Tropical Ecology **53**(3): 295-305, 2012 ISSN 0564-3295

www.tropecol.com

N-transformation rates and nitrifier population dynamics in traditional agro-ecosystem of central Himalaya

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Abstract: A study was conducted to understand the effect of sole versus intercropping of wheat and lentil on the soil nitrogen dynamics and observe the pattern of temporal fluctuation in nitrifier population and N transformation across the cropping season. The experiment was laid out in a completely randomized block design with wheat sole crop (SC), lentil (SC) and wheat-lentil intercrops (IC) in three ratios (wheat: lentil; 4:2, 3:3 and 2:4) in substitutive design as treatments in triplicate. Nitrogen transformation rates and nitrifier population values were in the order IC3:3 > IC4:2 > IC2:4 > Wheat SC > Lentil SC, suggesting that intercropping enhanced biological activity of soils in comparison to sole cropping. Based on dry matter yield the intercropped plots were 52 to 69 % more efficient than sole cropped plots. The optimum spacing regime for the present study was intercropping ratio of 3: 3 where the available land was used most effectively to produce greatest yield. Our study demonstrated that the traditional practice of growing wheat and lentil as intercrops is beneficial in terms of soil nitrifier population and N dynamics.

Resumen: Se realizó un estudio para entender el efectodel cultivo puro y mixto de trigo y lenteja sobre ladinámica del nitrógenodel suelo,y para observarel patrón de fluctuacióntemporal en la población nitrificante y la transformacióndel N durante la época de cultivo. El experimentofue establecido con un diseño de bloques completamente aleatorizados con el cultivo puro de trigo (SC), de lenteja (SC) y el cultivo mixto de trigo-lenteja (IC) en tresproporciones (trigo:lenteja; 4:2, 3:3 y 2:4), en un diseño sustitutivocomo tratamientos por triplicado. Las tasas de transformaciónde nitrógenoy los valores de la población nitrificante tuvieron el siguiente orden: IC3:3 > IC4:2 > IC2:4 >Trigo SC > Lenteja SC, lo que sugiere queel cultivo mixto incrementa la actividad biológicade los suelos en comparación con los cultivos puros. De acuerdo con la cosecha de materia seca, las parcelas con cultivo mixtofueron entre 52 y 69% más eficientesque las parcelas con cultivos puros. El régimen de espaciamiento óptimo para el presente estudiofueun cociente de plantado mixto de 3:3, ya que en él la tierra disponible fue la más eficiente para producir la mayor cosecha. Nuestro estudio demostró que lapráctica tradicionalde cultivar trigomezclado con lenteja es benéfica para la población nitrificante del suelo y la dinámicadel N.

Resumo: Para entender o efeito da monocultura de trigo, versusa consociação com a lentilha, realizou-se um estudo sobre a dinâmica do azotono solo e a observaçãodo padrão de flutuação temporal dapopulação nitrificante e transformação do N durante o tempo de cultura. O delineamento experimental foi o de blocos casualisados completos com monocultura de trigo (SC), lentilha (SC) e trigo-lentilha em cultura consociada (IC) segundo três tipos de proporções(trigo: lentilha, 4:2, 3:3 e 2:4) numdelineamento substitutivo com tratamentos em

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triplicado. As taxas de transformação do azoto e os valores da população nitrificante posicionaram-se na seguinte ordem IC3: 3 > IC4: 2 > IC2: 4 > Trigo SC > Lentilha SC, sugerindo que a consociação aumentou a atividade biológica dos solos em comparação com a monocultura. Com base no rendimento em matéria seca,as parcelas consociadas foram de 52a 69% mais eficientes do que nas cultivadas com uma cultura única. O regime de espaçamento óptimoneste estudo foi de uma proporção de 3:3, e na qual a terra disponível foi usado da forma mais eficaz para produzir maior rendimento. O nosso estudo demonstrou que a prática tradicional de cultivo de trigo e lentilha como culturas intercalares é benéfica em termos da dinâmica populacional da população nitrificante e do azoto no solo.

Key words: Central Himalaya, intercropping, nitrification, nitrifier population, N-mineralization, sole cropping.

