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Field measurements of the CO_2 evolution rate under different crops during an irrigation cycle in a mountain oasis of Oman

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Abstract

For millennia oasis agriculture has been the backbone of rural livelihood in the desertic Sultanate of Oman. However, little is known about the functioning of these oasis systems, in particular with respect to the C turnover. The objective was to determine the effects of crop, i.e. alfalfa, wheat and bare fallow on the CO_2 evolution rate during an irrigation cycle in relation to changes in soil water content and soil temperature. The gravimetric soil water content decreased from initially 24% to approximately 16% within 7 days after irrigation. The mean CO_2 evolution rates increased significantly in the order fallow (27.4 mg C m^{-2} h^{-1}) < wheat (45.5 mg C m^{-2} h^{-1}) < alfalfa (97.5 mg C m^{-2} h^{-1}). It can be calculated from these data that the CO_2 evolution rate of the alfalfa root system was nearly four times higher than the corresponding rate in the wheat root system. The decline in CO_2 evolution rate, especially during the first 4 days after irrigation, was significantly related to the decline in the gravimetric water content, with $r = 0.70$. CO_2 evolution rate and soil temperature at 5 cm depth were negatively correlated ($r = -0.56$, $n = 261$) due to increasing soil temperature with decreasing gravimetric water content.

Keywords: Arid climate; Soil respiration; Sustainability

1. Introduction

Only 0.3% of Oman is covered by field and permanent crops (FAO, 1997) due to the dry and hot climate with an average annual precipitation rate of 100 mm and temperatures up to 45 °C (Dorvlo and Ampratwum, 1999). Due to these very harsh conditions for plant growth, almost the entire agriculture relies on irrigation (Norman et al., 1998). A sustainable type of oasis agriculture was developed more than 2500 years ago in the mountainous regions of northern Oman. Understanding the reasons for the sustainability of these mountain oases might help to improve the sustainability of other agricultural land use systems in arid regions. The productive area in mountain oases consists of man-made terraces and the fertility of these terrace soils relies on the soil organic matter content and its turnover, which are both strongly influenced by irrigation management.

CO_2 evolution under field conditions represents respiration by plant roots and soil organisms. Consequently, CO_2 evolution is a sensitive indicator of

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abiotic controls, crop residue decomposition, soil organic matter turnover, and ecosystem disturbance (Paul et al., 1999). However, no information is available on CO_2 evolution under the specific environmental conditions of arid mountain oases, mainly due to the many difficulties in getting access to these important and interesting forms of arid agricultural land use systems. For this reason, our objective was to determine the effects of crop, i.e. alfalfa, wheat and bare fallow, on the CO_2 evolution rate during an irrigation cycle in relation to changes in soil water content and soil temperature. This study was part of a larger project focussing on the sustainability of oasis systems, especially with respect to the question of how the current levels of agricultural inputs affect C and nutrient balance under regular irrigation and high ambient temperatures (Wichern et al., 2003).

2. Materials and methods

2.1. Study site

In the rugged western Akhdar Mountains in the north of the Sultanate of Oman the environment is characterised by high temperatures, low rainfall and high evaporation. In this arid mountainous area lies the oasis of Balad Seet (23.19°N, 57.39°E), 995 m above sea level. Two distinct seasons exist: a very hot summer with temperatures up to 45 °C lasts from May to September, whereas during the colder season from October to April temperatures decline to 5 °C. This oasis is a classic example of concentration agriculture where the input of water, organic matter and nutrients is restricted to the small areas of the field terraces. Fertilising is mainly done organically but the application of mineral fertiliser is increasing. A major source of organic matter is farmyard manure produced by the animals of the oasis or bought from nomads. Except for a few cattle, the animal husbandry is dominated by sheep and goats.

