduction of the area planted to annual crops: from 36.3% of the total oasis area in 2007 to 8.5% in 2009. In 2009, farmers were not able to grow garlic at all (Figure 7).

From their analysis of a time series of aerial photographs of 1975-2005 Luedeling and Buerkert (2008) concluded that long-term landuse of the Al Jabal Al Akhdar oases shifted towards perennial trees which caused a higher vulnerability of the systems to changes in water availability. In our study, irrigation frequency was higher and water tension lower in 2008 than in 2009, indicating farmers' efforts to cope with increasing water scarcity while sacrificing yield (Figure 6).

Table 4. Annual horizontal inputs, outputs and partial balances of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) for garlic fields (n = 6) at the oases of Ash Sharayjah and Masayrat ar Ruwajah in northern Oman (2008/09 – 2009/10). Partial balances values with different superscript letters and stars were significantly different (paired T-test at $P < 0.05$)

			Input and output (kg ha^{-1} yr^{-1})			
Oases	**Season**	**Source**	**C**	**N**	**P**	**K**
Sharayiah	2008/09	Manure	43119.2	2086.9	280.0	1265.4
		Cloves (sowing)	15.6	1.1	0.2	1.2
		Irrigation water	44.3	61.2	0.0	0.3
		Rainfall	162.1	33.6	n.a	n.a
		Photosynthetic C	24222.1			
		Total	**67563.3**	**2182.8**	**280.2**	**1266.9**
		Crop yield	17301.5	1180.5	193.1	1318.4
		Partial balance	**50261.8**	**1002.3**	**87.2**^{b}	**-51.5**^{b}
	2009/10	Manure	34143.8	1915.6	354.3	1076.4
		Cloves (sowing)	15.7	1.0	0.2	1.7
		Irrigation water	37.7	52.2	0.0	0.3
		Rainfall	162.1	33.6	n.a	n.a
		Photosynthetic C	21319.8			
		Total	**55679.2**	**2002.4**	**354.5**	**1078.4**
		Crop yield	15228.4	958.0	189.2	1654.0
		Partial balance	**40450.7**	**1044.3**	**165.3**^{a}	**-575.6**^{a}
Masayrat	2008/09	Manure	41821.3	2100.1	276.1	849.0
		Cloves (sowing)	15.7	1.0	0.2	1.4
		Irrigation water	123.2	104.5	0.0	0.5
		Rainfall	113.0	13.1	n.a	n.a
		Photosynthetic C	23506.3			
		Total	**65579.6**	**2218.7**	**276.4**	**850.9**
		Crop yield	16790.2	1100.9	264.0	1484.6
		Partial balance	**48789.3**	**1117.7**	**12.4****	**-633.7****
	2009/10	Manure	34442.0	1655.3	336.0	1061.0
		Cloves (sowing)	15.8	1.0	0.2	1.5
		Irrigation water	118.7	100.6	0.0	0.5
		Rainfall	113.0	13.1	n.a	n.a
		Photosynthetic C	20419.2			
		Total	**55108.6**	**1770.0**	**336.3**	**1062.9**
		Crop yield	14585.1	921.1	224.5	1369.8
		Partial balance	**40523.5**	**849.0**	**111.8*****	**-306.8*****

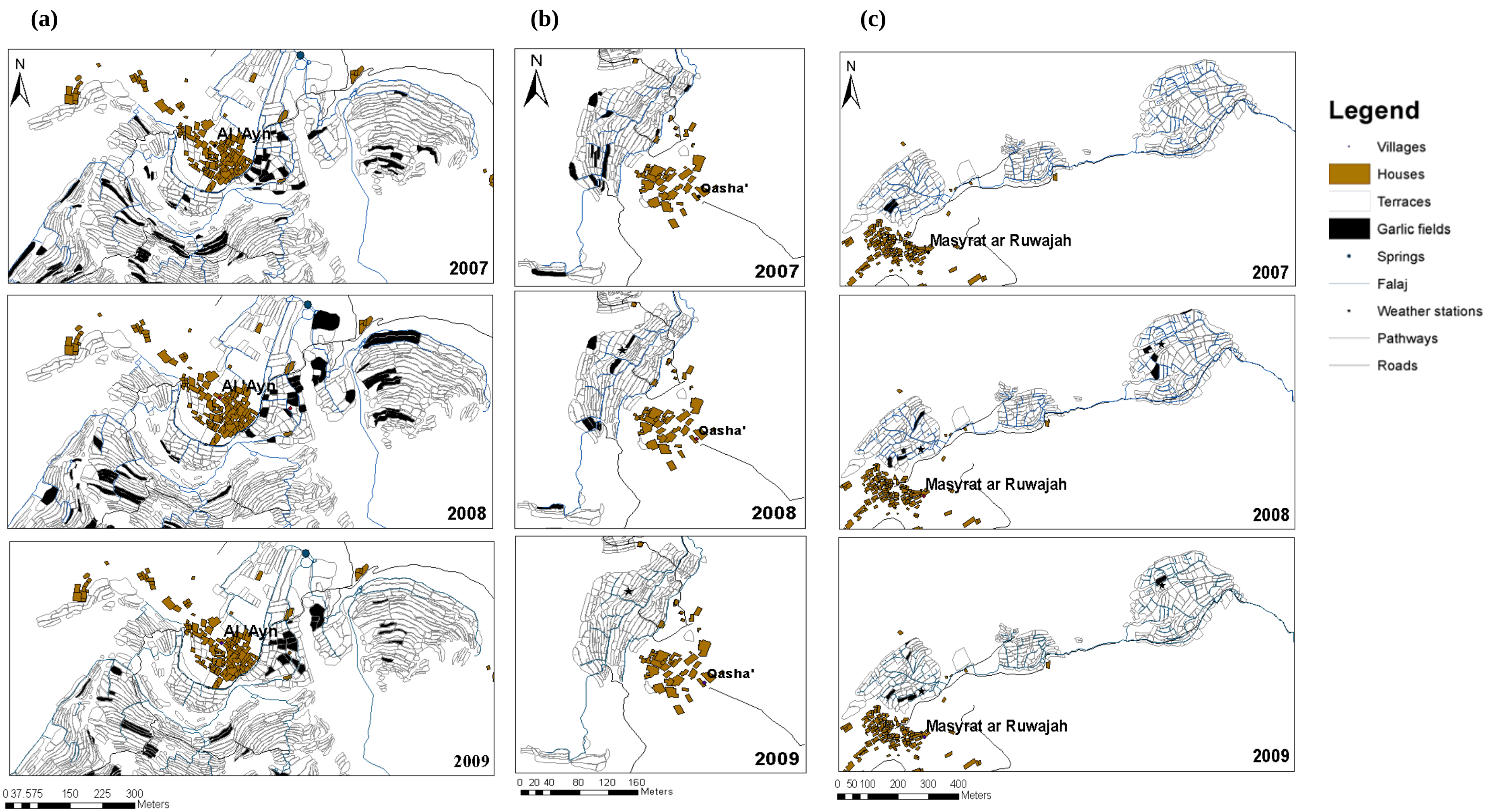


Figure 7. Changes of garlic growing areas during the period of 2007-2009 in oases of (a) Al'Ayn, Ash Sharayjah and Al'Aqr, (b) Qasha' and (c) Masayrat ar Ruwajah, Wadi Muaydin, northern Oman.

Because of its short cropping cycle and the long growing season starting in April and ending in November, farmers try to compensate eventual shortages in winter fodder crops by growing large areas with fodder maize often grown as an understorey crop immediately after torrential summer precipitation. In March, April and May, farmers of the high altitude oases allocate substantial amounts of irrigation water to fields cultivated with roses (*Rosa damascena* Mill.) for rose water production. From May to November, irrigation water is diverted to pomegranate (*Punica granatum* L.). Our data revealed that the area of mixed cropping fields (annual crops grown under trees) decreased from 4.5, 0.9, 0.4, 1.8, and 2.2 ha in 2007 to 2.8, 0.4, 0.6, 0.2, and 1.3 ha in 2009 of the total area of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha', and Masayrat respectively.

Due to population increase and changes in lifestyle, the modern settlement of the town of Sayh Qatanah on the Sayq plateau at the top of Wadi Muyadin has been growing profusely (Figure 1). Two wells located on top of the plateau supply drinking water to houses in Sayh Qatanah and other villages leading to a 2,5-fold increase in water extraction in less than a decade (from 149,600 m^3 in 2001 to 373,470 m^3 in 2009). This water is partly used for irrigation of homestead gardens devoted to growing crops and trees in the backyards of Sayh Qatanah, even if people have also established underground tanks to harvest rainwater as an alternative source of irrigation water.

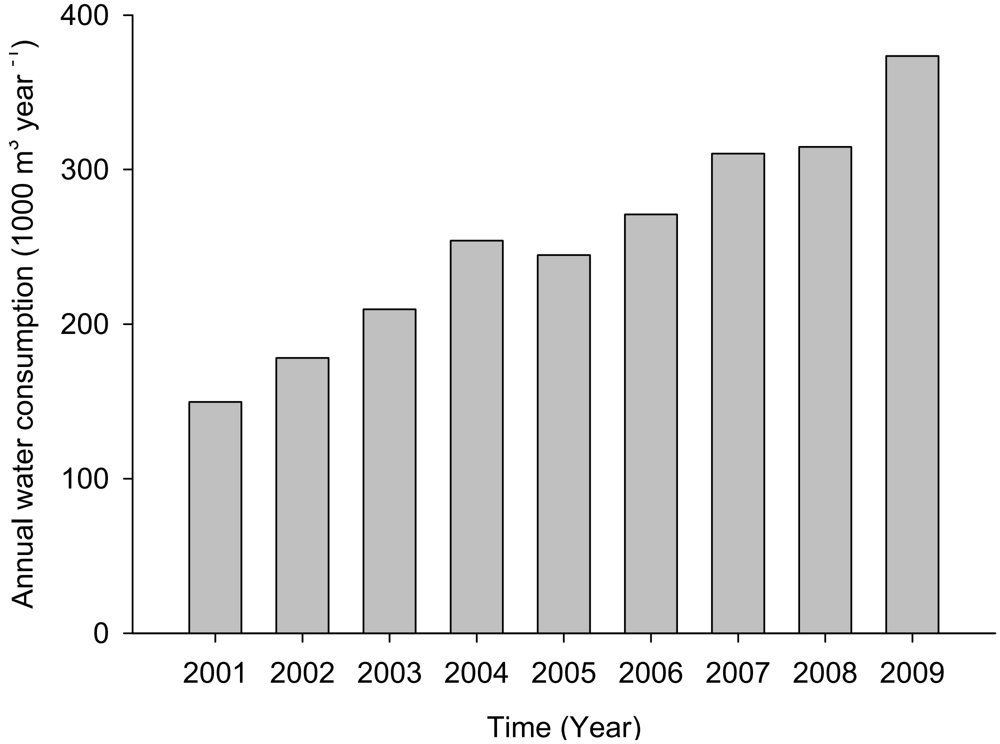


Figure 8. Total water consumption in Sayh Qatana and other oases of Al Jabal Al Akhdar, northern Oman, from 2001 to 2009. (Source: Public Authority for Electricity and Water, Al Jabal Al Akhdar Water Office, Sultanate of Oman)

2.5 Conclusions

The high altitude aquifer of Wadi Muaydin is under increasing pressure from water extraction to satisfy the drinking and irrigation water needs of the rapidly growing town of Sayh Qatanah. This affects flow rates of springs below the plateau as water consumption likely exceeds the long term recharge. Oasis farmers adapt to shortage of irrigation water by reducing areas planted to annual crops whereby the variation in landuse changes differs among the oases of Wadi Muaydin. In Qasha', where farmers shared irrigation water from the same spring with Al'Ayn and Al'Aqr, changes were most pronounced. Further studies should clarify the competitive effects and relative water use efficiencies of the recently introduced homestead gardens in Sayh Qatanah compared to the water consumption of the traditional terraces.

Acknowledgements

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Chapter 3. Carbon and nutrient balances in three mountain oases of Oman[2]

Abstract

To fill knowledge gaps on the sustainability of irrigated subtropical agriculture we used a nutrient balance approach to assess carbon (C) and nutrient fluxes of two cropping systems in three mountain oases of different altitudes in Al Jabal Al Akhdar mountains of northern Oman. These comprised garlic (*Allium sativum* L.) at Ash Sharayjah (1,900 m asl) and Masayrat ar Ruwajah (1,030 m asl), pomegranate (*Punica garanatum* L.) in Ash Sharayjah and Qasha' (1,640 m asl), and date palm groves (*Phoenix dactylifera* L.) at Masayrat. Goat manure was applied to garlic fields at 47 and 40 t dry matter (DM) ha^{-1} at Ash Sharayjah and 42 and 37 t DM ha^{-1} at Masayrat during the growing seasons of 2008/09 and 2009/10. Pomegranates at Ash Sharayjah and Qasha' received dairy cattle manure at 66 and 60 t DM ha^{-1} yr^{-1}, respectively. Annual total gaseous C losses ranged from 20.9 to 61.2 t C ha^{-1} to which CH_4-C contributed < 2%. Total annual C surpluses were 12.5 t ha^{-1} in garlic fields at Ash Sharayjah, while C deficits of -5.5 t ha^{-1} were obtained at Masayrat. Annual C balances in pomegranate and date palm were 16.7, 7.5 and 1.7 t ha^{-1} in Ash Sharayjah, Qasha' and Masayrat, respectively. Due to manure application rates of 78 t ha^{-1} $year^{-1}$, date palm groves had total annual N surpluses of 1857 kg N ha^{-1} while pomegranate fields at Ash Sharayjah and Qasha' had annual surpluses of 1414 and 1500 kg N ha^{-1}. The removal of potassium (K) with garlic was higher than inputs from manure resulting in substantial deficits at both oases. The results underline the intensive C and nutrient turnover under irrigated subtropical conditions and the importance of the continuous applications of large amounts of manure to the man-made terraces to sustain their productivity.

Keywords: Al Jabal Al Akhdar; gaseous emission; leaching; nutrient use efficiency; soil organic matter.

