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Total and Mineral Nitrogen in a Wheat-Based Rotation Trial under Dryland Mediterranean Conditions

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Abstract

Cropping systems involving rotations have evolved in the Middle East region to cope with the ever-present constraint of limited soil moisture due to low and generally erratically distributed rainfall, and to the inherently low fertility mainly due to lack of nitrogen (N). Most dryland rotational systems involve conserving moisture in the fallow year for the subsequent cereal crop and input of N through N-fixation by legumes in the alternate year. Rotations have variable influences on crop yield, soil moisture, diseases, and especially nutrients. In this paper we report the influence of seven rotations, four N fertilizer application rates, and three stubble grazing management regimes in a 14-year cereal rotation trial in relation to total soil and mineral N (ammonium and nitrate). Total N was significantly higher in topsoil samples of the medic (*Medicago* spp.) and vetch (*Vicia sativa*) rotation, with lowest values being in the fallow and melon *(Citrullus vulgaris*) and continuous wheat rotation. Intermediate values were from the chickpea (*Cicer arietinum*) and lentil (*Lens culinaris*) rotations. The enrichment in total N in the medic rotation occurred down to 40-60 cm depth. By comparison with total N, mineral N values were about two orders of magnitude lower and showed no consistent trend with rotation. Interestingly, the mean effect of added fertilizer N was to consistently increase total N from 744 mg ha^{-1} in the control to 804 mg N kg^{-1} at the 90 kg^{-1} N application rate. Similarly, mineral N increased consistently with applied N showing a two-fold increase at the highest N rate. However, variable grazing of the stubble had no consistent effect on total or mineral N. Thus, in addition to the favourable effect on legume-based rotations on crop yields and water-use efficiency, this study clearly showed that forage legumes, and to a lesser extent food legumes, can lead to a build-up of soil N mainly as organic forms in semi-arid soils, which can subsequently contribute to cereal nutrition following mineralization. Such nutrient accumulation is critical for maintenance of soil quality and sustainability of land use, especially in rainfed Mediterranean cropping environments.

Keywords: Dryland crop rotations, soil nitrogen forms, rainfed cereal production, Mediterranean cropping systems.

Introduction

Agricultural production in the Mediterranean area is beset with many obstacles, notable limited rainfall and water resources (Smith & Harris 1981). The region has largely a Mediterranean-type climate with two distinct seasons, a humid one, from late fall to early summer, in which rainfed cropping occurs and a hot, dry summer season, in which cropping is possible only with irrigation (Kassam 1981). The farming system is predominately rainfed agriculture (Cooper et al. 1987), despite the increases in irrigation in recent decades (Ryan 2002).

The rainfed system basically involves cereals, bread wheat (*Triticum aestivum* L.), durum wheat (*T. turgidum* L. var. *durum*), and barley (*Hordeum vulgare* L.) grown alternatively with fallow, legumes or other crops, or with continuous cereal cropping. Due to land-use pressure, fallowing as a moisture-conserving practice has decreased in all but the very dry areas (< 300 mm yr^{-1}), while continuous cropping is unlikely to be sustainable due to disease build-up and moisture and nutrient depletion (Ryan 2002). Livestock, mainly sheep, are an integral part of Middle Eastern agriculture, being raised mainly on the cereal stubble or straw and winter-grown forages (Cooper et al. 1987). The greatest challenge in today's Middle Eastern farming is to maximize water-use efficiency (WUE) (Harris 1994) and to continue cropping in a sustainable manner (Jones 1993). Likely strategies involve adaptation of appropriate rotations (Harris 1995) and the use of chemical fertilizers, especially nitrogen, which is now considered essential for economic crop production in today's irrigated and rainfed farming (Harmsen 1984, Ryan 2002).