Balad Seet is a core oasis and has approximately 650 inhabitants. Its agricultural area of about 11 ha is divided into palm gardens and fields. Palm gardens cover about 60% of the area and are connected by six cropping terrace systems with an area of 4.5 ha on which annual and perennial crops are cultivated. Roughly 50% of the field area is used for the cultivation of animal fodder. Perennial alfalfa (*Medicago sativa* L.), which is used as animal fodder, is harvested up to 12 times a year. Yield decline after 3–4 years, most likely due to nematode infestation, is reported by local farmers and has been confirmed in recent surveys. Alfalfa is the crop contributing the largest part of the N input into the oasis system and was consequently chosen for the experimental survey. From October to March mainly wheat (*Triticum aestivum* L.), but also onion (*Allium cepa* L.), garlic (*Allium sativum* L.) and coriander (*Coriandrum sativum* L.) are grown once, whereas barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and maize (*Zea mays* L.) are grown twice, harvested before ripening and used as animal fodder. Typically, wheat is harvested including the roots. The straw is then fed to the animals. Wheat is the dominating crop for human nutrition and was consequently chosen for the experimental survey. The wheat was at the milky stage during the period of measurements. During the hot season from April to September about 40% of the field area is left uncultivated. On the remaining fields millet (*Sorghum bicolor* (L.) Moench) is grown twice.

With a size of 2 ha, Mazra is the largest terrace system in the oasis. A terrace system consists of terraces on different levels, which are divided into small irrigation plots (jalba) of 1–5 m^2. For irrigation the water is led from the springs through small channels (aflaj) to the particular terraces. These plots are flooded regularly every 9–21 days according to the demand of the crops and following an ancient agricultural calendar of water distribution. Due to rising evaporative demand during summer the duration of irrigation cycles is shortened.

2.2. Soil sampling and properties

In March 2002 at the end of the winter season, soil samples were taken at a depth of 0–20 cm from five fallow, five wheat, and five alfalfa plots (terraces) in the terrace system of Mazra. The samples were sieved (<2 mm), air-dried and transferred to Germany. Soil physical and chemical properties were analysed as described by Wichern et al. (2003) using standard analytical methods. The soils contained on average 36% carbonate with a large percentage of dolomite, which resulted in a relatively low soil pH between 7.8 and 7.9 (Table 1). The carbonate-free mineral material

Table 1
Soil pH, cation exchange capacity (CEC), soil organic C, total N, and the soil C-to-N ratio of the different terrace soils used for measuring the CO_2 evolution rate at the oasis of Balad Seet, Oman

Plot type	Soil pH (H_2O)	CEC (μmol C g^{-1} soil)	Soil organic C (mg g^{-1} soil)	Total N (mg g^{-1} soil)	Soil C-to-N
Fallow	7.8 a	207 a	32.4 a	3.0 a	10.9 ab
Wheat	7.9 b	224 a	26.7 a	2.7 a	9.7 a
Alfalfa	7.9 b	203 a	31.1 a	2.6 a	11.9 b

Different letters indicate a significant difference (Tukey/Kramer, $P < 0.05$, $n = 5$).

consisted of 25% sand, 56% silt and 19% clay. The cation exchange capacity (CEC) was on average 213 μmol C g^{-1} soil (Table 1) and was occupied with 2% Na, 2% K, 27% Mg, and 69% Ca. After an irrigation event, soil water content was estimated thermo-gravimetrically (about 24 h at 105 °C) in samples taken daily in duplicate at a depth of 0–20 cm from three alfalfa, three wheat and three fallow plots.