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3.1 Introduction

Located at the eastern tip of the Arabian Peninsula, the Sultanate of Oman is characterized by a hyperarid, subtropical climate with an annual precipitation of 0 to 240 mm compared to a potential evapotranspiration of > 2000 mm (Nagieb et al., 2004). Under such harsh arid conditions, where water is the most limiting factor for plant production, the millennia-old mountain oases systems in northern Oman have recently received considerable attention of scientists interested in the causes of the apparent sustainability of these agroecosystems (Wichern et al., 2004; Buerkert et al., 2005; Golombek et al. 2007; Siebert et al., 2007). One determinant of the bio-physical sustainability of Omani irrigated oasis agriculture is the turnover of carbon (C) and plant nutrients (N, P, and K) for which solid field data from irrigated subtropical conditions are scarce. The existing studies reported high application rates of organic fertilizer to the man-made terrace soils leading to the apparent accumulation of organic C despite very high emanation of gaseous C and N (Wichern et al., 2004; Buerkert et al., 2010). Soil organic mater (SOM) not only supplies energy and nutrients for macro-microorganisms and plants, it also contributes to soil textural stability and water holding capacity (Nyberg et al., 2006) thereby also governing drainage, a key component in irrigated agricultural systems (Luedeling et al., 2005). The turnover of SOM is heavily controlled by the characteristics of organic matter (C/N ratio and the concentration of lignin and secondary metabolites such as tannins), soil properties (pH, clay content, redox potential), macro and microorganism communities, crop management practices, and by environmental factors (Kladivko et al., 1987; Deng and Tabatabai, 2000; De Neve and Hofman, 2002; Agehara and Warncke, 2005; Burgos et al., 2006). Microbial activities are known to be altered by the water status in the soil leading to aerobic or anaerobic conditions, so that mineralization takes different pathways (Franzluebbers, 1999; Cannovo et al., 2004). Similarly, the presence of plants stimulates soil C and nutrient mineralization through root exudation (Paré et al., 2000; Zaman and Chang, 2004).

In this study, we used a soil system balance approach (Mikkelsen, 2005) by (i) measuring horizontal inputs and outputs of C, N, P, and K, and (ii) quantifying fluxes of gaseous C and N emissions and leaching of mineral N and P on representative terraced fields in three oases of different altitudes in Al Jabal Al Akhdar mountains of northern Oman. We hypothesized that C and nutrient turnover are faster in low altitude oases because of their higher ambient temperature and more frequent irrigation-dependent wet-dry cycles.

3.2 Materials and methods

3.2.1 Study area

The study was carried out in the mountain oases of Ash Sharayjah (57°39'30"E, 23°04'10"N, 1,900 m asl) located on the top of the Wadi Muaydin watershed, adjoining the edge of the Sayq plateau in the northern Hajar mountains of Oman (Figure 1). Just below this oasis is the village of Qasha' (57°39'50"E, 23°04'00"N, 1,640 m asl), while the lowest oasis of the watershed is Masayrat ar Ruwajah (57°40'13"E, 23°02'37"N, 1,030 m asl). The terraced agricultural area of Ash Sharayjah amounts to 14.4 ha and farmers irrigate their terraces with water from two springs that emerge near the neighboring oasis of Al'Ayn which was not included in this study. Qasha' contains 2.6 ha of terraced fields and obtains its water also from one of the springs of Al'Ayn, from where the water flows through a steep channel down to the oasis. In Ash Sharayjah and Qasha' crops are dominated by temperate species such as alfalfa (*Medicago sativa* L.), garlic, oat (*Avena sativa* L.), onion (*Allium cepa* L.), wheat (*Triticum* spp.) pomegranate, peach (*Prunus persica* L.), and roses (*Rosa damascena* L.) for rose water production. Agriculture in Masayrat (3.3 ha), in turn, is dominated by the annuals alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench) and barley (*Hordeum vulgare* L.), and the typical subtropical perennials date palm, and lime (*Citrus aurantiifolia* L. Swingle). The three oases were selected due to their representative character reflecting altitudinal differences in the typical oasis agriculture of this hyperarid region.

At each oasis, six representative fields were monitored during two growing seasons (2008/09-2009/10) for annual crops, and during one year for perennial crops in order to investigate fluxes of C and nutrients in typical oasis cropping systems. To this end garlic and pomegranate were selected in Ash Sharayjah, pomegranate in Qasha', and garlic and date palm in Masayrat.

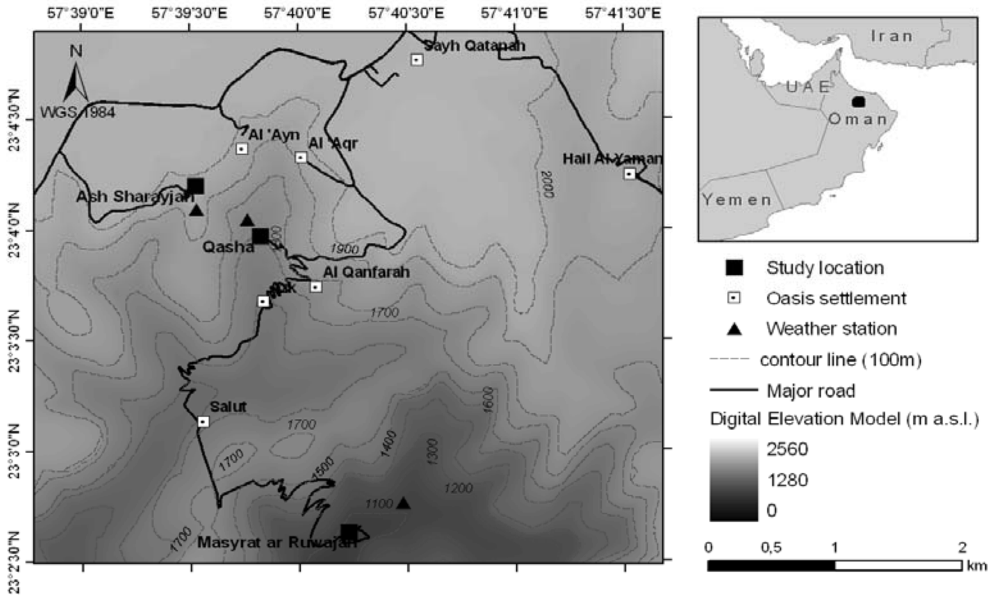

Figure 1. Relief map based on a 100 m digital elevation model of Al Jabal Al Akhdar Mountain in northern Oman showing the location of the three study oases of Ash Sharayjah, Qasha', and Masayrat ar Ruwajah in northern Oman.

3.2.2 Soil properties and climatic conditions

In each field three subsamples of the topsoil (0-0.15 m) were collected randomly, air dried, sieved to < 2 mm, and pooled before and after each cropping cycle or once per year in the case of perennials. Prior to determining particle size distribution in the soil using the sieve-pipette method (Gee and Bauder, 1986), organic matter and calcium carbonate ($CaCO_3$) were destroyed by addition of hydrogen peroxide (H_2O_2) and hydrochloric acid (HCl), respectively. Soil pH was measured in a 1:2.5 distilled water solution, whereas soil salinity was determined as electrical conductivity (EC) in a 1:10 distilled water solution using a digital conductivity meter (GMH 3410, Greisinger electronic, Regenstauf, Germany). Soil total C and N were measured by a thermal conductivity detector (Vario MAX CHN Analyser, Elementar Analysensysteme GmbH, Hanau, Germany). The percentage of $CaCO_3$ in soil was calculated using the volumetric calcimeter method (Williams 1948). Soil P was extracted with sodium bicarbonate ($NaHCO_3$) according to Watanabe and Olsen (1965) and measured by spectrophotometry (U-2000, Hitachi Ltd, Tokyo, Japan). For soil K analyses, samples were extracted with calcium acetate lactate and measured with a flame photometer (743 AutoCal, Instrumentation Laboratory Co, Lexington, MA, USA).

To estimate micro-climate differences at the three oases reflecting the effect of the different elevations, air temperature and relative humidity were recorded at 30 min intervals throughout the research period using Hobo-Pro® climate loggers (Onset Corp.; Bourne, MA, USA). In addition to these devices full Watchdog® weather stations (Spectrum Technologies Inc., Plainfield, IL, USA) were placed at Ash Sharayjah and Masayrat.

3.2.3 Sampling and analysis

During harvest, garlic plant samples were collected from three 1 m^2 subsamples in each of the six fields at each location, weighed to obtain total fresh matter, sun-dried to constant weight for DM determination, and subsequently ground to < 2 mm for C and nutrient analysis. For pomegranate and date palms fruit yields were quantified for each tree. To this end the total number of pomegranate fruits was counted and classified into three categories: small, medium, and big. Subsequently, average weight, volume, and nutrient concentrations were determined from representative samples to compute fruit yield per tree and surface area occupied. Plant and manure samples were oven-dried at 60 ^{o}C, ground (< 2 mm), and analysed for C, N, P, and K as described above for the soil samples. For samples of irrigation water, of which frequency and amounts were determined regularly, dissolved organic carbon (DOC) and total N were determined using a Dimatec 100® CHN-Analyzer (Dimatec Analysentechnik GmbH, Essen, Germany).

3.2.4 Horizontal C and nutrient fluxes

Horizontal balances were determined by calculating the differences between the total amounts of C, N, P, and K in all inputs such as manures, mineral fertilizers (if applicable), planted garlic cloves, irrigation water, and rainfall, and outputs such as crop removals at harvest including understory maize (wherever present in planted perennials) and fruit yields of pomegranate and date palm. In order to account for the contribution of roots to C balances, total amount of photosynthetic C was estimated for garlic and understory maize by multiplying total harvested DM by a factor of 1.4 based on the assumption that 30% of the total assimilated C was allocated to root DM and exudation (Kuzyakov and Domanski, 2000).

3.2.5 Apparent nutrient use efficiency (NUE)

Horizontal nutrient fluxes were used to calculate NUE for the different cropping systems. NUE for each of the elements of N, P, and K was calculated as: (∑nutrient output with harvest products / ∑ nutrient inputs) (Hedlund et al., 2003). For perennial trees, understory maize was included in output calculations wherever present.

3.2.6 Estimation of vertical carbon and nutrient fluxes

Collection and analysis of leachates

Cumulative leaching losses of mineral N and P were quantified with mixed-bed ion-exchange resin cartridges (Bischoff, 2007; Lang and Kaupenjohann, 2004; Predotova et al., 2011). To this end PVC-cartridges were filled with a 2:3 mixture of anion-cation exchange resins and pure silica sand of 120 – 700 µm (Majan Glass Co., Sohar, Oman; Siegfried et al., 2011). For each cropping system, seven cartridges were buried in each of the selected fields below the rooting zone at 0.50 m depth and removed after each crop harvest or annually for pomegranate and date palm. After removal from the soil, the resin-sand mixture was separated horizontally into five layers to be able to determine a concentration gradient within each cartridge. From each layer, a subsample of 30 g was extracted eight times with 100 ml of 0.5M NaCl by shaking for one hour followed by filtration into a plastic vial. Subsequently, samples were analyzed for their concentration of leached nutrients with an ICP-AES (Spectroflame, Spectro GmbH, Kleve, Germany). Calculations of annual cumulative leaching losses of N and P were made following the approach described by Siegfried et al. (2011).

Monitoring of gaseous C and N emissions

On the same fields where leaching cartridges were installed, gaseous emissions of CO_2-C, CH_4-C, NH_3-N and N_2O-N were measured using a photo-acoustic infrared multi-gas analyzer (INNOVA 1312-5, AirTech instruments, Ballerup, Denmark; Predotova et al., 2010, 2011). A cuvette of 0.30 m diameter and 0.11 m height made of standard PVC tube was used to tightly cover PVC rings installed in the soil of the experimental field in order to create a closed chamber, while inside temperature and humidity were monitored with an attached thermo-hygrometer sensor (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany). Measurements were conducted immediately after the first irrigation and repeated for three days during each irrigation cycle in order to correctly estimate emission rates at different soil moisture levels (day of irrigation event, day in the middle of the irrigation cycle, and day before the next irrigation event). For each measurement day, gaseous emissions were quantified from three repetitive measurements in all four rings installed in each cropping system (totaling 12 measurements per day). At the same time, volumetric soil water content was determined at 0.05 m depth with a TDR/FDR soil moisture meter (Theta Probe Sensor attached to Infield7b instrument, UMS, Munich, Germany). Soil temperature was recorded with a digital thermometer (Carl Roth GmbH, Karlsruhe, Germany). Emission measurements were conducted in the early afternoon hours (12:00 – 02:00 pm) representing the highest emission rates during the hottest hours in these agroecosystems (Buerkert et al., 2010). For an annual extrapolation of our daily measurements of afternoon gaseous C and N losses, the average percentage changes in emissions between minimum and maximum emission rates (morning/midday) measured at the same oases in a previous study were used to estimate daily average emission values (Al-Rawahi et al., 2012).

3.2.7 Total carbon and nutrient balances

Total balances of C, N, P, and K were calculated as the difference between horizontal balances minus vertical fluxes. Since we were unable to obtain complete plant nutrient data for pomegranate and date palm (due to difficulties to account for nutrient storage in woody plant parts and roots, and losses by twigs and leaves), these calculations had only limited value. To partly fill this data gap, we assumed that approximately 39 % of the total annual emitted C was derived from root respiration and root-derived organic matter microbial respiration (Atarashi-Andoh et al., 2011). Without consideration of C stored in leaves, stem, and growing roots, this percentage was considered as the photosynthetic C input allocated to below-ground roots and consequently deducted from the total gaseous C emitted from both species for total C balance calculations.

3.3 Statistical analysis

Data were analyzed using SPSS version 17.0 (SPSS Inc., Chicago, USA), while graphs were made with Sigma Plot 10.0 (Systat Software Inc., San Jose, CA, USA). The analysis of variance was followed by LSD post-hoc multiple mean comparisons to test for differences between the two cropping systems (annual *versus* perennial species).

Data of which residuals were not normally distributed were log-transformed before statistical analysis.