While the concept of growing different crops in sequence for the benefit of both dates back to antiquity (White 1970), the many benefits of a rotational system in terms of yield, water-use efficiency, soil biology, diseases and pests, and soil physical properties (Karlen et al. 1994) suggest that crop rotations should be crucial to the future of Middle Eastern agriculture. Indeed, the rationale behind the many long-term rotation trials established by The International Center for Agricultural Research in the Dry Areas (ICARDA) in the 1980's (Ryan & Abdel Monem 1998) was to identify possible alternative agronomic practices that are economically viable, environmentally sustainable, and socially acceptable.

Another major plank in the platform for development of Middle Eastern agriculture is nutrients, particularly phosphorus (P) and nitrogen. Although the region's soils are prone to P deficiency (Matar et al. 1992), regular fertilization in the past few decades has led to a build-up of available P and the elimination of widespread crop deficiency (Ryan 2002). Given the widespread nature of N deficiency in the region (Harmsen 1984), arising from the low levels of soil organic matter (Ryan 1998), allied to the continuous need for N inputs to sustain crop yields, the issue of N fertilization is a perennial one. While crop responses to applied N, especially cereals, are common in today's Mediterranean agriculture (Mossedaq & Smith 1994, Lopez-Bellido et al. 2000), the response to N within a more complex cropping system involving rotations, especially legumes that add N to the soil

through N fixation (Diaz-Ambrona & Miniquez 2001) needs clarification. Similarly, grazing of cereal stubble or retention of residues can be expected to influence N dynamics in rotational systems (Rasmussen & Collins 1991).

These were considerations in the long-term "Cropping Systems Productivity" trial at ICARDA in northern Syria (Harris, 1995), which examined the influence of N fertilization and variable stubble grazing with a 14-year trial involving wheat in rotation with crop alternatives including fallow, continuous wheat, and feed and food legumes. While cereal crop data have been reported for the first 7 years of the trial (Harris 1995, Harris et al. 1995), and WUE for the full 14 years (Pala et al. 2007) this paper sought to identify the effect of the major factors in the trial on total and mineral N in the soil as these parameters have implications for yield responses and sustainable cropping.

Materials and Methods

Rotation

The measurements that form the basis of this paper came from the main long-term trial "Cropping Systems Productivity" established at Tel Hadya experimental station, the headquarters of the International Center for Agricultural Research in the Dry Areas near Aleppo in northern Syria. The extensive trial (23 ha) was set up in 1983 and terminated in 1998. The initial 2 years involved establishment of the rotations; for the subsequent 12 cropping seasons, N fertilizer and grazing management regimes were applied. While the trial has been described in by Harris (1995) and Ryan (1998), and in more detail by Harris et al. (1995), it is pertinent to present the main features.

The main plots represented the seven rotations (each 3.24 ha, and individual plots, 0.54 ha) or cropping systems being assessed. Thus, durum wheat (*Triticum durum* L. var. *durum*) was grown with the range of common alternatives in the West Asia region. These were: traditional fallow to conserve moisture, but which is disappearing rapidly; continuous cereal cropping, which is increasing; and rotations with food legumes, i.e., chickpea (*Cicer arietinum* L.) and lentil (*Lens culinaris* Medik.*),* and forage legumes, i.e., vetch (*Vicia sativa* L.) and a mixture of common medic varieties (*Medicago* spp.). A variant of fallow, involving growing watermelon (*Citrullus lanatus* (Thunb.) Matsum & Nakai) planted when residual moisture was adequate for summer cropping, was also included. The secondary treatment (sub-plots) involved N fertilizer (0, 30, 60, 90 kg ha^{-1}) applied as urea to the cereal phase, while tertiary treatment (sub-sub-plots) involved variable grazing intensity of the cereal stubble, i.e., moderate and high intensity grazing, and no grazing or stubble retention. While detailed biomass yield, grain and straw, was taken from all plots at harvest, and animal offtake or productivity was assessed for the forage rotations, the focus of this paper was on soil N forms.