2.3. Soil respiration

On three alfalfa, three wheat, and three fallow plots, soil respiration was measured daily over a period of 2 min using a transportable infrared gas analyser with two to five replicates (Blanke, 1996). The dynamic system consisted of a chamber (100 mm diameter, 150 mm height) coupled to a portable infrared gas analyser (IRGA) in a closed circuit (PP Systems, Hitchin, Herts, UK). The flow rate through the IRGA sensor cell during measurements was approximately 0.5 l min^{-1}. Mixing the air in the closed chamber during measurements was ensured by a small fan running at very low speed inside the chamber. Each measurement took less than 2 min. The IRGA contained software to calculate CO_2 evolution rates, including corrections for a non-linear increase in chamber CO_2 concentrations, and the capacity to store all measurements in a data logger. Soil temperature at 5 cm depth was measured concurrently using an attached temperature probe. Between measurements, the chamber fan automatically ran at maximum speed for approximately 10 s to restore the tubing and IRGA sensor to the ambient CO_2 concentration. Periodical measurements were taken between 10:00 and 13:00 h local time on different days after an irrigation event from three to six plots per treatment in duplicate or triplicate subsamples.

2.4. Statistics

The results presented in the tables are arithmetic means and expressed on an oven-dry basis (about 24 h at 105 °C). The significance of differences was tested by the Tukey/Kramer test or the Scheffé post-hoc test after one-way analysis of variance. All statistical analyses were performed using StatView 5.0 (SAS Institute Inc.).

3. Results and discussion

The gravimetric soil water content decreased from initially 24% to approximately 16% within 7 days after irrigation (Fig. 1). The water content for the different crops was not significantly different, even though the decline under alfalfa was slightly faster than in the wheat and fallow plots. However, the possibility of higher transpiration losses of alfalfa in comparison to wheat are certainly important for the planning of crop rotations on the terrace soils of oases.

The mean CO_2 evolution rates increased significantly in the order fallow < wheat < alfalfa but varied considerably during the observation period (Table 2). The highest CO_2 evolution rates were measured on the first day after irrigation and the lowest at the end of the observation period (Fig. 2). However, between day 6 and 11 the differences in CO_2 evolution rate were small. The decline in CO_2 evolution rate in the alfalfa plots, especially during the first 4 days after irrigation was significantly related to the decline in the gravimetric water content with $r = 0.70$ (Fig. 3). A similar decrease was predicted by the model of Ouyang and Zheng (2000) using experimental data from a clayey silt loam in Missouri, USA, reported by Buyanovski and Wagner (1983) and by Buyanovski et al. (1986).

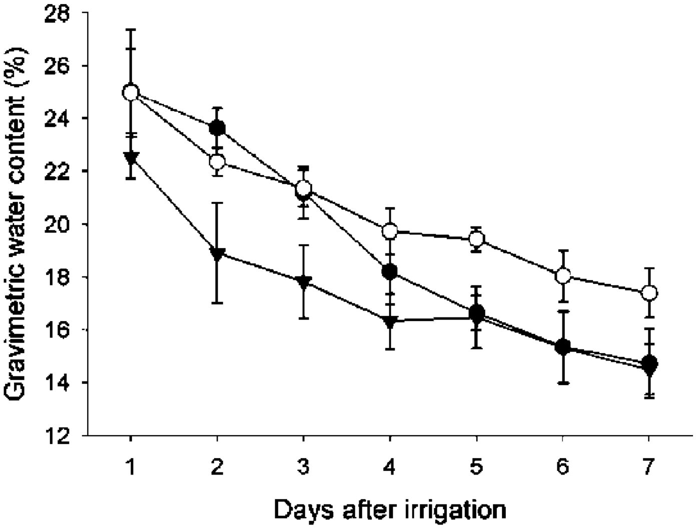

Fig. 1. Gravimetric water content (%) after irrigation under fallow (▼), wheat (○) and alfalfa (●) in an oasis soil at Balad Seet, Oman. Error bars show ±1 S.E.M.