3.4 Results

3.4.1 Soil properties and climatic conditions

The man-made irragric Anthrosols on the terraces were similar for all three oases and classified as loamy soils with a particle size distribution of about 15% clay, 41% silt, and 44% sand. High inorganic carbon (C_{inorg}) was determined in all soil samples reflecting a $CaCO_3$ concentration of 44% at Ash Sharayjah and 40% at Masayrat. Soil pH averaged 8.2 at Ash Sharayjah, 8.0 at Qasha', and 8.3 at Masayrat. Also, soil organic C was higher at Masayrat than at Ash Sharayjah and at Qasha' (Table 1). Average ambient air temperature was 21.2 ^{o}C at Ash Sharayjah, 21.6 ^{o}C at Qasha', and 25.4 ^{o}C at Masayrat (Figure 2). In 2009, annual precipitation totaled 205 mm at Ash Sharayjah and 224 mm at Masayrat, while in 2010 more rainfall events occurred and annual precipitation totaled 639 and 379 mm at Ash Sharayjah and Masayrat, respectively (Figure 3). Garlic fields received a total precipitation of 131 mm at Ash Sharayjah and 43 mm at Masayrat during the growing season from November 2008 to April 2009. Rainfall was higher during the second season (2009/2010) with cumulative values of 299 mm at Ash Sharayjah and 124 mm at Masayrat.

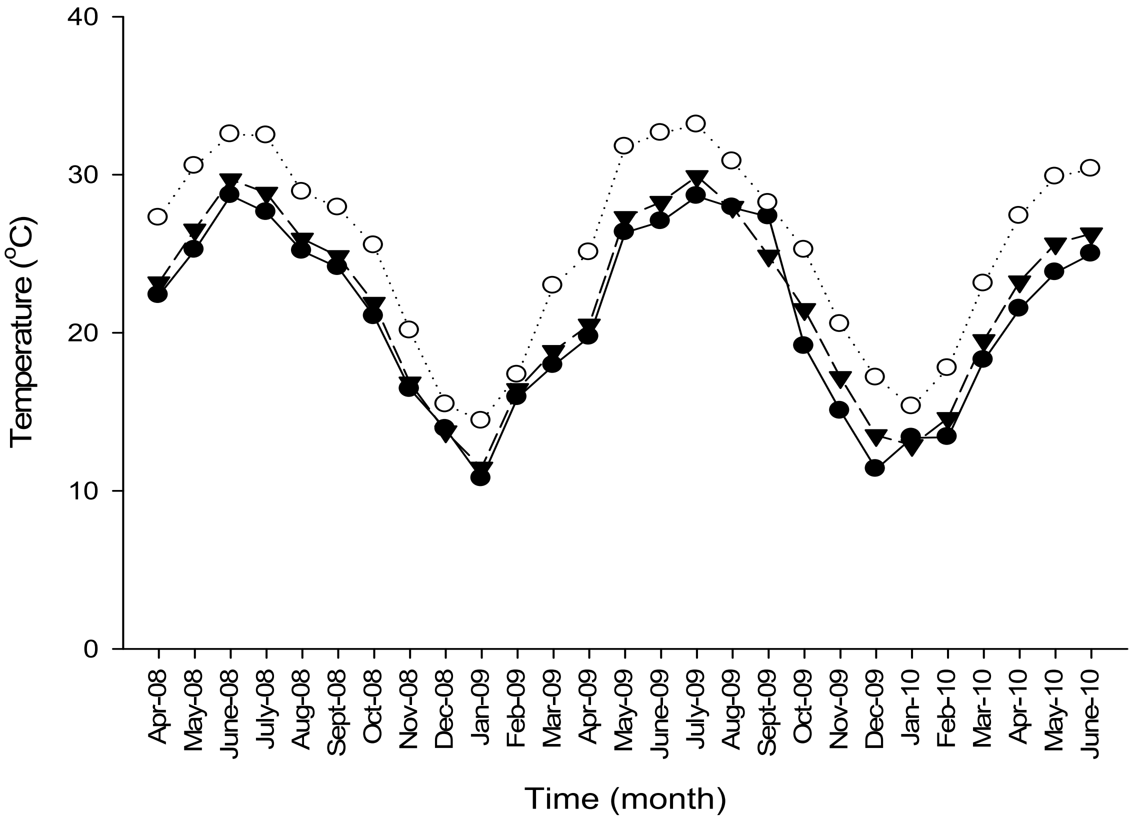

Figure 2. Mean monthly air temperatures recorded at the oases of Ash Sharayjah, Qasha', and Masayrat ar Ruwajah in northern Oman during the research period.

Table 1. Soil chemical properties (0-0.15 m) of the selected fields (n = 6) before and after cropping cycles at the oases of Ash Sharayjah, Masayrat ar Ruwajah and Qasha', northen Oman (2008-2010).

Oases	Crop	Year	Cropping Cycle	C_{org} %	N %	P (Olsen) P_2O_5 g/100g	K mg/g	EC dS/m	pH	$CaCO_3$ %
Ash Sharayjah	Garlic	2008	November	2.76	0.25	0.016	0.14	0.20	8.17	45.4
		2009	May	3.10	0.34	0.022	0.40			
		2009	November	3.68	0.31	0.025	0.20	0.17	8.37	44.3
		2010	May	4.13	0.37	0.027	0.24			
	Pomegranate	2009	May 2009	3.72	0.38	0.031	0.31	0.25	8.10	44.7
		2010	April 2010	4.19	0.42	0.040	0.33			
Masayrat	Garlic	2008	November	5.95	0.39	0.024	0.14	0.24	7.97	38.9
		2009	May	6.19	0.43	0.016	0.12			
		2009	November	5.34	0.33	0.013	0.14	0.15	8.10	37.2
		2010	May	6.87	0.50	0.019	0.14			
	Date Palm	2009	May 2009	6.93	0.31	0.006	0.11	0.20	7.87	40.0
		2010	April 2010	5.57	0.46	0.010	0.14			
Qasha'	Pomegranate	2009	May 2009	2.41	0.30	0.014	0.16	0.16	8.26	36.6
		2010	April 2010	2.87	0.35	0.022	0.17			

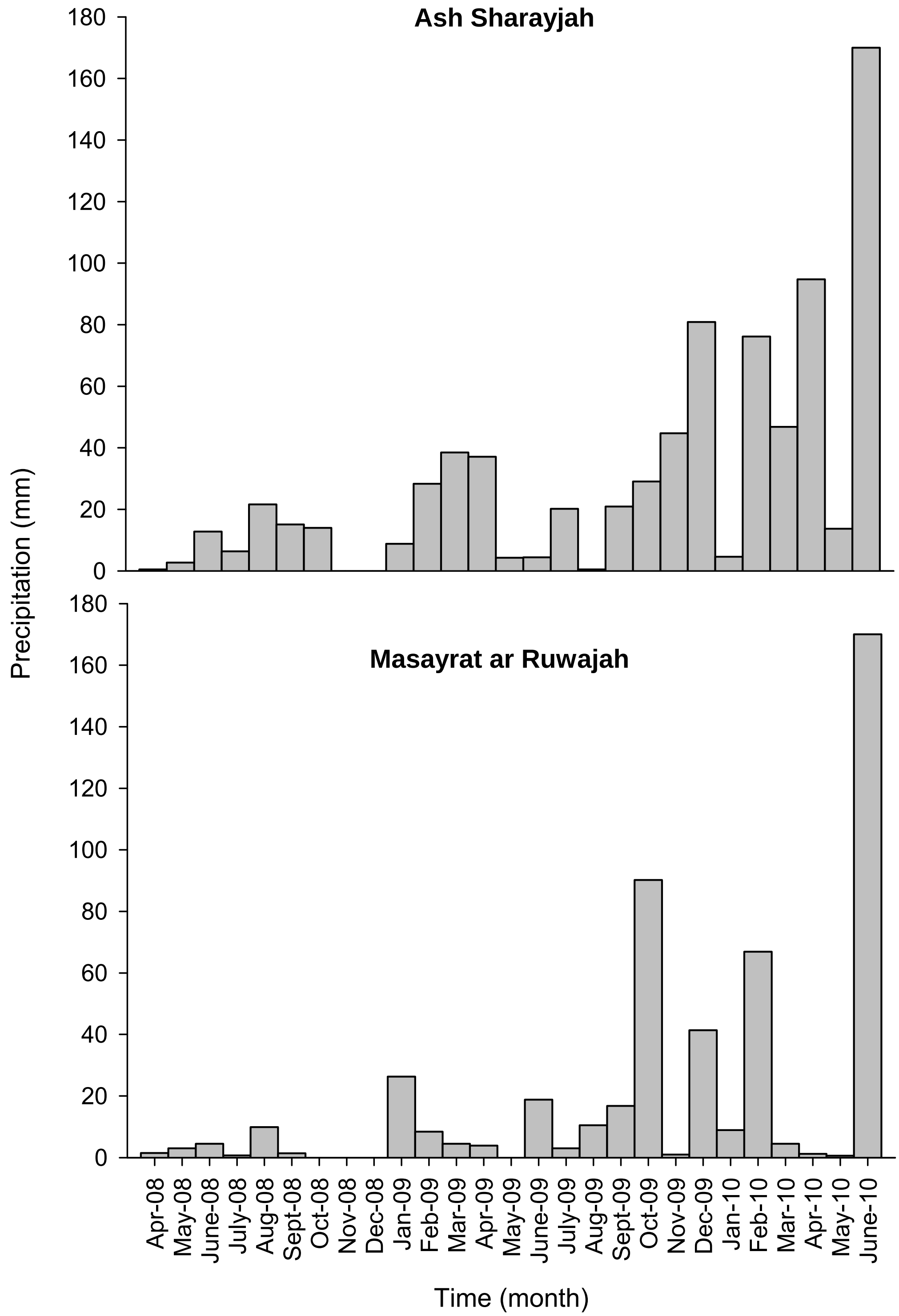

Figure 3. Average monthly precipitation (mm) recorded at the oases of Ash Sharayjah and Masayrat ar Ruwajah, Al Jabal Al Akhdar (Oman) from April 2008 to June 2010.

3.4.2 Horizontal C and nutrient fluxes

Manure was the main source of C and nutrient inputs (Table 3). Although we tried to select fields with similar application rates of manure, application seemed to depend on such different factors as cropping system (annual *versus* perennial species), availability and frequency of irrigation water, distance and access to the fields, and season (winter *versus* summer). Manure was surface applied by the farmers 2-3 times during the experimental period on the irrigated garlic fields forming a manure layer of 0.03 m height. At Ash Sharayjah, garlic fields received goat manure at average rates of 47 and 40 t DM ha^{-1} during the growing seasons of the years 2008/2009 and 2009/2010, respectively (Table 2). Similarly, goat manure was applied to garlic fields at Masayrat with an average application rate of 42 and 37 t DM ha^{-1} during the 2-years growing seasons. Farmers also applied goat manure to date palms at Masayrat at an average rate of 78 t DM ha^{-1}. In contrast, pomegranates at Ash Sharayjah and Qasha' received dairy cattle manure at 66 and 60 t dry matter ha^{-1}.

Average annual inputs of C and N from manure were 62% of total C and 95% of total N in Ash Sharayjah garlic fields and 63% of C and 94% of N in Masayrat garlic fields, whereas average annual inputs of photosynthetic C were 37% and 36% of total C in garlic fields at Ash Sharayjah and Masayrat, respectively. Total annual C and nutrient inputs in garlic fields were similar ($P>0.05$) in both oases (Table 3). As a result, garlic total DM yield and annual horizontal balances for both oases were not significantly different ($P>0.05$).

Although our data showed major differences between annual and perennial cropping systems, partial C balances of garlic and date palm were not significantly different ($P>0.05$). Nitrogen surpluses, in contrast, were significantly larger ($P<0.05$) in date palm than in all other crops. Phosphorus and K partial balances of pomegranate at Qasha' and date palm at Masayrat were similar to those of pomegranate at Ash Sharayjah. Although annual horizontal K balances in garlic fields of both oases were negative, they were positive for pomegranate and date palm. Average annual C, N, P, and K exported with understorey maize were 4.3, 4.9, 3.4 and 1.4-fold higher than in pomegranate yields at Ash Sharayjah and 6.9, 9.9, 1.4 and 1.0-fold higher than in harvested dates. Compared to pomegranate, date palm fields received higher C and N inputs and lower P and K inputs. Partial balances of C, N, and P in date palm therefore were 46, 29 and 12% higher than balances calculated from pomegranate at Ash Sharayjah, while K balance was 48 % lower.

Table 2. Total amounts of goat and dairy cattle manures and concentrations of nitrogen (N), phosphorus (P), potassium (K), and carbon (C) in that have been applied by farmers at the oases of Ash Sharayjah, Qasha', and Masayrat ar Ruwajah, Al Jabal Al Akhdar (northern Oman) during the experimental period (2008-2010).

Crop	Oases	Type	Year	Total application	N	P	K	C
				t (DM) ha^{-1}	----------	mg g^{-1}	-----------	%
Garlic	Sharayjah	goat	2008/09	47	22.5	3.0	13.6	46.42
			2009/10	40	24.0	4.4	13.5	42.82
Garlic	Masayrat	goat	2008/09	42	25.2	3.3	10.2	50.20
			2009/10	37	22.3	4.5	14.3	36.32
Pomegranate	Sharayjah	cattle	2009	66	25.3	3.8	31.4	37.25
Pomegranate	Qasha'	cattle	2009	60	25.2	7.1	26.2	28.53
Date palm	Masayrat	goat	2009	78	25.2	3.3	13.2	47.20

Table 3. Annual horizontal inputs, outputs and partial balances of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) for garlic, pomegranate, and date palm fields (n = 6) at the oases of Ash Sharayjah, Qasha', and Masayrat ar Ruwajah in northern Oman (2008-2010). Partial balances values with different superscript letters were significantly different (P < 0.05, LSD).