Introduction

Intercropping is the traditional method of sowing, practiced extensively by the farmers of Central Himalayan region and it is called *Baranaaja* system (mixture of twelve crops); (Ghosh & Dhyani 2004). The neglect of this *Baranaaja* system and use of traditional food crop has not only weakened the household nutrition security system of the hill people but also prevented the Himalayas from becoming the home of the health foods of the future. The cultivation of traditional food crops still provides an opportunity for building a dynamic eco-food industry. Site Specific Nutrient Management (SSNM) strategies in these traditional fields must ensure the net release of plant available residual nitrogen (N) in synchrony with crop demands to support reasonable crop yields. Information on nitrogen transformation rates and nitrifier population dynamics in the intercropped agro-ecosystem in the Central Himalayan region is fragmentary. The gap needs to be filled for promotion of traditional intercropping system in the region for sustainable development. Developing an understanding of nitrifier population and N-transformation fluctuations during growing season is desirable from the standpoint of exploiting the supply of nutrients that might become available for crop use.

The rate of supply of plant available N is critical for the functioning of agro-ecosystems. The available N pools (NH_4^+-N and NO_3^--N) accounting for less than 2 % of the total N content of soils (Melillo 1981), are produced through N-mineralization, which thus governs the supply rate of N to plants. The conversion of NH_4^+-N to NO_3^--N in the process of nitrification, is brought about by two groups of gram-negative chemoautotrophic bacteria belonging to the Nitrobacteraceae, ammo-nium to nitrite (converting NH_4^+- to NO_2^-) and nitrite - oxidizing converting NO_2^- to NO_3^- bacteria (Schmidt 1982). Sources and properties of substrates affect nitrifier population. The net production of nitrate is a key ecological process that can affect the chemistry and nutrient capital of soils. An insight into the dynamics of nitrifier population and their related processes (N mineralization and nitrification) will provide knowledge for improving crop management to optimum nutrient use efficiency.

In this study, we quantified the soil physico-chemical properties, nitrifier population size and rate of N mineralization and, nitrification across the cropping season. We studied the temporal fluctuations of the above mentioned parameters and examined the effect of sole versus inter-cropping of wheat and lentil on the nitrifier population and N transformation rates. The ultimate aim was to find whether existing inter-cropping system was beneficial for maintaining fertility of soil and enhancing productivity of the crop.

Materials and methods

Study site

The study site was situated in the Katarmal experimental station of the G. B. Pant Institute of Himalayan Environment and Development (GBPI HED) and located at 29° 36' N latitude and 79° 37' E longitude at 1250 m amsl. The region has a warm temperate climate with typical monsoonal character. May and June are the warmest months of the year with a maximum temperature around 33° C, January is the coldest month with minimum temperature dipping below the freezing point. In general, June - September receives approximately 800 mm, October - December 78 mm, January - March 237 mm and April - May 118 mm of rainfall, which constitutes 65, 6, 19 and 10 % of the annual precipitation, respectively (Singh *et al.* 2000). The soil is Inceptisol, sandy loam in texture and has a neutral reaction, well drained and moderately fertile (Singh *et al.* 2000).

Experimental design

The crops selected were wheat (*Triticum aestivum*) and lentil (*Lens esculenta*). These crops are traditionally grown as intercrops for grain production in Central Himalaya. The experimental plots (5 m x 3 m) were laid out in a completely randomized block design with wheat sole cropping (SC), lentil SC and wheat-lentil intercropping (IC) as treatments with three replicates. Following ploughing to a depth of 20 cm and sowing, farm-yard manure was applied at a rate of 1000 kg ha^{-1} after seed emergence. The farmyard manure was surface - applied and lightly incorporated (upto 10 cm) in the soil. The farmyard manure consisted of dung, animal urine, bedding leaves and feed leftovers. The percent nutrient composition of the farm yard manure applied was (mean ± SE) 33.17 ± 2.33 C, 0.83 ± 0.20 N and 0.26 ± 0.09 P. Seeds of wheat and lentil (local selection) were sown by dibbling method with a row to row distance of 20 cm and hill to hill distance of 15 cm. The intercrop design was based on the replacement principle, with mixed wheat and lentil grain sown in three ratios of 4:2, 3:3 and 2:4 (de Wit & Van den Bergh 1965). Rainfall was the only source of irrigation during the cultivation period. The site was managed according to organic agriculture practiced locally with no use of chemical fertilizers or herbicides and manual weeding after seedling emergence and early tillering.