The relationship of the decline in CO_2 evolution rate with time after irrigation was closer than that with the gravimetric water content indicating that moisture was not the only environmental factor contributing to this gradient with time. No excessive flush of CO_2 evolution rates was measured after irrigation, which has been reported as typical for a drying and rewetting event (Wichern et al., 2003). The lack of this flush may be the main reason why in this study the CO_2 evolution rate amounted to only 6% of that measured in an 18-day laboratory study with a similar soil, which was sun-dried and rewetted (Wichern et al., 2003). The CO_2 evolution rates of the present study are within the range of 0–300 mg CO_2–C m^{-2} h^{-1} obtained by others using the static chamber method for field measurements at arable sites in humid temperate regions (Franzluebbers et al., 1995; Jensen et al., 1996; Piao et al., 2000). In addition, they are also in the range of those results obtained with the dynamic chamber method in humid temperate regions (Jensen et al., 1996). These authors reported a 33% coefficient of variation between the replicate measurements for this method, which is only slightly above the present results.

CO_2 evolution rate and soil temperature at 5 cm depth were negatively correlated ($r = -0.56$, $n = 261$) for the three treatments combined, because soil temperature increased with decreasing gravimetric water content. Our findings from medium-term irrigation cycles are in contrast to other authors who found significant interactions between soil water content and soil temperature in regard to the CO_2 evolution

Table 2

Weighted mean, minimum and maximum of the CO_2 evolution rate and of the soil temperature at 5 cm depth during the measurement of the CO_2 evolution rate over a 12-day irrigation cycle for three plot types at the oasis of Balad Seet, Oman

Plot type	CO_2 evolution rate (mg C m^{-2} h^{-1})			Temperature (°C)			Number (n)
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	
Fallow	27.4 a	2.7	136.4	27.6 c	20.0	39.9	98
Wheat	45.5 b	8.2	98.2	24.7 b	19.4	33.7	75
Alfalfa	97.5 c	38.2	201.8	22.4 a	17.5	31.6	88

Different letters indicate a significant difference (Scheffé, $P < 0.05$).

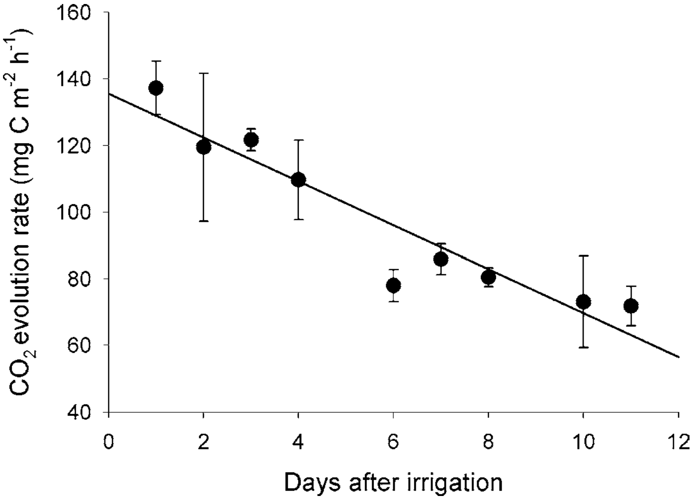

Fig. 2. Decline of the on-field CO_2 evolution rate after irrigation under alfalfa in an oasis soil at Balad Seet, Oman. Error bars show ±1 S.E.M.

rate when considering long-term seasonal variations (Franzluebbers et al., 1995) or short-term daily variations in non-irrigated arable land (Ouyang and Zheng, 2000). Soil temperature was also significantly affected by actual terrace use, i.e. the temperature decreased in the order fallow > wheat > alfalfa, indicating that shading of the soil surface by the crops markedly decreased the soil temperature at 5 cm depth (Table 2).