			Input and output (kg ha^{-1} yr^{-1})			
Crop	**Oases**	**Source**	**C**	**N**	**P**	**K**
Garlic	Sharayjah	Manure	38632	2001	317.2	1170.9
		Cloves (sowing)	16	1	0.2	1.5
		Irrigation water	41	57	0.0	0.3
		Rainfall	162	34	n.a	n.a
		Photosynthetic C	22771			
		Total	**61620**	**2093**	**317.4**	**1172.7**
		Crop yield	-16265	-1069	-191.1	-1486.2
		Partial balance	**45355^{a}**	**1024^{c}**	**126.3^{cd}**	**-313.5^{c}**
Garlic	Masayrat	Manure	38132	1878	306.1	955.0
		Cloves (sowing)	16	1	0.2	1.4
		Irrigation water	121	103	0.0	0.5
		Rainfall	113	13	n.a	n.a
		Photosynthetic C	21963			
		Total	**60345**	**1995**	**306.3**	**956.9**
		Crop yield	-15688	-1011	-244.2	-1427.2
		Partial balance	**44657^{a}**	**984^{c}**	**62.1^{d}**	**-470.3^{c}**
Pome-granate	Sharayjah	Manure	24728	1682	249.7	2084.9
		Irrigation water	33	46	0.0	0.2
		Rainfall	138	29	n.a	n.a
		Photosynthetic C *	7536			
		Total	**32435**	**1757**	**249.7**	**2085.1**
		Crop yield	-2238	-39	-7.8	-70.8
		Understory maize	-5383	-209	-46.0	-308.4
		Partial balance	**24814^{b}**	**1509^{b}**	**195.9^{bc}**	**1705.9^{a}**
Pome-granate	Qasha'	Manure	17237	1524	430.7	1585.7
		Irrigation water	58	62	0.0	0.2
		Rainfall	138	29	n.a	n.a
		Photosynthetic C	n.a			
		Total	**17433**	**1615**	**430.7**	**1586.0**
		Crop yield	-2728	-39	-8.5	-72.8
		Partial balance	**14705^{b}**	**1576^{b}**	**422.2^{a}**	**1513.2^{a}**
Date palm	Masayrat	Manure	36452	1946	256.0	1019
		Irrigation water	154	131	0.0	0.6
		Rainfall	101	21	n.a	n.a
		Photosynthetic C *	5085			
		Total	**41792**	**2098**	**256.0**	**1019.3**
		Crop yield	-1788	-16	-3.0	-39.6
		Understory maize	-3632	-131	-33.0	-96.8
		Partial balance	**36372^{a}**	**1951^{a}**	**220.0^{b}**	**882.9^{b}**

* Photosynthetic C was estimated only for understorey maize.

3.4.3 Apparent nutrient use efficiency NUE

Annual apparent NUE was highest in garlic with average N, P, and K use efficiencies of 51, 60, and 127% at Ash Sharayjah and 50, 60, and 149% at Masayrat. Average apparent NUEs of pomegranate at Ash Sharayjah, Qasha', and date palm at Masayrat were 15, 3, and 7%, respectively. In perennial trees, PUE and KUE tended to be higher for pomegranate at Ash Sharayjah (22 and 19%) compared to date palm at Masayrat (14 and 13%), while PUE and KUE were with 2 and 5% smallest in pomegranate at Qasha'.

3.4.4 Vertical C and nutrient fluxes

Cumulative leaching losses

Most mineral N was leached as NO_3-N, whereas NH_4-N was below detection limit for all cartridges. Annual cumulative leaching losses of mineral N and P were much higher in garlic fields than in perennial crops (Table 4). Annual mineral N leaching losses ranged between 0.45-0.61 kg N ha^{-1} year^{-1} for garlic and 0.05 - 0.23 kg N ha^{-1} year^{-1} for perennial trees. Apparent annual mineral P leaching from perennial trees was below 0.01 kg P ha^{-1} year^{-1}.

Table 4. Annual cumulative leaching losses of mineral nitrogen (N) and phosphorus (P) (mean ± one standard error) determined by ion exchange resin cartridges from the experimental fields at the oases of Ash Sharayjah, Qasha', and Masayrat ar Ruwajah, Oman (2008-2009).

		Cumulative leaching g ha^{-1} year^{-1}	
Crop	Oases	Mineral (N)	Mineral (P)
Garlic	Ash Sharayjah	452 ± 26.9	25 ± 2.8
Garlic	Masayrat	613 ± 65.2	102 ± 27.1
Pomegranate	Ash Sharayjah	232 ± 31.5	3 ± 0.5
Pomegranate	Qasha'	48 ± 7.7	7 ± 0.67
Date palm	Masayrat	73 ± 13.8	4 ± 1.5

Gaseous emissions

Estimated annual gaseous C and N losses were higher in garlic than in perennial cropping systems (Table 5) and regardless of the cropping system gaseous C losses were higher at Masayrat than at Ash Sharayjah despite the higher application rate of manure at the latter site. Total annual gaseous N losses from garlic fields were 109 kg ha^{-1} $year^{-1}$ at Ash Sharayjah and 157 kg N ha^{-1} $year^{-1}$ at Masayrat, whereas annual gaseous C losses were 33 t ha^{-1} $year^{-1}$ at Ash Sharayjah and 50 t C ha^{-1} $year^{-1}$ at Masayrat. While NH_3-N constituted 63% of total gaseous N losses in garlic fields at Ash Sharayjah, they were 48% at Masayrat. Regardless of cropping system and altitude, NH_3-N and N_2O-N fluxes were highest during the first few days after manure application and gradually decreased thereafter (Figure 4).

Table 5. Estimated annual carbon and nitrogen gaseous losses from selected experimental fields at the oases of Ash Sharayjah, Qasha',and Masayrat, northern Oman (2008-2010). Data represent means ± one standard error.

Crop	Oases	Gas	Afternoon emission		Estimated annual losses
			Mean	Std.Er	
			kg ha^{-1} $year^{-1}$		ha^{-1} $year^{-1}$
Garlic	Sharayjah	CO_2-C	49442 ±	3036	
		CH_4-C	449.1 ±	108.24	32.8 t C
		NH_3-N	106.9 ±	16.66	
		N_2O-N	67.3 ±	8.52	108.6 kg N
Garlic	Masayrat	CO_2-C	59279 ±	3958	
		CH_4-C	506.0 ±	107.95	50.2 t C
		NH_3-N	108.6 ±	17.03	
		N_2O-N	122.3 ±	12.12	156.5 kg N
Pomegranate	Sharayjah	CO_2-C	31164 ±	2381	
		CH_4-C	597.2 ±	112.22	20.9 t C
		NH_3-N	75.3 ±	15.42	
		N_2O-N	75.7 ±	16.04	93.4 kg N
Pomegranate	Qasha'	CO_2-C	27756 ±	2328	
		CH_4-C	377.0 ±	73.79	18.5 t C
		NH_3-N	73.3 ±	14.17	
		N_2O-N	48.7 ±	8.91	76.3 kg N
Date palm	Masayrat	CO_2-C	72420 ±	4827	
		CH_4-C	466.5 ±	81.42	61.2 t C
		NH_3-N	68.1 ±	9.86	
		N_2O-N	68.5 ±	7.55	92.7 kg N

For perennials, time-dependent fluxes of C and N were surprisingly similar across the three oases (Figure 5). In January, flux rates reached their annual minima. Total estimated gaseous NH_3-N and NO_2-N losses were highest in pomegranate at Ash Sharayjah (93 kg N ha^{-1} $year^{-1}$) and at Qasha' (76 kg N ha^{-1} $year^{-1}$) despite the much higher temperature and manure application rate in date palm at Masayrat (93 kg N ha^{-1} year^{-1}). CO_2-C emissions in date palm at Masayrat were about 3 times higher than in pomegranate at Ash Sharayjah and Qasha', reaching a maximum flux rate of 11 kg ha^{-1} h^{-1} in September (Figure 5). Consequently, annual gaseous C losses in perennials were 21, 19, and 61 t C ha^{-1} year^{-1} at Ash Sharayjah, Qasha', and Masayrat, respectively (Table 5).

3.4.5 Total carbon and nutrient balances

Total annual C balances of garlic fields were positive (a surplus of 12.5 t ha^{-1}) for Ash Sharayjah and in deficit (-5.5 t ha^{-1}) for Masayrat (Figure 6), while annual N balances in garlic were with 915 and 826 kg ha^{-1} similarly positive at Ash Sharayjah and Masayrat. Annual P surpluses were with 130 kg ha^{-1} twice as positive in garlic at Ash Sharayjah than at Masayrat (60 kg P ha^{-1}). Garlic annual K balances, in contrast, were negative in both oases reflecting the high amounts of K exported with the harvested produce (Table 3). Annual C surpluses in pomegranate and date palm were 16.7, 7.5, and 1.7 t ha^{-1} at Ash Sharayjah, Qasha', and Masayrat, respectively (Figure 7). At manure application rates of 78 t ha^{-1} year^{-1}, date palm had with 1860 kg N ha^{-1} the highest total annual N surplus, while the average annual K balance was 880 kg ha^{-1}. Pomegranate at Ash Sharayjah and Qasha' had annual N surpluses of 1414 and 1500 kg ha^{-1}. Total annual P surpluses in pomegranate at Ash Sharayjah were 196 kg ha^{-1} and at Qasha' 420 kg ha^{-1}, whereas annual K surpluses amounted to 1710 and 1510 kg ha^{-1}.

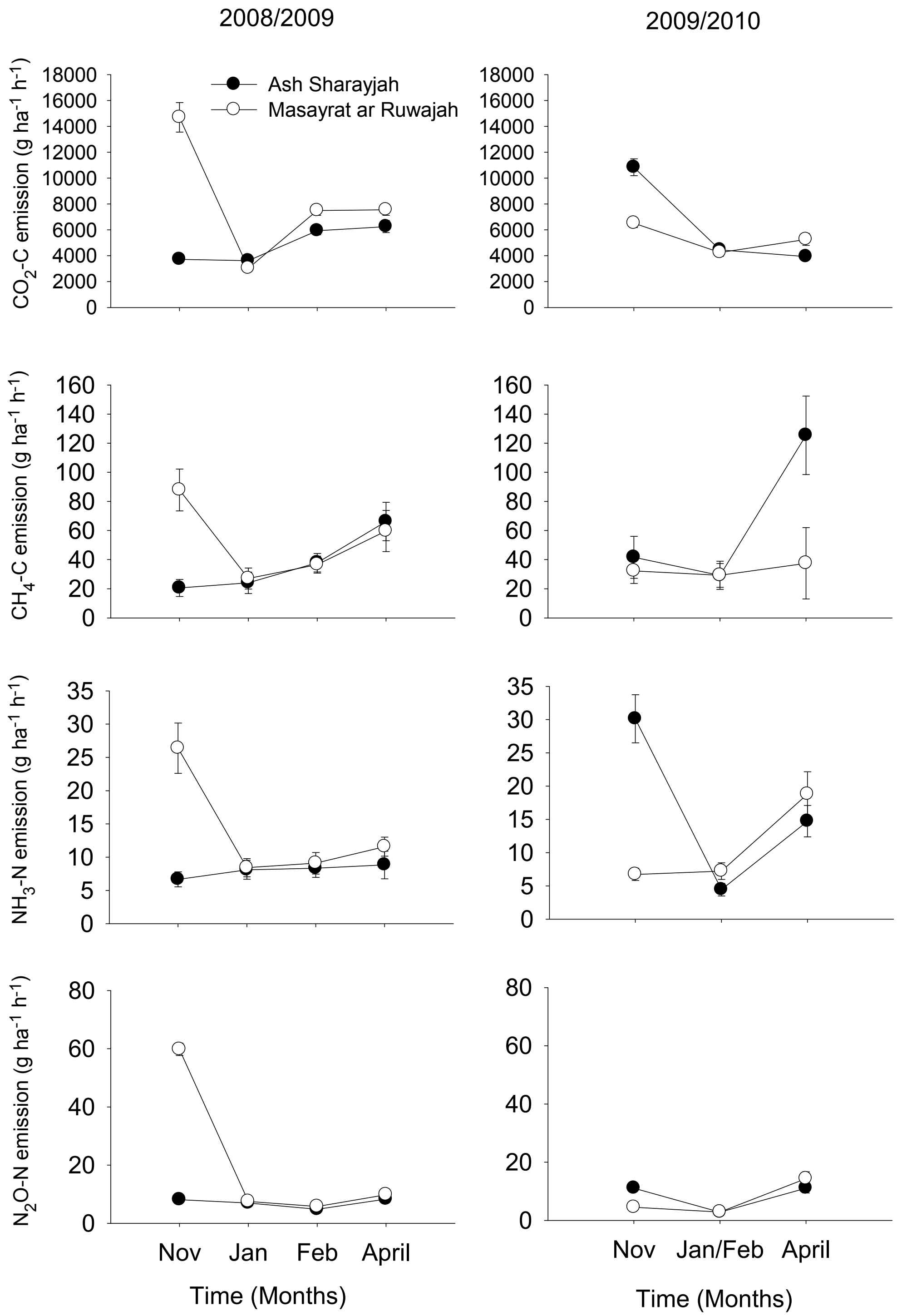

Figure 4. Emissions of CO_2-C, CH_4-C, NH_3-N, and N_2O-N, from garlic fields at the oases of Ash Sharayjah and Masayrat ar Rawajah throughout two growing seasons (2008/2009 – 2009/2010). Vertical bars indicate ± one standard error of the mean.