Site description

The soil at the site varied in depth from 0.5 to >2m above bedrock or parent material, but was high in clay (50-60%), cation exchange capacity (45-55 cmol kg^{-1}), calcium carbonate (20-30%, decreasing with profile depth), and organic mat-

ter (0.9-1.2% decreasing with depth). Classified as a fine-clay, thermic, Calcixerollic Xerochrept, merging to a Chromic Calcixerert (Ryan et al. 1997), the experimental site was relatively uniform with a gentle slope across the cropped area.

Weather

A variety of measurements of variable intensity was made throughout the 14 years of the trial. Weather data pertinent to the trial site were recorded at an adjacent weather station at the experimental station; these included daily rainfall, maximum and minimum air temperature, class A pan evaporation, relative humidity, and wind speed.

In the trial's first 2 years, rainfall was close to the long-term average (330 mm) being 326 and 333 mm, respectively. The following year (1987-88) had the highest rainfall (486 mm) while the following three seasons had lower than average rainfall, i.e. 235, 221, and 286 mm, respectively. The following 3 years were erratic, i.e., 1991-92 (349 mm), 1992-93 (276 mm), 1993-94 (373 mm), and 1994-95 (310 mm). However, the last three years of the trial all had above average rainfall (404, 410, and 392 mm). The period of the trial reflected the range in rainfall normal to the region, as well as variable distribution within season (Kassam 1981). Typical patterns of seasonal changes in maximum and minimum temperatures are described by Harris (1995) for the trial.

Soil analysis

The trial was subjected to a battery of chemical measurements and some physical ones, mostly in the fall prior to the season's cropping, and same throughout the season. For purposes of this paper, all plots were sampled to a depth of 0-20 cm and analyzed for total N (Kjeldahl) as well as ammonium and nitrate forms of mineral N (Bremner 1982). Some rotations, i.e., fallow, continuous wheat, and medic were sampled in 20 cm increments down to 1 m. As rainfall has such a dominant influence on crop yields as well as soil N, it is pertinent to mention the seasonal rainfall.

Statistical analysis

The experiment was a split-strip plot design with three replications, and with rotations being the main plots, N application rates the sub-plots, and grazing intensity being the sub-sub plots. The total variation was partitioned into a number of strata generated by the experimental design representing plot totals and plot × year totals (Jones & Singh 1995). The partitioning of the total sum of squares into main effects and interactions of the treatment factors rotation, nitrogen and residues, and the time factor was carried out to produce the analysis of variance by using commands from the Genstat statistical software (Payne 2000).

Results

All four main factors (phase, rotation, fertilizer and residues) in the trial had significant effects on total and mineral N (Table 1[1]), but most interactions were insignificant (the effects of rotation and N on total N were already significant when measurements were first made in 1989, but the effects of grazing only became significant from 1992 onwards). Thus, the effect was highly significant ($P \leq 0.001$) for rotations within phases

[1] Please see the tables section - Appendix

and N fertilization on total and mineral N forms, ammonium and nitrate. The effect of residues was significant for total N, but inconsistent for mineral N forms. Similarly, the effect of phase (e.g., sampling in the all-cereal plots or in the alternative rotation plots) was less marked than the three main factors, thus indicating that sampling in either phase influenced the outcome, except for total N.

The only interaction that was significant was the N x phase in the case of mineral N forms but not for total N. Thus, added N fertilizer had a differential effect on soil mineral in the cereal and the alternative crop phase. This is to be expected since N was added to the cereal phase and there would be little leftover mineral N to be detected when sampling the following year, in the alternative crop phase. In contrast, the effects of added N on total soil N would be unlikely to change from one phase to the next. However, the phase x N interaction on soil N parameters suggests that these changed over the years of the trial.