Soil sampling

Soil samples were collected every 15 to 20 days from the date of sowing. A short-term time scale is important for annual crops, where over a period of 90 - 150 days there are large fluxes or changes in nutrition demand of the plants. Three soil samples were collected randomly from each treatment plot from the upper 10 cm soil layer and mixed to form a composite sample to account for spatial variation in the field. Soil monoliths (10 x 10 x 10 cm) were removed and stored in polyethylene bags and brought to the laboratory. Each composite soil sample was divided into two parts. One part in the field moist condition was used for determination of pH and soil moisture. The second part also in field moist condition was used for assessing the nitrifier population, mineral N, N mineralization and nitrification rates. Soil samples were taken at regular intervals e.g., 20 days after sowing (DAS), at active tillering (40 DAS), panicle initiation (60 DAS), flowering, anthesis (80 DAS), physiological maturity (100 DAS) and pre-harvest (120 DAS). The samples were brought to the laboratory, spread on paper sheets and visible roots and fragments of organic debris were removed and the soil was sieved (2 mm mesh).

Soil analyses

Particle size analysis was done by using sieves of different mesh size following Anderson & Ingram (1989). Bulk density was determined by using a soil corer and measuring the weight of dry soil of a unit volume to a depth of 10 cm. Water holding capacity was determined by using perforated circular brass boxes (Piper 1944). Organic carbon in soil was analysed following the Walkley & Black technique by using dichromate oxidation and titration with ferrous ammonium sulphate (Walkley 1947). Total N was analysed by micro-kjeldahl digestion (Jackson 1958).

Soil pH (1 : 2, soil : water) was measured using a pH meter equipped with glass electrode. Gravimetric soil moisture content was measured with freshly pulled out soil according to the following equation (Buresh 1991).

$$M = \frac{\text{WCWS-WCDS}}{\text{WCDS - WC}} \times 100$$

where, M = gravimetric soil moisture content (%); WCWS = weight of can plus wet soil (g); WCDS = weight of can plus dry soil (g); WC = weight of moisture can (g).

Extractable soil ammonium nitrogen was estimated colorimetrically by the phenate method (APHA 1985). Nitrate nitrogen was measured by phenol disulphonic acid method (Jackson 1958). *In situ* rates of N mineralization were measured for thirty-day period at the sampling points using the buried bag procedure (Eno 1960). A soil corer (5.0 cm diameter x 10 cm depth) was used to obtain an initial sample that was placed in a plastic bag and brought back to the laboratory for analysis. Immediately adjacent to the initial sample further soil cores of the same size were taken. Each intact soil core was wrapped and sealed in a polyethylene bag (after removing coarse roots and large fragments of organic debris in order to avoid any marked immobilization during incubation (Schimel & Parton 1986). The sealed polyethylene bags were replaced into the hole from which they were extracted and retrieved after thirty days (herein referred to as the incubated sample). Identical laboratory procedures were used for both the initial and the incubated samples. The samples were sieved through a 2 mm mesh to remove fine roots and large stones. Sub-samples of 10 g were placed in extraction cups to which 100 ml of 2 M KCl was added. The supernatant was analyzed for ammonium concentrations using the phenate method (APHA 1985). Similarly NO_3 - N concentration were measured by the phenol disulphonic acid method (Jackson 1958) after extracting the soil in $CaSO_4$. $2H_2O$. The remaining soil material was dried for 24 h at 105^0 C to determine soil dry mass. Rate of N mineralization was calculated as the difference in the concentration of inorganic N ($NH_4^+$and NO_3^-) ions in the incubated and initial sample (Hart *et al.* 1994). Net nitrification was calculated as the difference in the NO_3 - N concentration in the incubated and initial sample (Hart *et al.* 1994). Rate of N- mineralization and nitrification is expressed in units of µg N per gram dry soil per thirty day. Unless otherwise stated, all results were calculated on an oven dry (105 °C) soil weight basis.

Counts of nitrifiers

The viable population of nitrifiers i.e. ammonium oxidizers and nitrite oxidizers was estimated by the most probable number (MPN) technique (Alexander & Clark 1965). Inocula were prepared as follows: 10 g soil and 90 ml sterile distilled water were placed in a sterile universal bottle (for each composite soil sample) and shaken vigorously on a wrist action shaker for 30 min. Serial ten fold dilutions were made by adding 1 ml of the suspension to 9 ml sterile water. Each successive dilution was shaken by hand for 30 s before a 1 ml portion was withdrawn. For both ammonium and nitrite oxidizers 10^{-2} to 10^{-9} dilutions were used. For each dilution five replicate culture tubes were employed. Ammonium - calcium carbonate medium [$(NH_4)_2 SO_4$, 0.5 g; K_2HPO_4, 1.0 g; $FeSO_4$. $7H_2O$, 0.03 g; NaCl, 0.3 g; $MgSO_4$. $7H_2O$, 0.3 g; $CaCO_3$, 7.5g; water, 1 litre)] was used for ammonium oxidizing bacteria and nitrite calcium carbonate medium (KNO_2, 0.006 g; K_2HPO_4, 1.0 g; NaCl, 0.3 g; $MgSO_4$ $7H_2O$, 0.1 g; $FeSO_4$.$7H_2O$, 0.03 g; $CaCO_3$, 1.0 g; $CaCl_2$, 0.3 g; water, 1 litre) for nitrite oxidizing bacteria. The inoculated media were incubated in the dark at 28 ± 2 °C. Tests for nitrifying activity were made after thirty days by testing each tube for nitrite using Griess-Ilosvay reagent. The number of tubes positive or negative to the test was noted and the most probable number of organisms present was calculated from an MPN table (Cochran 1950).