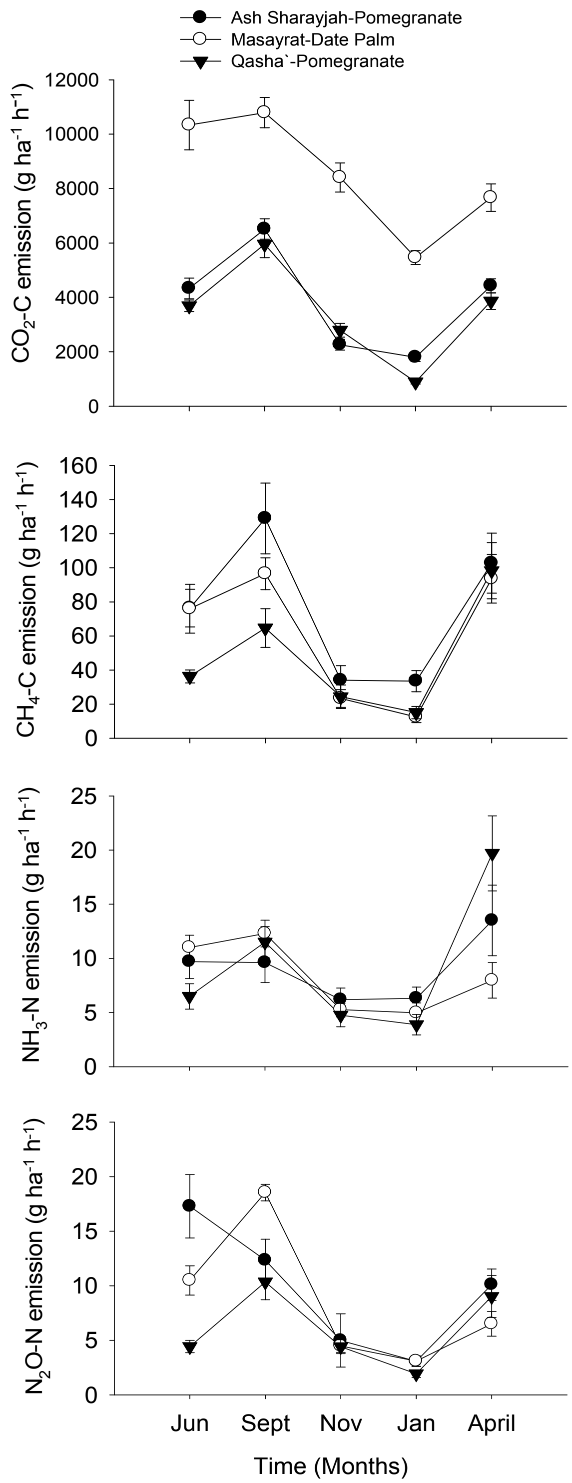

Figure 5. Emissions of CO_2-C, CH_4-C, NH_3-N, and N_2O-N, from pomegranate fields at the oases of Ash Sharayjah and Qasha' and from date palm fields at Masayrat ar Rawajah, Al Jabal Al Akhdar, Oman (2009-2010). Vertical bars indicate ± one standard error of the mean.

3.5 Discussion

The surprisingly large N_2O-N fluxes from garlic fields at Masayrat compared to the prevailing dominance of NH_3-N emissions in fields at Ash Sharayjah (Table 5) may be caused by the difference in wet-dry cycles at both locations. Over the 180 day growing season there were 15 cycles at the high altitude oasis of Ash Sharayjah compared to 26 cycles at the low altitude oasis of Masayrat. Annual C losses from date palm at Masayrat were 67% higher than from pomegranate at Ash Sharayjah and Masayrat which probably reflected the very high annual manure input of 78 t DM ha^{-1} to date palm fields as well as the much higher air temperature at the low altitude oasis of Masayrat (Figure 2). In their study of gaseous N and C losses from the northern Oman costal plain of Al-Batinah, Siegfried et al. (2011) reported similarly high fluxes that were related to a very fast C and nutrient turnover. Although they used lower manure application rates than in our study, total gaseous N and C losses were similar. This it is likely due to the very high temperatures in the Omani lowlands.

Regardless of the cropping system, cumulative annual leaching losses of mineral N and P were very low compared to the findings from sandy lowland soils by Siegfried et al. (2011). These low rates may be due to a combination of low seepage, differences in the particle size distribution and the higher organic C content of our soils. In any case, it should be noted that resin technique to measure leachates does not allow measuring organic N and P. Ouédraogo at al. (2001) have reported that the application of large amounts of organic matter can lead to an increase of soil cation exchange capacity (CEC) in subtropical soils and Jarecki et al. (2008) reported that the higher CEC in clay soils led to a substantial adsorption of NH_4^+. Also, Szili-Kovács et al. (2007) reported that application of organic substrates may enhance N immobilization in the microbial biomass

As a result of the high nutrient exports in harvested garlic, nutrient surpluses in perennials were much higher, especially for N and K. Carbon balances, instead, seemed to largely depend on C inputs from manure and photosynthetic C rather than on C exports at harvest. Despite the higher application rates of goat manure to garlic fields, K inputs to pomegranate were higher given the use of cow manure in this system. Our results indicate that cattle manure had a much higher K concentration than goat manure (Table 1). Although the manure application rates in date palm were higher than in garlic, both systems had similar horizontal C balances, whereby our total annual C and nutrient exports were much lower than reported for in the more intensively managed palm groves studied by Buerkert et al. (2005). This difference may also be due to a serious infection of the date palms at Masayrat with the dubas bug (*Ommatissus binotatus lybicus*) during our experimental period leading to unusually low date yields. During their life cycle and development, these insects attract deleterious fungi that feed on honeydew on infected leaves and fruits which causes a reduction of photosynthesis and subsequent growth depression (Klein and Venezian, 1985).

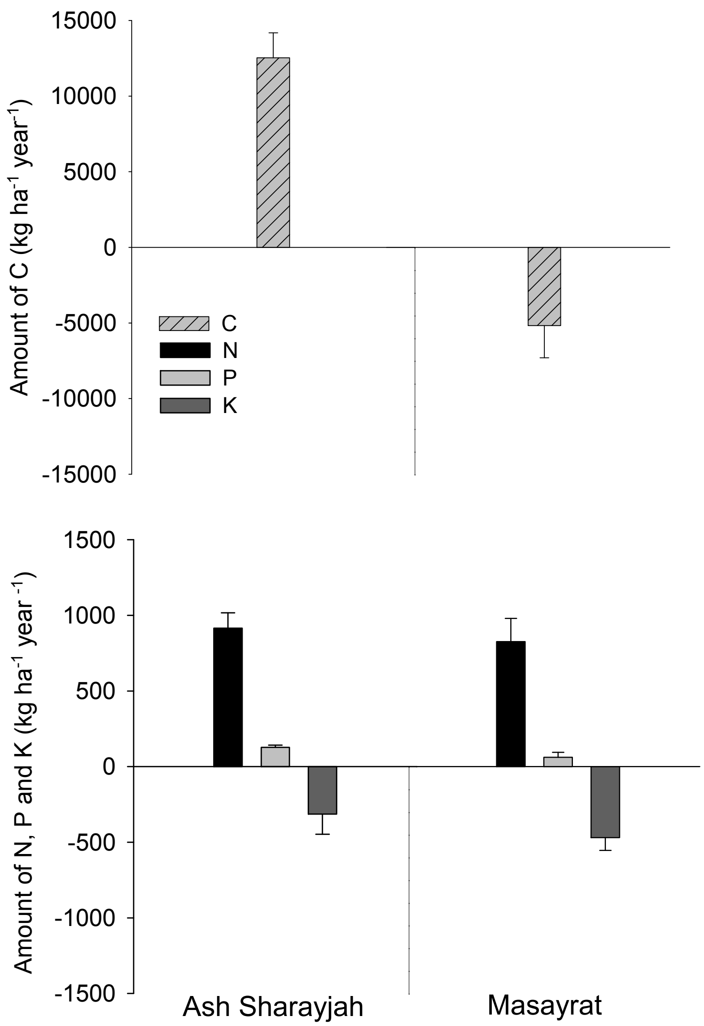

Figure 6. Annual total balances of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) in garlic fields (n = 6) at the oases of Ash Sharayjah and Masayrat ar Ruwajah in northern Oman. Data represent means of two growing seasons (2008/2009 – 2009/2010) with vertical bars indicating ± one standard error.

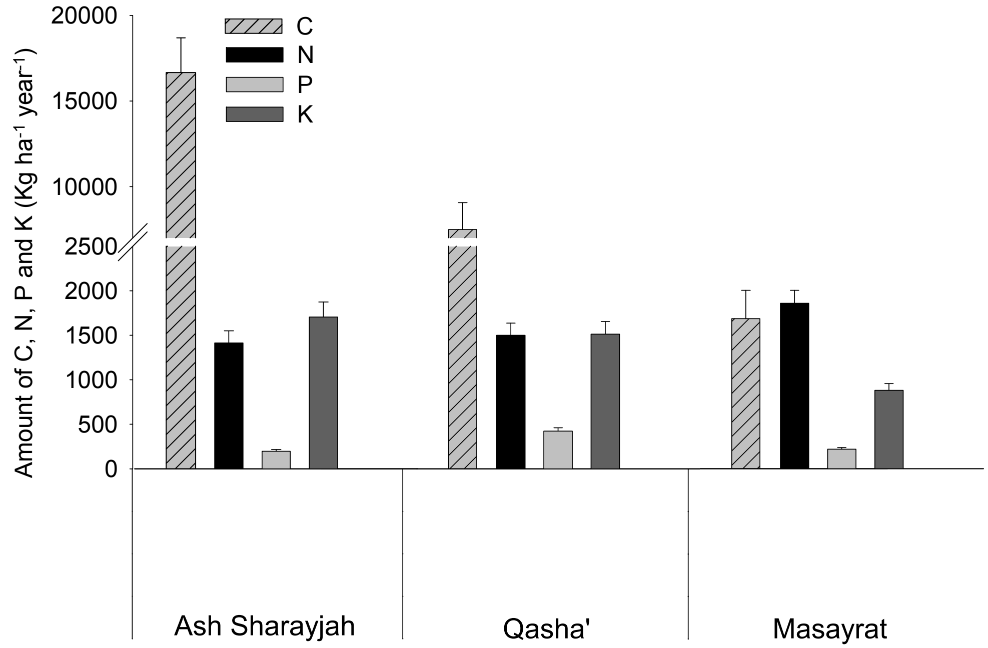

Figure 7. Annual total balances of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) in pomegranate fields (n = 6) at the oases of Ash Sharayjah and Qasha', and in date palm fields at the oasis of Masayrat ar Ruwajah in northern Oman during the period of April 2009 to April 2010. Data represent means with vertical bars indicating ± one standard error.

Annual apparent NUE was much higher in annual crops than in perennials. Similar to our results, data obtained from 197 countries indicated average use efficiencies of 50% for N, 40% for P, and 75% for K (Sheldrick et al., 2002). The lower NUE of the perennial trees compared to garlic was largely due to much lower nutrient outputs in fruit production. However, calculation of the annual apparent NUE in perennial trees based on harvested yield does not take into account total nutrient uptake and storage by the trees (Hedlund et al., 2003). The high K uptake by garlic crops raise questions about soil K sources. Further investigations can play an important role in assessing the effect of soil K depletion on long-term crop production.

The reliability of our total C balances is severely hampered by the lack of reliable data on root C contributions which has been the subject of much recent research (Kuzyakov et al., 2001; Kuzyakov, 2002; Werth and Kuzyakov, 2008; Pumpanen et al., 2009). From their comprehensive studies under controlled conditions Kuzyakov and Larionova (2006) concluded that root respiration contributed approximately 40% to the total CO_2 efflux from soils. Kelting et al. (1998) have partitioned soil respiration into: (1) 32% as a root respiration, (2) 20% as microbial respiration in the rhizosphere, and (3) 48% as root free soil respiration (basal respiration). A recent study (Atarashi-Andoh et al., 2011) on the partitioning of soil heterotrophic and autotrophic respiration using ^{14}C concluded that about 31-39% of the total CO_2 efflux from the soil were from root-derived C. Such isotope studies would be necessary to trace the fate of the assimilated C by annual and perennial trees in agroecosystems such as ours.

3.6 Conclusions

The patterns of annual C and N emissions reflected the high application rate of manure as well as the variation of air temperature along the altitudinal gradient within the three oases. The removal of K in harvested garlic greatly exceeded inputs. Our data indicate a very high soil biological activity in all three oases and support previous findings demonstrating the very high C and N turnover under irrigated subtropical conditions such as in our study area. To better tailor plant nutrient uptake to release from the large amounts of manure applied, further research under controlled conditions may be necessary that systematically examines the role of manure quality and incorporation on decomposition.

Acknowledgement

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Chapter 4. Gaseous nitrogen and carbon emissions from Al Jabal Al Akhdar oasis systems in northern Oman[3]

Abstract

The effects of temperature, irrigation, and manure quality on gaseous nitrogen (N) and carbon (C) emissions from irrigated agriculture in subtropical high mountain agriculture are poorly investigated. To fill this gap of knowledge, we conducted a study in two oases of different altitudes in Al Jabal Al Akhdar mountains of northern Oman. In 2009 and 2010 goat manure was applied to maize (*Zea mays* L.) at a typical rate of 29 and 24 t dry matter.ha^{-1}, C/N ratios of 18 and 16, and a total N concentration of 2.4 and 2.2% in Al'Ayn (57^{o}39$^'$30$^"$E, 23^{o}04$^'$10$^"$N, 1,900 m asl) and Masayrat ar Ruwajah (57^{o}40$^'$13$^"$E, 23^{o}02$^'$37$^"$N, 1,030 m asl), respectively. Despite the significantly higher air temperature ($P<0.001$) during the whole experimental period at the lower oasis, emissions of NH_3-N (119 g ha^{-1} h^{-1}) and N_2O-N (184 g ha^{-1} h^{-1}) were highest at Al'Ayn during the first day after manure application. Subsequently, these emissions decreased very fast and reflected changes in air temperature rather than soil temperature. In contrast, CO_2-C emissions were very high throughout the entire experimental period averaging 9.2 and 7.7 kg ha^{-1} h^{-1} in Masayrat and Al'Ayn, respectively. Similarly, CH_4-C emissions were higher in Masayrat and showed a positive correlation with air temperature (r^2=0.647, $P<0.001$). The higher initial NH_3-N and N_2O-N emissions in Al'Ayn most likely reflect the higher rate of manure application with higher C/N ratio and total N concentration. Overall the data reflect the high biological activity of the man-made soils in these irrigated agro-ecosystems.

Keywords: Ammonia; carbon dioxide; di-nitrous oxide, gaseous emission; methane; mountain agriculture.

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Introduction

Recently, agro-ecosystem of the ancient arid mountain oases of Oman received increasing attention in order to unravel the causes of their often millennia old sustainable productivity (Golombek et al., 2007; Siebert et al., 2007). Crop rotation, diverse germplasm (Gebauer et al., 2007), high quality irrigation water and a well managed irrigation of man-made soils with superior drainage (Luedeling et al., 2005), and the regular application of large amounts of manure composts are thought to be key features in maintaining soil fertility on the silt-filled terrace fields of these oases (Buerkert et al., 2005). On the other hand these systems are model cases for the role that intensive irrigated agriculture plays in enhancing nitrogen (N) and carbon (C) emissions as ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) to the atmosphere (Cole et al., 1997; Dobbie and Smith, 2001; Velthof et al., 2005; Gregorich et al., 2005; Konda et al., 2008; Predotova et al. 2010). Gaseous N emissons from soils are due to complex microbial processes that are dependent in time and space on a soil's redox potential, pH, temperature, and microbial processes (Ji and Brune, 2006; Saad and Conrad, 1993; Dobbie and Smith, 2001). Previous studies reported high N_2O emissions as a result of denitrification at water filled pores space (WFPS) ≥ 70%, while N_2 production was observed at WFPS ≥ 90% (Ruser et al., 2006).