As the rotation within-phase effect was significant, the influence of the wheat and the alternative crop phases on soil N forms is presented in Table 2. Thus, all rotations had higher total N levels in the alternative crop phase than in the cereal phase, most rotations being significantly so. In contrast, most mineral N values tended to be higher in the cereal phase. Regardless of differences between phases, mean values for the rotations across phases for total N were highest for medic (875 mg kg^{-1}) and vetch (811 mg ha^{-1}), intermediate for chickpea (77 mg kg^{-1}) and lentil (762 mg kg^{-1}), and lowest for continuous wheat (747 mg kg^{-1}), fallow (725 mg kg^{-1}), and melon (710 mg kg^{-1}). Differences between rotations/phases with respect to mineral N were inconsistent, but highest values were observed for the medic rotation (17.1 mg kg^{-1}).

As rotation phase x year was significant with respect to N forms, mean values are presented for the cereal and alternative crop phase on a yearly basis in Table 3. Given the yearly variability in environmental conditions that influence crop growth and N input via fixation and offtake via yield, as well as influencing seasonal N losses, it was hardly surprising that there was no consistency between the two phases over the years of measurements. In some years, the N values were highest in the cereal phase, and in others they were highest in the alternative crop phase.

As rotations significantly influenced total soil N, the effect was consistent in the years when measurements were taken, but there was no significant interaction with years. Therefore while the rotation effects were consistent over the years, the data in Table 4 indicate not only trends, but variability from year to year due to sampling variability. Though the trial was under the rotations since 1983/84, by the time the first measurements were taken in 1989/90, the rotations had already produced significant differences, with apparent enrichment in the feed and food legume rotations. Though no measurements of total N were taken at the beginning of the trial, it is reasonable to assume that total N values were relatively similar across the trial site. Notwithstanding the differences between years with respect to total N, there was a tendency for values to increase with time, i.e., cropping frequency, except for fallow and melon (essentially

fallow) which changed little between the first sampling in 1989/90 and the last one in 1996/97.

As most measurements of N forms came from soil samples from the top 0-20 cm soil layer, sampling with depth on selected rotations revealed differences in N distribution. Thus, mineral N values were consistently higher with soil depth in the medic rotation in comparison with the fallow rotation. The patterns for vetch were similar to that of medic, indicating an enrichment of N beyond the surface layer. Though not enough measurements were made to identify statistically significant trends, total N values tended to be higher in the subsoil for the medic and vetch rotations than the other rotations, especially the fallow.

As N fertilizer had significant effects on all forms, these are presented in relation to N fertilizer application rate across all rotation and residue treatments (Table 5). Thus, each increment of applied N significantly increased total soil N, or soil N reserves. Although the mineral N forms were much lower than total N, both ammonium and nitrate N increased linearly with added N fertilizer.

Despite the overall significant effect of variable stubble grazing intensity on total soil N, with minor effects on mineral N, the overall effects of grazing intensity were poorly expressed by comparison with rotations and N fertilizers (Table 6). Thus, the highest total N was with stubble retention, with slight decreases for the medium and heavy grazing regimes. In contrast, ammonium N, where values were relatively small, increased with grazing intensity, with no apparent trend for nitrate N.

Discussion

This study adds a sustainability dimension from the soil perspective to cropping systems in the fragile, drought-stressed, semi-arid Mediterranean ecosystems (Cooper et al. 1987, Kassam 1981). In addition, where fertilizer inputs such as N are an essential but expensive input for economic crop production for resource-poor farmers in the Mediterranean region, it offered the alternative of N-fixation through the integrated use of legumes in rotation with cereals, the dominant crops of the region. The long-term "Cropping System Productivity" rotation trial that provided the basis for our observations on soil N forms is but a piece in the entire mosaic of positive attributes to emanate from this comprehensive study.