Plant growth and land equivalent ratio

Plant growth was measured from randomly selected fixed sites in each treatment at 15 - 20 days intervals starting from 20 days after seed emergence for all the treatment plots. One wheat/lentil hill was harvested from each plot on each sampling date and roots were collected from a soil block (15 x 20 x 15 cm depth). The soil was carefully washed with tap water on a sieve (0.2 mm). Subsequently roots and shoots were separated from each other and were dried at 65^0 C for 48 h to constant weight, for biomass determination. All estimates described above were conducted in triplicate. IC was separated into the wheat and lentil components. Each component was weighed and subsamples were taken for determination of total dry matter (DM) content. Land Equivalent Ratio (LER) for a wheat-lentil intercrop is the sum of the partial LER values for wheat (*Lw*) and lentil (*Ll*), in accordance with de Wit & Van den Bergh (1965).

$$Lw = \text{Y wheat}_{\text{IC}} / \text{Y wheat}_{\text{SC}} \quad (1)$$

$$Ll = \text{Y lentil}_{\text{IC}} / \text{Y lentil}_{\text{SC}} \quad (2)$$

$$\text{LER} = Lw + Ll \quad (3)$$

Y = yield in total harvested dry matter

Statistical analysis

GLM (general linear model) repeated measures analysis was performed using software (SPSS 2002) on the major soil parameters with successive sampling dates as the repeated measure. Relationships between soil properties were compared using Pearson's correlation (n = 72).

Results

Physicochemical properties of soil

Physicochemical features of soils are summarized in Table 1. The soil was sandy loam with the bulk density ranging from 0.90 ± 0.05 - 0.98 ± 0.02 g cm^{-3} and pH from 6.5 ± 0.08 to 7.08 ± 0.09 and organic C ranged from 0.79 ± 0.04 - 1.05 ± 0.10 % and total N fluctuated between 0.07 ± 0.02 - 0.09 ± 0.01 %. The WHC ranged from 31.2 ± 1.67 to 36.8 ± 0.78 % (Table 1). The lowest organic C and N values were obtained from soils under sole cropping of lentil and wheat followed by IC 2:4, IC 4:2, and IC 3: 3. Within the cropping period, the soil moisture content of top 10 cm soil layer ranged from 17.11 ± 2.80 - 19.74 ± 3.10 % (Table 1). Amongst all the treatment the soil moisture was lowest in wheat SC and highest in IC3 : 3. There were significant differences in soil moisture due to cropping pattern, sampling time and cropping pattern x sampling time interaction (Table 2). The organic C and total N ratio in soil ranged from 10.52 to 14.45 (Table 3). The organic C content was correlated with total N (r^2 = 0.23, P < 0.05). Soil pH showed correlation with rate of N mineralization (r^2 = 0.24, P < 0.05), ammonium (r^2 = 0.38, P < 0.01) and nitrite oxidizers (r^2 = 0.21, P < 0.05).

N mineralization, nitrification rates and mineral N content of soil

The mineral N content in soil was highest in lentil SC plots and the lowest cropping season average of mineral N was recorded in IC 4: 2 (Table 4). The ammonium N fraction ranged from 3.66 to 7.87 µg g^{-1} dry soil across the treatments and the nitrate N ranged from 0.90 to 3.39 µg g^{-1} dry soil across the treatment. The ammonium N / nitrate N fraction was always greater than 1 (Table 3). The mineral N content in soil was significantly affected due to cropping pattern, time and their interaction (Table 2). The mineral N in soil showed a correlation with microbial biomass N (r^2 = 0.22, P < 0.05), and negatively correlated with soil moisture (r^2 = -0.52, P < 0.01). The temporal change in mineral N pattern has been depicted in Fig. 1.