CO_2 emissions from agricultural soils are governed by root, microbial and faunal respiration, and by the oxidation of soil organic matter by soil microorganisms. Likewise, CH_4 fluxes from agricultural soils depend on the anaerobic decomposition of soil organic matter and the activities of methanogenic and methanotrophic soil microbes (Segers, 1998; Metay et al., 2007; Pozdnyakov et al., 2010)

Due to the typically high manure application rates reflecting the connectedness of agricultural and pastoral components of the landuse systems, Omani oases were described as a temporary nutrient sink (Buerkert et al., 2005). However, little information is available on gaseous losses of C and N under such irrigated subtropical conditions with year-round high temperatures (Wichern et al., 2004). Based on preliminary findings, we hypothesized for this study that across irrigation cycles with resulting changes in soil moisture, gaseous N and C emissions varied strongly with altitude (Buerkert et al., 2010).

Materials and Methods

4.2.1 Site description

The study was conducted along one of the steepest elevation gradients of agriculturally used land on the Arabian Peninsula. We used the two mountain oases of Al'Ayn (57°39'30"E, 23°04'10"N, 1,900 m asl) at the top of the Wadi Muaydin watershed limiting the Sayq Plateau of Al Jabal Al Akhdar (Arabic: 'Green Mountains') to the south, and of Masayrat ar Ruwajah (57°40'13"E, 23°02'37"N, 1,030 m asl), the lowest oasis of the watershed. During winter, the minimum air temperature was 1 °C at Al'Ayn and 9 °C at Masayrat, while respective summer maxima were 37 °C and 43 °C. Erratic rainfall is a major factor limiting the sustainability of irrigated agriculture in northern Oman (Luedeling et al., 2005; Luedeling and Buerkert, 2008). Therefore since centuries farmers in these oases irrigate their terraced agricultural area using an *Aflaj* irrigation system (Arabic: '*aflaj*' is the plural of '*falaj*') whose sophisticated management is considered a key factor for the sustainability of agricultural production in Oman (Siebert et al., 2007).

In Al'Ayn agricultural production relies on typical Mediterranean perennials such as pomegranate (*Punica garanatum* L.), rose (*Rosa damascene* L.), apricot (*Prunus armeniaca* L.), peach (*Prunus persica* L), walnut (*Juglans regia* L.), apple (*Malus domestica* L.), plum (*Prunus domestica* L.), pear (*Pyrus communis* L.), fig (*Ficus carica* L.), and grape (*Vitis vinifera* L.), and on annual crops like garlic (*Allium sativum* L.), alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.), and barley (*Hordeum vulgare* L.). In Masayrat instead, agriculture is dominated by groves of date palm (*Phoenix dactylifera* L.), lime (*Citrus aurantiifolia* L.), sweet lime (*Citrus limettioides* L.), bitter orange (*Citrus aurantium* L.) citron (*Citrus medica* L.) orange (*Citrus sinensis* L.), lemon (*Citrus lemon* L.), banana (*Musa x paradisiaca* L.), papaya (*Carica papaya* L.), guava (*Psidium guajava* L.), and mango (*Mangifera indica* L.) while annual crops are similar to those in Al'Ayn.

4.2.2 Climatic conditions and soil properties

In both oases experimental data were collected during the summer months (May-September) of 2009 and 2010 in fields prepared to grow fodder maize. For this purpose six fields were selected at each location and prior to measurements of gas emissions four representative samples were collected from the topsoil (0-0.15m) of each field, pooled, air-dried, and sieved to < 2 mm. Soil pH was measured at 1:2.5 soil/water and salinity as electrical conductivity (EC) in a 1:10 soil/water solution (GMH 3410, Greisinger Electronic, Regenstauf, Germany). Soil total N and C were measured by a thermal conductivity detector (Vario MAX CHN Analyser, Elementar Analysensysteme GmbH, Hanau, Germany). The percentage of inorganic soil C (C_{inorg}) was quantified using a calcimeter as 12% of $CaCO_3$. Soil phosphorous (P) was extracted with $NaHCO_3$ according to Olsen (Watanabe and Olsen, 1965) and measured with a spectrophotometer (U-2000, Hitachi Ltd, Tokyo, Japan). To determine soil potassium (K) concentration, samples were extracted with calcium acetate lactate and extracts measured with a flame photometer (743 AutoCal, Instrumentation Laboratory Co., Bedford, MA, USA).

For the analysis of the effects of elevation on air temperature and relative humidity, the latter were measured at 30 min intervals throughout the research period using Onset Hobo-Pro® climate loggers (Onset Computer Co., Bourne, MA, USA). In addition to these devices Watchdog® weather stations (Spectrum Technologies Inc., Plainfield, IL, USA) were placed at representative locations at Al'Ayn and Masayrat oases to record climatic data throughout the research period.

4.2.3 Application of manure

Before planting of crops, farmers divided their terraced fields into typical 1-6 m^2 ridge-surrounded irrigation plots (Arbic: '*Jalba*') to facilitate flood irrigation and manure application. The amount of dry goat manure applied to each experimental field was 29 t ha^{-1} in Al'Ayn and 24 t ha^{-1} in Masayrat. From each oasis six manure samples were collected at application, pooled, dried at 60 ^oC, ground, and analysed for N, P, K, sodium (Na) and organic carbon (C_{org}).

4.2.4 Measurements of N and C emissions

As labour constraints did not allow to measure gaseous emissions of NH_3-N, N_2O-N, CO_2-C, and CH_4-C in true replicate plots simultaneously over time and space, these were quantified in three plots (sub-samples) of one representative field at each oasis. Consequently relationships between gaseous emissions, soil moisture, and air temperature were reported for each oasis separately. Fluxes were measured using a photo-acoustic infra-red multi-gas analyzer (INNOVA 1312-5, INNOVA AirTech instruments, Ballerup, Denmark) to which a Teflon®-coated cuvette made of a standard

PVC tube with 0.30 m diameter and 0.11 m high was attached (Predotova et al., 2010, 2011). To insure a tight fitting of the cuvette (closed chamber) during measurements intervals, four PVC rings with a diameter of 0.30 m and height of 0.06 m were installed into the ground of each plot to avoid leakage or gas penetration from the outside. Inside of the cuvette a thermo-hygrometer sensor (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany) allowed to monitor temperature and humidity. Measurements were carried out on five occasions per day, lasting from 6 am until 8 pm. Each measurement lasted for two hours (6-8 am, 9-11 am, 12-2 pm, 3-5 pm, and 6-8 pm). All measurements were repeated three times per ring to obtain a total of 12 measurements per occasion. Measurements started immediately after the first irrigation and application of manure and were repeated every day throughout two irrigation cycles. To quantify the effect of soil moisture content and temperature on gaseous emissions, volumetric water content of the soil was determined at 5 cm depth with a TDR/FDR soil moisture meter (Theta Probe Sensor attached to Infield7b, UMS, Munich, Germany) and soil temperature with a digital thermometer (Carl ROTH GmbH, Karlsruhe, Germany).

4.2.5 Statistical analysis

Data were analyzed with SPSS version 17.0 (SPSS Inc., Chicago, USA), while graphs were made with Sigma Plot 10.0. Normality of data was tested by the Kolmogrov-Smirnov test and climatic differences between the two oases with a t-test at $P < 0.05$. Data whose residuals were not normally distributed were log-transformed before statistical analysis was performed. Repeated measures analysis of variance (ANOVA) with Greenhouse-Geisser correction for sphericity was performed for gases at each oasis separately to determine possible trends of emissions over time.

Results

4.3.1 Climatic conditions

Due to the major altitude differences air temperatures at Masayrat were significantly ($P<0.001$) higher than those at Al'Ayn (Figure 1b) with maximum / minimum values of 37.6°C / 26.3°C and 30.5°C / 23.5°C, respectively. Water availability-dependent average irrigation frequency was 2-3 days at Masayrat and 4-5 days at Al'Ayn. Between irrigation events volumetric soil moisture content varied between 40% after irrigation to 20% before the next event. Wind speed was significantly higher ($P<0.001$) at Al'Ayn than at Masayrat, reaching respective maxima of 10.6 and 2.2 km h^{-1} (Figure 1c). On the other hand, relative air humidity was higher (P=0.04) at Masayrat

4.3.2 Soil and manure properties

Soil inorganic carbon (C_{inorg}) was > 4% in both oases reflecting $CaCO_3$ percentages > 40% (Table 1), and organic carbon (C_{org}) values were 5.3 and 6.6% in Al'Ayn and Masayrat, respectively. Soil N concentrations and pH values were similar in both oasis soils. Although electrical conductivity (EC_o) was higher at Masayrat than at Al'Ayn, the data did not indicate saline conditions. Total N and C_{org} values in the applied goat manure were higher in Al'Ayn than in Masayrat with C/N ratios varying between 18 and 16 at similar P, K and Na concentrations (Table 2).

Table 1. Soil chemical properties of the selected fields at the oases of Al'Ayn and Masayrat ar Rawajah on Al Jabal Al Akhdar, northern Oman.

Villages	EC	pH	C_{inorg}	$CaCO_3$	C_{org}	N	P (Olsen)	K
	dS/m		%	%	%	%	P_2O_5 g/100g	mg/g
Al'Ayn	0.15	7.98	5.1	42.6	5.3	0.5	0.032	0.1
Masayrat	0.22	7.95	4.3	40.0	6.6	0.4	0.019	0.2

Table 2. Concentration of carbon (C) and mineral elements in goat manure collected from the oases of Al'Ayn and Masayrat ar Rawajah on Al Jabal Al Akhdar, northern Oman.

Manure	N	P	K	Na	C_{org}	C/N ratio
	-------------------- mg g^{-1} --------------------				%	
Al'Ayn	24	4.4	13.5	2.7	42.8	18
Masayrat	22	4.5	14.3	3.2	36.3	16

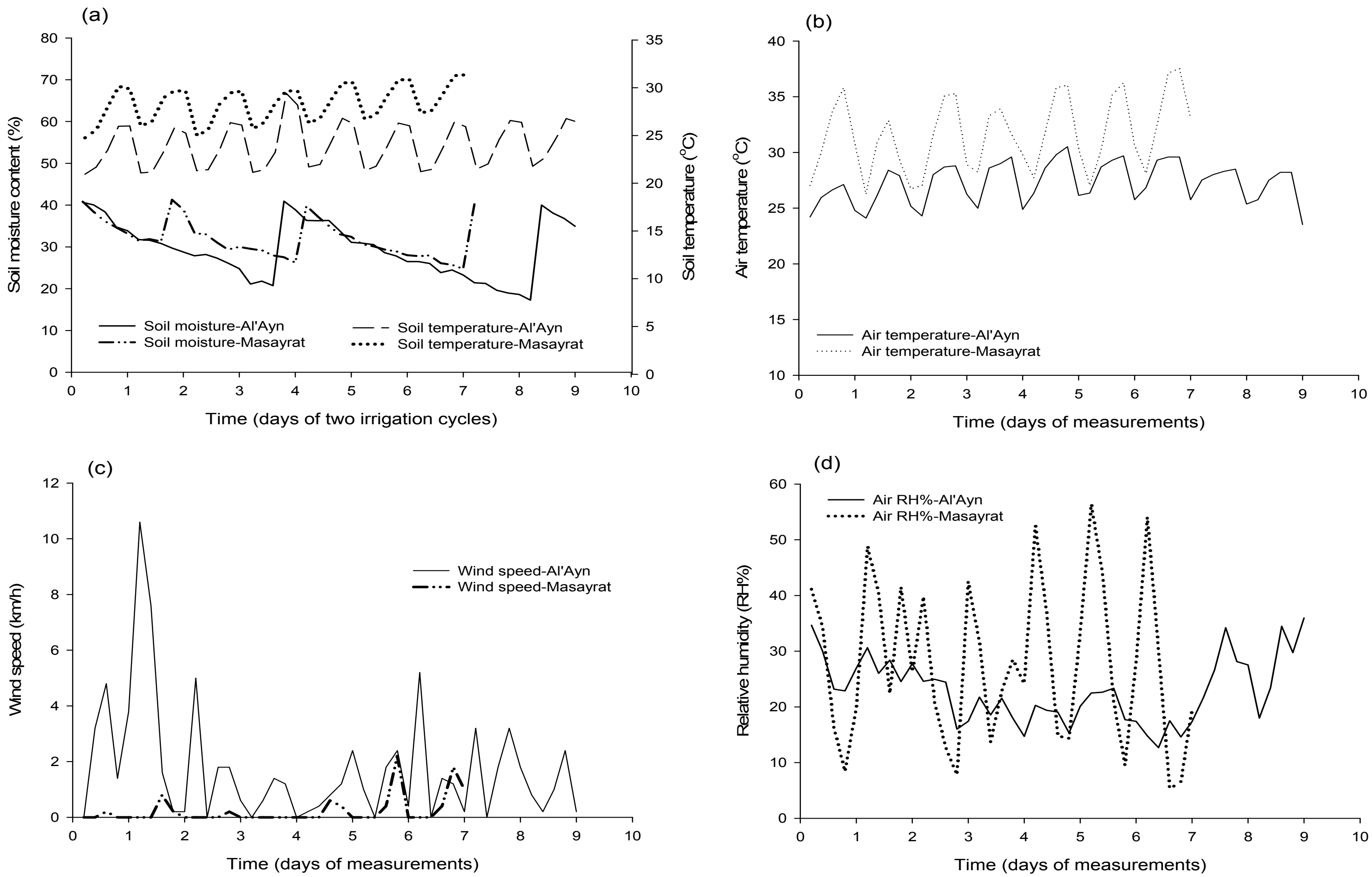

Figure 1. Average soil moisture and temperature at 5 cm depth (a), ambient air temperature (b), wind speed (c) and ambient air relative humidity (RH %; d) during the experimental period (10 days) at the oases of Al'Ayn and Masayrat ar Rawajah, Al Jabal Al Akhdar, northern Oman.