Earlier observations after the initial 7-years of the trial indicated positive effects of legume-based rotations on cereal grain and straw yields and suggested these as alternatives to continuous cropping or fallow (Harris 1995, Harris et al. 1995). Subsequently, data for the entire 14-years were to confirm these observations with respect to crop yields (Pala et al. 1999, Ryan et al. 1999). Indeed, preliminary observations were to indicate the economic benefits of legume-based rotations (Rodriguez et al. 1999). In addition, the indications are that such rotations lead to improve crop quality in terms of protein (Ryan et al. 2008), increased efficiency of water-use in the system as a whole (Harris 1994, Pala et al. 2007), and improved soil aggregation (Masri & Ryan 2006). The evidence with respect to another indicator of sustainability, organic matter, is equally positive, especially with forage legumes such as vetch and medic (Ryan 1998).

As N is a prerequisite to economic cereal yields, the sustained build-up in soil N reserves is particularly encouraging; with such build up response to fertilizer is reduced (Campbell et al. 1993). Indeed, the increased mineral N associated with the legumes, is likely to meet the N-fertilizer requirements of dryland wheat. The few studies reported for Mediterranean dry land conditions (Diaz-Ambrona & Minguez 2001, Lopez-Bellido et al. 2000) showed reduced N responses after legumes in terms of crop yields, but did not show any supporting soil N data. A laboratory study associated with this trial showed that mineralization of organic N reserves is the major factor in maintenance of mineral N in the soil solution for N uptake by the crop (Ryan et al. 2003). As the enhanced total and mineral N values were observed in both the cereal and the alternative phase, it is clear that the benefits of the legumes carryover to the subsequent cereal crop.

An interesting feature of the results was the consistent build-up in total N, as well as mineral N, with increasing N application rates, in contrast to popular perception of N fertilizer depleting soil fertility. The accumulated N reserves with fertilization are likely due to increased root biomass arising from the crop growth responses to added N. While the effects of stubble grazing management on soil N were statistically significant, they were not expressed in the early years of the trial and were not comparable to the more pronounced effects of the rotations and N fertilizer. The minimal effect of stubble retention lies in the fact that the N content of the straw was very low (0.3-0.5 %) by comparison with grain, while the actual amounts of straw produced by dryland cropping was low, ranging from 1 t ha^{-1} or less in poor years to 5 t ha^{-1} in favourable rainfall years. This is equivalent to 4 to 20 kg N input if all the straw was incorporated. However, with surface deposition and high temperatures, a substantial portion of the straw N is likely to be lost through volatilization. Thus, with such limited N input through the straw, the impact of such residues on soil N is minimal and can only be assessed after many years of incorporation.

The duration of the trial here was not adequate to quantify the effect of residue retention. However, it is likely that the rotation and N fertilizer effects shown here would have been accentuated if the trial had been continued. As with the classical long-term trials in Rothamsted, it is difficult to predict, at establishment, what the eventual outcome in terms of scientific output would be. Despite the relative brevity of the long-term trial reported here, the issue of examining the impact of cropping systems on soil N only emerged several years after establishment. Because the trial was prematurely terminated, at least as far as soil properties are concerned, the extent to which legume-based cereal rotations or inorganic N fertilizer can built up N to an equilibrium level in soils of Mediterranean agroecosystems will remain unanswered.

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Appendix

Table 1: *Significance of main factors, rotation, phase fertilizer, and stubble residue grazing, and interactions with respect to soil nitrogen forms*

Factor	**Soil N forms**			
	Total	Ammonium	Nitrate	Mineral
Phase	**	**	N.S	N.S
Rotation in Phase	***	***	***	***
Nitrogen Fertilizer	***	***	***	***
Residues	***	***	N.S	*
Nitrogen x Phase	N.S	***	***	***
Nitrogen x Rotation	N.S	N.S	*	N.S
Rotation x Residues	N.S	N.S	N.S	N.S
Phase x Year	***	***	**	***

P≤ 0.05 = *; 0.01 = **; 0.001 = ***

Table 2: *Rotation and of cereals and alternative crops or phases in relation to soil nitrogen forms*