The contents of soil organic C and total N did not differ significantly between the three treatments (Table 1), indicating that the differences in CO_2 evolution rate were mainly due to actual root growth in the soil. The significantly increased soil C-to-N ratio in the Alfalfa treatment could be explained by the increased percentage of less decomposed organic material, probably derived from alfalfa roots. The

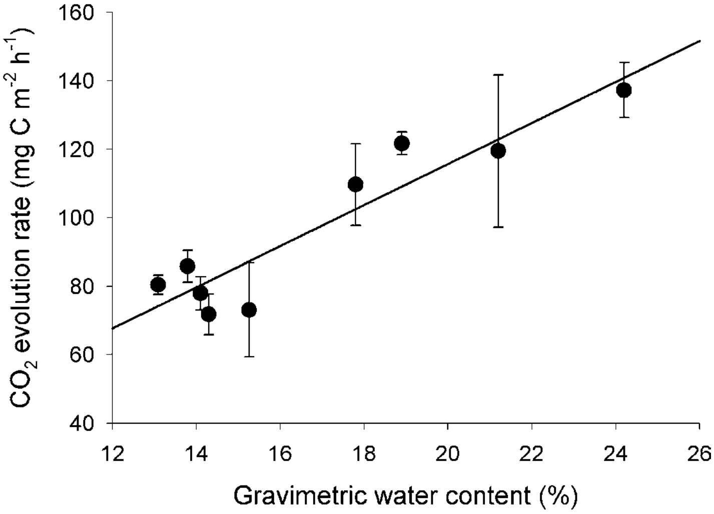

Fig. 3. Relationship between on-field CO_2 evolution rate and gravimetric water content after irrigation under alfalfa in an oasis soil at Balad Seet, Oman. Error bars show ±1 S.E.M.

contribution of plant roots and rhizosphere microorganisms to the mean CO_2 evolution rate can be calculated by subtracting the result of the fallow treatment from those of the two crop treatments (Table 2), assuming that crop growth, the observed differences in gravimetric soil water content and soil temperature had no further effects on the decomposition of soil organic matter. Under this assumption wheat contributed 18.1 mg C m^{-2} h^{-1} and alfalfa 70.1 mg C m^{-2} h^{-1} to the mean CO_2 evolution rate, i.e. 40 and 72% of the total mean CO_2 evolution rate under the respective crop treatments. This would mean that the CO_2 evolution rate of the alfalfa root system was nearly four times higher than the corresponding rate in the wheat root system although mean soil water content and temperature were lower under alfalfa than under wheat. Data using a similar methodological approach are not available. However, these results are in accordance with the C input data of Körschens (1992) who reported a mean C input of alfalfa 3.5 times larger than that of wheat. Also Paul et al. (1999) observed highest CO_2 evolution rates from alfalfa plots. It should also be considered that root respiration can be doubled due to the energy demand of N_2-fixation by the symbiotic *Rhizobium meliloti* in comparison to plants with mineral N supply (Merbach et al., 1999).

Losses of CO_2–C due to carbonate formation can be excluded because this process typically starts at soil pH levels above 8 (Usdowski et al., 1982). Also a CO_2–C drainage down into the calcareous subsoil can be excluded due to the counteracting gradient under the CO_2 partial pressure reported under these alkaline conditions (Andres et al., 1983). Unknown is the contribution of abiotic CO_2 evolution from the dissolution of carbonates (Ahrens and Thalmann, 1970; Powlson and Jenkinson, 1976). However, this process is probably of minor importance due to the presence of high percentages of hardly soluble dolomite, as indicated by the relatively low soil pH in comparison to the high carbonate content. Furthermore, this process can be assumed to be identical in all investigated terraces. The slightly alkaline conditions may lead to a retardation of the CO_2 evolution rate due to absorption of CO_2 in the soil solution. However, this CO_2 is physically released and transported to the soil surface during drying.

4. Conclusions

- Field measurements of the CO_2 evolution rate give important insights into the effects of different crops on C turnover in soil and on its controlling abiotic factors, i.e. the interaction between CO_2 evolution rate, soil water content and soil temperature.
- As an important component within the prevailing crop rotations, alfalfa contributes considerably as a nitrogen and carbon source to the fertility of the terrace soils.
- The CO_2 evolution rates of the terrace soils from the mountain oasis Balad Seet are in the range of those measured in arable land under temperate humid climatic conditions.

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