4.3.3 Gaseous emissions

In Al'Ayn, fluxes of NH_3-N and N_2O-N reached maximum values of 119 and 184 g ha^{-1} h^{-1} during the first day after manure application, however, thereafter emissions quickly declined (Figure 2). Although N_2O-N emissions were enhanced by the second irrigation event on the fourth day, differences were insignificant after the second day. As a result of the difference in flux rates between the first two days and the subsequent ones, NH_3-N and N_2O-N data were not normally distributed (K-S test, $P<0.001$) and both periods were thus analyzed separately. Similar trends were determined from Masayrat fields with maximum initial NH_3-N emissions of 36 g ha^{-1} h^{-1} and N_2O-N fluxes of 39 g ha^{-1} h^{-1}. Annual gaseous N emitted from maize plots in Al'Ayn and Masayrat totaled 225 and 297 kg ha^{-1} yr^{-1}, respectively.

Throughout the entire experimental period, CO_2-C fluxes averaged 7.7 and 9.2 kg ha^{-1} h^{-1}, whereas CH_4-C fluxes averaged 0.11 and 0.17 kg ha^{-1} h^{-1} in Al'Ayn and Masayrat. Consequently, cumulative gaseous C emitted from maize fields in Al'Ayn was 68.4 t ha^{-1} yr^{-1} compared to 82.1 t ha^{-1} yr^{-1} from Masayrat.

The linear regression analysis revealed that air temperature significantly affected N and C emissions, more than soil moisture in both oases. However, this was not the case for the N_2O-N emissions from Al'Ayn ($P=0.071$). Meanwhile, no significant relationship ($P>0.05$) was observed between soil temperature and any of the emissions in either oases. During the first two days, NH_3-N and N_2O-N emissions were positively correlated with soil moisture ($r^2=0.753$, $P<0.001$), ($r^2=0.532$, $P=0.010$), respectively. Thereafter, N_2O-N emission was weakly correlated with soil moisture ($r^2=0.128$, $P=0.020$), while the effect of soil moisture on NH_3-N emissions was statistically not significant ($P=0.282$). In contrast, air temperature enhanced fluxes of CO_2-C ($r^2=0.253$, $P<0.001$) and CH_4-C ($r^2=0.154$, $P=0.005$).

In Masayrat, air temperature positively affected N and C emissions, while there was no obvious correlation ($P>0.05$) with soil moisture. Due to the non-normally distributed residuals, log-transformed NH_3-N and N_2O-N variables were used to perform regression analysis. The NH_3-N, N_2O-N, CO_2-C, and CH_4-C emissions were affected by air temperature ($r^2=0.407$, $P<0.001$), ($r^2=0.367$, $P<0.001$), ($r^2=0.279$, $P<0.001$), and ($r^2=0.647$, $P<0.001$), respectively.

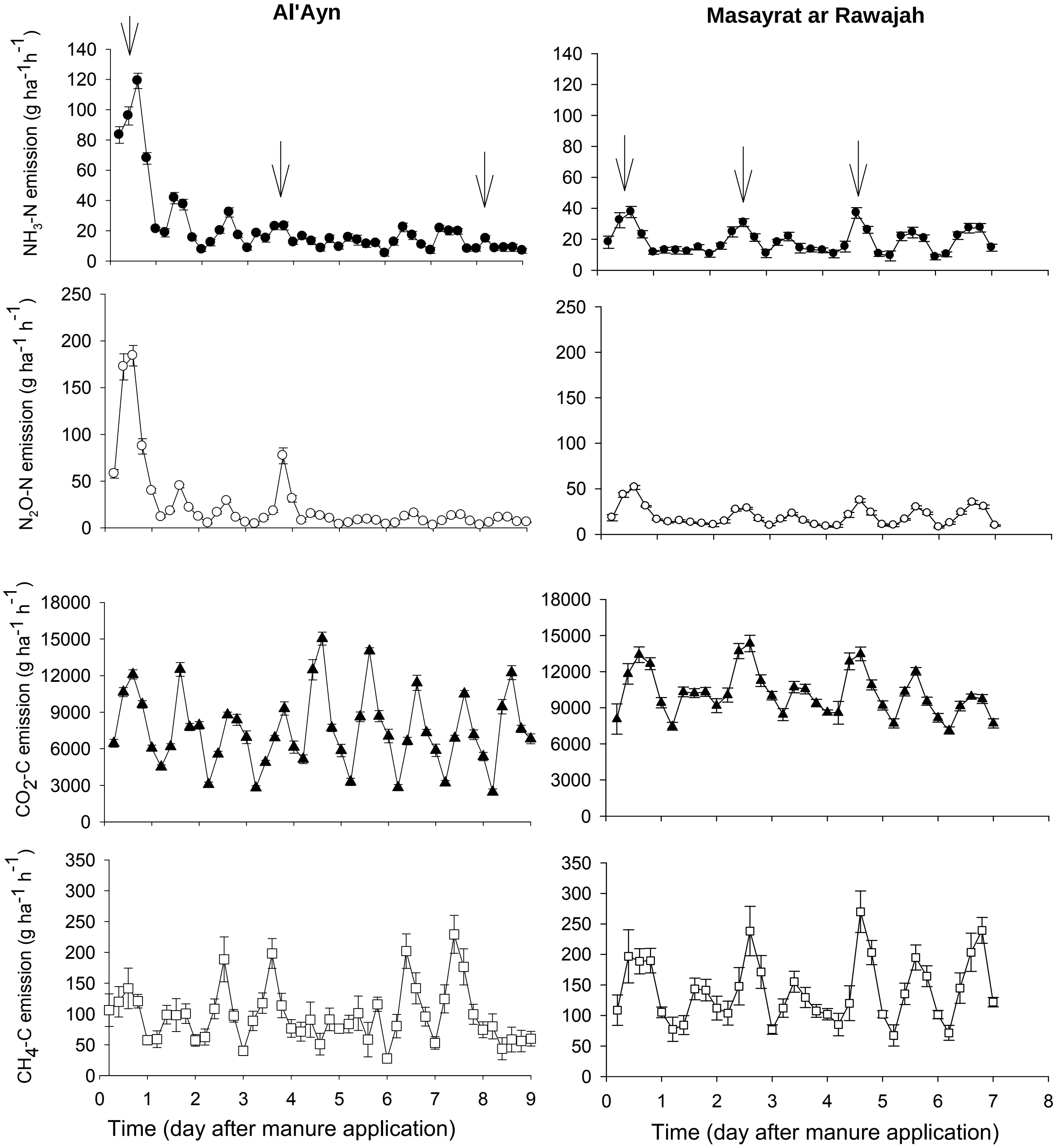

Figure 2. NH_3-N, N_2O-N, CO_2-C and CH_4-C emissions from the two oases of Al'Ayn and Masayrat ar Rawajah at Al Jabal Al Akhdar, northern Oman, throughout the research period. Vertical bars indicate standard errors of the means. Arrows indicate irrigation events.

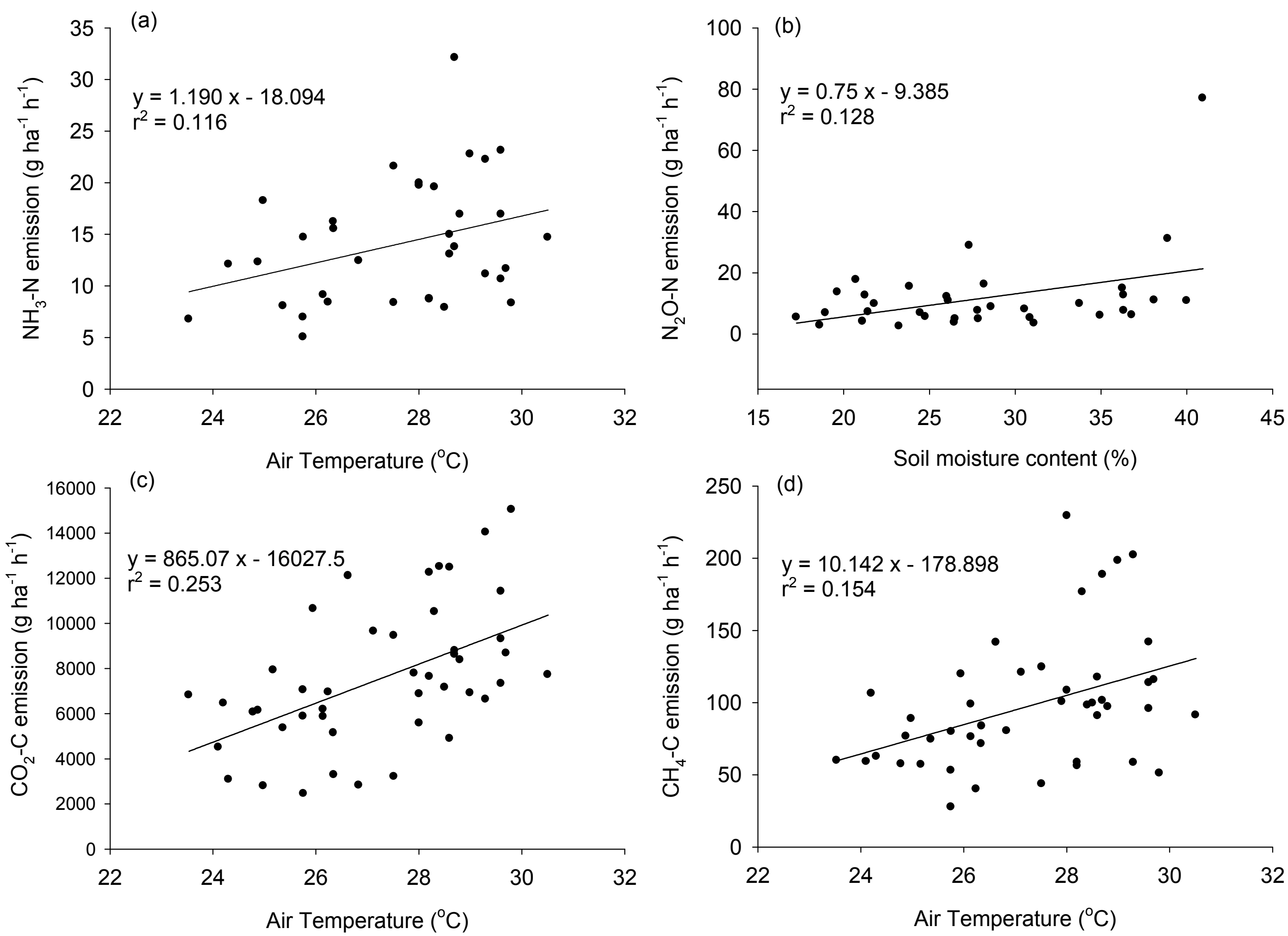

Figure 3. Relationship between gaseous emissions of NH_3-N, N_2O-N, CO_2-C, and CH_4-C with air temperature and soil moisture at the oasis of Al'Ayn, Al Jabal Al Akhdar, northern Oman, during the experimental period.

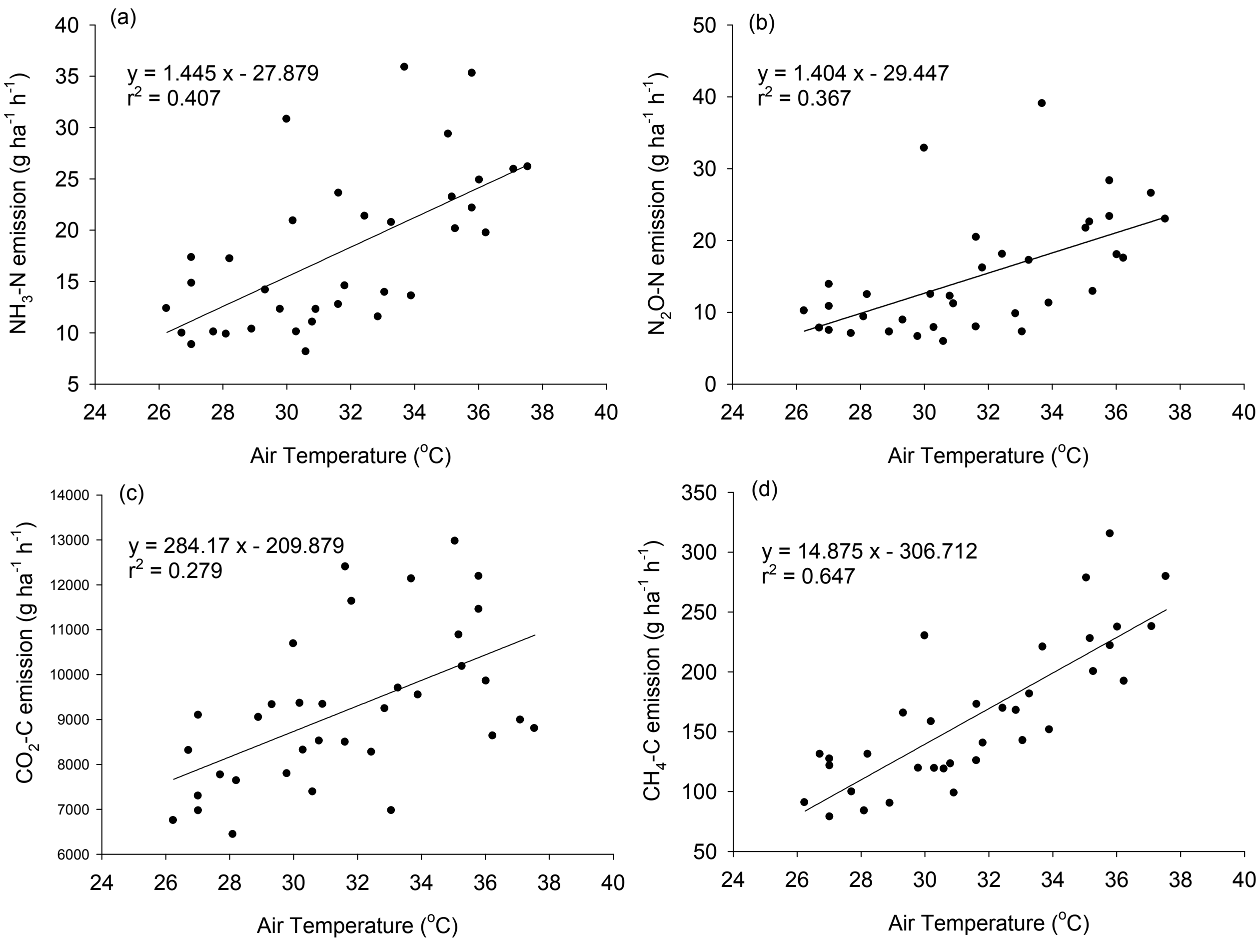

Figure 4. Relationship between gaseous emissions of NH_3-N, N_2O-N, CO_2-C, and CH_4-C with air temperature and soil moisture at the oasis of Masayrat ar Ruwajah, Al Jabal Al Akhdar, northern Oman, during the experimental period.