Rotation	**Phase**	**Soil N forms**			
		Total	Ammonium	Nitrate	Mineral
		---------- mg kg $^{-1}$ ----------			
Fallow	Wheat	714	5.3	8.2	13.5
	Fallow	736	2.9	10.9	13.8
Melon	Wheat	707	4.5	7.3	11.8
	Melon	714	2.9	11.5	14.4
Wheat	Wheat	735	5.1	7.9	13.0
	Wheat	759	3.1	4.7	7.8
Lentil	Wheat	734	5.3	8.5	13.8
	Lentil	785	2.9	7.3	10.2
Chickpea	Wheat	757	5.1	10.2	15.3
	Chickpea	791	2.4	5.5	7.9
Vetch	Wheat	803	4.7	8.9	13.6
	Vetch	819	4.3	9.7	14.0
Medic	Wheat	872	5.2	13.7	18.9
	Medic	879	6.0	9.4	15.4
SEM +/-		11	0.3	0.9	0.9

SEM= Standard Error of Mean

Table 3: *Relationship between cereal and alternative phase in relation to soil nitrogen forms on a yearly basis*

Year	**Rotation**	**Soil N forms**			
		Total	Ammonium	Nitrate	Mineral
		mg kg $^{-1}$			
1989	Wheat	687	5.9	6.8	12.7
	Alternative	756	4.5	5.1	9.6
1990	Wheat	779	0.4	9.4	9.8
	Alternative	718	0.4	10.4	10.8
1991	Wheat	675	3.1	8.1	11.2
	Alternative	742	3.1	6.9	10.0
1992	Wheat	821	8.6	8.5	17.1
	Alternative	727	5.8	7.4	13.2
1993	Wheat	773	10.8	12.4	23.2
	Alternative	807	4.3	8.8	13.1
1994	Wheat	822	8.1	13.3	21.4
	Alternative	742	5.2	9.8	15.0
1995	Wheat	766	2.3	9.5	11.8
	Alternative	869	2.1	9.8	11.9
1996	Wheat	800	1.8	7.8	9.6
	Alternative	739	1.8	9.7	11.5
1997	Wheat	798	3.3	6.8	10.1
	Alternative	828	3.5	9.0	12.5
SEM ±		16	0.53	0.86	0.91

SEM = Standard Error of Means

Table 4: *Total soil nitrogen in rotations over years of trial measurements*

Year	Fallow	Melon	Wheat	Lentil	Chickpea	Vetch	Medic
				mg kg^{-1}			
89/90	686	668	698	736	716	739	806
90/91	697	-	-	-	737	-	812
91/92	688	651	678	718	696	738	792
92/93	734	-	721	-	754	-	887
93/94	745	715	752	787	801	823	905
94/95	729	710	768	764	790	813	903
95/96	737	732	796	786	831	873	970
96/97	708	709	751	796	768	809	851
97/98	781	789	788	730	816	883	904
SEM±				23			
Mean	723	711	744	760	768	811	870
SEM±				13			

SEM = Standard Error of Means

Table 5: *Mean effect of nitrogen fertilizer application rates on soil nitrogen forms*

Fertilizer N	**Soil N forms**			
--kg ha^{-1}--	Total	Ammonium	Nitrate	Mineral
		mg kg^{-1}		
0	744	3.2	6.1	9.3
30	749	3.3	6.8	10.1
60	789	4.6	9.5	14.1
90	804	5.9	12.9	18.8
SEM +/-	6.7	0.19	0.22	0.30

SEM = Standard Error of Means

Table 6: *Mean effect of cereal stubble grazing intensity on soil nitrogen forms*

Grazing	**Soil N forms**			
Intensity	Total	Ammonium	Nitrate	Mineral
		mg kg^{-1}		
Low (none)	785	3.6	8.8	12.4
Medium	767	4.5	8.9	13.4
High	764	4.8	8.9	13.7
SEM +/-	2.8	0.21	0.18	0.31

SEM = Standard Error of Means