Discussion

4.4.1 NH_3-N and N_2O-N

Although over the entire experimental period of the first manure application air temperatures were higher at Masayrat than at Al'Ayn, highest emissions of NH_3-N (119 g ha^{-1} h^{-1}) and N_2O-N (184 g ha^{-1} h^{-1}) were recorded at Al'Ayn. While air and soil temperature and soil moisture are certainly the most important factors affecting NH_3-N and N_2O-N volatilization (Mkhabela et al., 2009), many other factors also determine this process (Mugasha and Pluth, 1995). The higher initial NH_3-N and N_2O-N emissions in Al'Ayn most likely reflect the higher rate of manure application with higher C/N ratio and total N (24 mg g^{-1}). The high post-application emissions of NH_3-N and N_2O-N from Al'Ayn probably reflected the high initial NH_4^+ and NO_3^- in the applied manure as a consequence of the aerobic microbial activity through ammonification and nitrification (Burger and Jackson, 2003). Breuer et al. (2002) reported that the nitrification process was positively correlated with increasing soil temperature, but negatively affected by increasing soil WFPS. After the initial two days of our experiment, N_2O-N emission from Al'Ayn was more affected by soil moisture (r^2=0.128, P=0.020), while the effect of soil moisture on NH_3-N emissions was statistically not significant (P=0.282). This likely reflects the fact that N_2O-N emissions are strongly governed by the soil moisture status (Bateman and Baggs, 2005). In our experiment manure storage may have affected manure quality as farmers in both oases typically store animal faeces in heaps or PE fiber bags laying in the fields until used for the next cropping season. Previous findings (Buerkert et al., 2010) indicated large N and C losses from prolonged field storage of manure under such conditions.

In both oases experimental soils were alkaline thereby enhancing temperature- and moisture-driven NH_3 volatilisation (Table1 and 2; Chantigny et al. 2004; Ji and Brune 2006). According to Huijsmans et al. (2001) NH_3 volatilization depends on the initial NH_4^+ content of the manure, application rate, wind speed, air temperature and relative humidity.

4.4.2 CO_2-C and CH_4-C

In both oases C-fluxes were substantially higher at mid-day than during morning and evening hours, reflecting the direct effect of temperature on the daily release pattern

(Figure 2). As a sequence of the shorter irrigation intervals at Masayrat, soil moisture over time did not differ in both oases even though air temperature was significantly ($P<0.001$) higher at Masayrat. The high CO_2-C flux rates measured at Al'Ayn and Masayrat confirm previous survey results of Buerkert et al. (2010) who determined similar values for irrigated soils of these oases. These C turnover rates are an indicator of microbial activities and root respiration (Dhillion et al., 1995; Kelting et al., 1998; Kuzyakov and Domanski, 2002) but the high soil carbonate concentrations ($CaCO_3$ or $MgCO_3$) could also have contributed to CO_2 emissions.

The measured CH_4-efflux reflects the net effect of methanotrophic and methanogenic processes (Whalen and Reeburgh, 1996; Trotsenko et al., 2009) that are governed by the soils' redox potential. Our results indicated high CH_4-C emissions even at low moisture of the surface soil such as at the end of the irrigation cycle. Previous findings underlined the role of anaerobic microsites in soil layers for CH_4 production (Smith et al., 2003) and of non-microbial aerobic CH_4 emission from dry and fresh organic matter and plant materials (Keppler et al., 2006; Vigano et al., 2008; Brüggemann et al., 2009). Additional work using isotope signatures may be necessary to understand the pathway of non-microbial aerobic CH_4 emissions and their role in irrigated C_{org}-rich soils such as ours (Vigano et al,. 2009).

Conclusions

Our data provide evidence of the high biological activity of the irrigated Irragric Anthrosols of intensively manured oasis agroecoystems in Oman. Under the given subtropical climate conditions, the turnover of soil organic matter is very fast and leads to large C and N emissions, particularly immediately after the addition of animal manure with a narrow C/N ratio. Our results showed a clear effect of air temperature and soil moisture on N and C fluxes that are modified by the quality and quantity of the applied manure. To better understand the interactions of temperature, moisture and substrate quality in these soils, further studies under controlled conditions are necessary to unravel the turnover processes for the different C and N pools.

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Chapter 5. General Discussion

5.1 Methodology

Agriculture in the ancient mountain oases of Al Jabal Al Akhdar relies heavily on regular application of large quantities of animal manure whose C and N turnover and release dynamics have been the subject of this study. Different approaches were used in chapter 2, 3 and 4 to assess C and N fluxes in order to verify data from previous studies (Buerkert et al. 2010; Diogo et al. 2010; Predotova et al. 2010; Siegfried et al. 2011). Our data confirmed that the large manure inputs are major sources of C, N, P, and K and the rate of applied manure as well as soil moisture along the altitudinal gradient within the oases in Wadi Muyadin determine release rates (chapter 4).

To quantify C and N gaseous losses, a portable photo-acoustic infra-red multi-gas analyzer (INNOVA 1312-5, INNOVA AirTech instruments, Ballerup, Denmark) was used as described previously (Buerkert et al. 2010; Predotova et al. 2010; Siegfried et al. 2011). The system has the advantage of enabling the simultaneous measurements of four different gases with a large number of replications under field conditions. However, in this study, the sources of electricity as well as the variable micro-topographic structure of the oasis terraces limited our ability to obtain even larger datasets to account for the typical spatio-temporal variability in gaseous emissions rates under field conditions.

Rottmann and Joergensen (2011) compared a NaOH-static-chamber, a GC-dynamic-chamber, an infrared (IR) analyzer and the photo-acoustic system (PAS) in determining CO_2 emanation from maize-staw-amended soil columns. They reported that all four methods were highly correlated, with *r* values between 0.90 and 0.93. However, CO_2 fluxes were significantly over-estimated by the PAS in their loamy experimental soil, compared to the other methods. They attributed this to soil properties and nevertheless concluded that short 2 min measurement intervals of the IR and PAS methods allow accurate rapid field measurements. In hot climates such as in Oman, our data indicated to use one minute measuring intervals to avoid an underestimation of gas accumulation due to the increase in temperature and humidity, which inside the closed chamber can reach saturation within only a few minutes (Predotova et al. 2009).

In our study we used ion-exchange resins to quantify leaching losses of mineral N. Previously ion exchange resins were used by many groups to determine the plant availability or leaching of ions under laboratory or field conditiond (Schnabel 1983; Crabtree and Kirkby 1985; Skogley and Dobermann 1996; Friedel et al. 2000; Langlois et al. 2003; Uusitalo and Ekholm 2003; Predotova et al. 2010; Safi et al. 2011; Siegfried et al. 2011). Siemens and Kaupenjohann (2004) compared methods of tensionmeter-controlled suction plates, wick samplers, and ion exchange resin boxes and Zotarelli et al. (2007) studied methods of soil coring, suction cups, and subsurface drainage lysimeters in monitoring nitrate leaching in sandy soils. The data show that each of these methods has its limitations, particularly with respect to their field applicability, labour and investment costs needed (Kosugi and Katsuyama 2004; Bischoff 2007; Zotarelli et al. 2007).

The current status and limitations of ion-exchange methods to quantify leaching losses are discussed by Bischoff (2007). Although he reported that this technique was used successfully to measure long-term leaching losses under field conditions, he recommended that no less than 10 replications per homogenous field be used to obtain data with a mean ±20% at >90% probability. Results of Templer and Weathers (2011) confirm that mixed ion-exchange resins can also be used to accurately measure natural abundance of isotopic values of NO_3 in samples of atmospheric deposition. Recently, Siegfried (2011) conducted a laboratory experiment to determine the average ion recovery rate from mixed bed anion-cation exchange resins. He reported recovery rates of 99% (± 6), 100% (± 8), 109% (± 6), and 151% (± 12) for NO_3-N, NH_4-N, PO_4-P, and K, respectively.

5.2 Carbon and nutrient balances

Over centuries farmers on Al Jabal Al Akhdar have learned to adapt to changing water availability and scarcity by reducing the size of irrigated plots (Arbic: ‘*Jalba*’), planting at intervals, pre-mature harvesting of crops and their use as fodder, and the development of multi-storey landuse systems with a high water use efficiency. Our results show that annual C surpluses in pomegranate and date palm fields were 16.7, 7.5, and 1.7 Mg ha^{-1} at Ash Sharayjah, Qasha’ and Masayrat, respectively (chapter 3). Date palm fields had with 1857 kg N ha^{-1} the highest total annual N surpluses, but pomegranate fields at Ash Sharayjah and Qasha’ also had positive annual N balances. In garlic fields, annual N surpluses were 915 and 826 kg ha^{-1} at Ash Sharayjah and Masayrat, respectively. In contrast annual K balances were negative in both oases. These results are in line with those of Siegfried et al. (2011) in a coastal oasis in northern Oman. However, the high K uptake by garlic crops raised many questions about the soil's K supply. Badraoui et al. (1992) observed high K uptake in ryegrass as a result of the release of non-exchangeable K from mica interlayers.

Although our calculations revealed large C surpluses of 12.5 t ha^{-1} for garlic at Ash Sharayjah, C balances were with -5.5 t ha^{-1} strongly negative at Masayrat. These negative C balances were mainly the consequence of high CO_2-C emissions. These results were consistent with those reported by Siegfried et al. (2011) for organic vegetable production in the coastal oasis of northern Oman. Although less manure was applied in these oases compared to those in our study, total gaseous C losses were nearly the same as those in our study. High CO_2-C emissions up to 26 t ha^{-1} yr^{-1} were also reported for urban vegetable fields in Niamey, Niger (Predotova et al. 2010).

Gaseous losses could be reduced by incorporating manure into soil surface. Webb et al. (2010) reported a 90% reduction in NH_3 and N_2O emissions after immediate manure incorporation by ploughing which also merits to be investigated in our landuse systems.

5.3 Land use changes

Optimizing the use of irrigation water is a major challenge for agriculture in these oases, particularly given ever increasing competition for this most limiting resource (chapter 2). Traditionally, farmers of these oases adapt to variation of irrigation water supply by minimizing the growing area of annual crops, leaving these areas uncultivated through drought seasons (Luedeling and Buerkert 2008). In this study, a remarkable reduction in annual crop area was observed in 2009 for all oases. Our results suggested that water scarcity as a result of low precipitation and the increase in urban water consumption cause such changes in land use.

Dickhöfer (2009) has reported major social and economical changes in these oases. In all households, children aged 6-18 attended school, while 28% of the households have at least one family member studying in college or undergoing professional training. In addition, many people have moved from the oases to Sayh Qatanah (the modern town in Al Jabal Al Akhdar) or to other lowland towns such as Birkat Al Mauz or even to Muscat, the country's capital. Consequently, unpaid family labour is no longer available for crop production and livestock husbandry and foreign labourers are hired to work the land.

Policy makers need to understand the complexity of the oases system in order to meet social, economic and ecological sustainability needs. Insuring the availability of water and skilled labour as well as proper marketing of agricultural produce are main factors in preserving Omani agro-pastoral oases as livelihood systems rather than as mere museum structures.

Table 1. Research hypotheses (chapter 1), their verification and future recommendations.

Research Hypotheses	Verification & Justifications	Implementations & Recommendations
• Variations of annual precipitation as well as the unsustainable exploitation of groundwater have a direct impact on the availability of irrigation water.	✓ Confirmed: Total domestic water consumption has more than doubled leading to greater pressure on ground water. ➢ Timing and quantity of precipitation has a direct impact on water flow rates from springs used for irrigation water.	❖ Government efforts to supply the area with desalinized sea water. ❖ Harvesting rainwater as an alternative source for irrigation. ❖ Further studies on water quality from rainwater harvesting systems.
• Oases are a large sinks for carbon and nutrients that are subjected to a fast turnover. • Carbon and nutrient turnover are faster at low altitude oases because of their higher temperature and more frequent wet-dry cycles.	✓ Confirmed: The turnover of soil organic matter is very fast under the given subtropical climate conditions and leads to large N and C emissions. ➢ The large manure quantities that are applied continuously to the man-made terraces are responsible for sustaining soil fertility.	❖ To better tailor carbon and nutrient release to crop needs, further studies are strongly recommended to investigate the effects of different manure application rates on yield and long-term soil fertility.
• Under hyper-arid hot climate conditions gaseous C and N emissions are larger than through leaching.	✓ Partly confirmed: Results revealed high N emissions and very low N leaching. ➢ Although nutrient budget calculations indicated large surpluses, the relationship between high gaseous emissions and low leaching rates remains unclear. ➢ The resin technique does not allow to determine leached organic C and N forms.	❖ Studies comparing different techniques to measure leached mineral and organic C and N fractions are needed .
• Gaseous N and C emissions depend on manure quality, soil moisture, and air temperature.	✓ Confirmed: High initial NH_3-N and N_2O volatilization in manure with a narrow C/N ratio. ➢ Thereafter, air temperature affects emissions of NH_4, CO_2, CH_4 and N_2O particularly in low altitude conditions more than manure quality and soil moisture.	❖ Field storage of manure should be avoided. ❖ Manure should be composted with straw to enlarge the C/N ratio and consequently decrease NH_3 and N_2O emission after manure application.

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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, January 2012 Mohamed Nasser Al-Rawahi