The N mineralization rates varied from 3.35 (wheat SC) to 5.86 µg g^{-1} $month^{-1}$ dry soil (IC 3 : 3; Table 4) and were significantly affected due to cropping pattern only (Table 2). Mineralization rates were correlated with soil pH (r^2 = 0.24, P < 0.05), ammonium oxidizers (r^2 = 0.0.31, P < 0.01) and total N (r^2 = 0.25, P < 0.05), content in soil. The nitrification rates were not affected due to cropping pattern, time and time x cropping pattern interactions (Table 2). The nitrification ranged from 0.83 (IC 2 : 4) to 1.24 µg g^{-1} $month^{-1}$ dry soil (IC 3 : 3) across the cropping season (Table 4). The rate of N mineralization and nitrification was higher at the beginning of the season and decreased gradually (Figs. 2 & 3).

Viable population of ammonium and nitrite oxidizers

The ammonium and nitrite oxidizer population was found to be highest in IC 3: 3 plots and IC 4: 2 plots, respectively, while the lowest population was recorded in wheat SC plots (Table 4). The nitrifier population was significantly affected due to cropping pattern and time (Table 2). Both ammonium and nitrite oxidizers were correlated with each other, rate of N mineralization, nitrification and mineral N. Both ammonium and nitrite oxidizers population fluctuated moderately across the season (Figs. 4 & 5).

Plant biomass production and land equivalent ratio

Land Equivalent Ratio (LER) from total dry matter yields reflected the efficiency of resource use in intercropping relative to sole cropping. The LER values for different intercropped ratios of wheat and lentil is presented in Table 5. Wheat-lentil planted in the ratio 3 : 3 showed the highest advantage of 69 % followed by IC 2 : 4 (55 %) and 4 : 2 (52 %). Wheat showed more proliferation of lateral roots in IC plots than in SC plots.

Discussion

Identifying the mechanisms by which cropping pattern changes soil chemistry is necessary to predict the effects of natural and man made modifications on nutrient cycling in agro-ecosystems. Our results clearly show that there are pronounced differences in nitrogen dynamics and nitrifier population beneath different cropping pattern. The changes in microbial mediated N transformations support our hypothesis that cropping patterns can induce changes in the rate of N mineralization, nitrification and nitrifying bacterial population. Differences in soil nutrient concentrations, standing crop biomass and fluctuations in nitrifier population can explain, in part, the differences observed.

The lowest organic C and N values were obtained from soils planted to sole crops, whereas higher values were recorded in soils under mixed cropping systems. The results are consistent with those of other studies showing that compared to sole crops mixed cropping system produce and conserve soil organic matter (Deng & Tabatabai 2000).

The soil under different cropping patterns differed both in relative amounts of inorganic N and

Table 1. General soil characteristics of plots planted to sole and intercropped ratios of wheat and lentil, cropping season averages ± 1 SE, n = 18.

Parameters	Treatments				
	Wheat SC	Intercrop ratios			Lentil SC
		4 : 2	3 : 3	2 : 4	
Soil texture					
Sand (%)	65.3 ± 0 .26	63.3 ± 2.72	63.5 ± 0.85	65.1 ± 1.09	61.6 ± 0.65
Silt (%)	30.1 ± 1.10	27.5 ± 2.56	24.5 ± 0.24	24.0 ± 0.85	22.5 ± 0.49
Clay (%)	4.6 ± 1.04	9.2 ± 5.18	11.6 ± 3.59	11.8 ± 1.55	15.4 ± 1.79
Soil moisture (%)	17.11 ± 2.80	19.44 ± 3.39	19.74 ± 3.10	18.75 ± 3.21	19.36 ± 1.89
Bulk density (g cm^{-3})	0.90 ± 0.05	0.92 ± 0.03	0.93 ± 0.03	0.95 ± 0.20	0.98 ± 0.02
pH	6.5 ± 0.08	7.08 ± 0.09	6.9 ± 0.19	6.5 ± 0.16	6.6 ± 0.18
WHC (%)	36.8 ± 0.78	30.7 ± 1.46	33.2 ± 0.24	32.6 ± 1.88	31.2 ± 1.67
Total N (%)	0.07 ± 0.02	0.07 ± .01	0.08 ± 0.01	0.08 ± 0.01	0.09 ± 0.01
Organic C (%)	0.79 ± 0.04	1.05 ± 0.10	0.97 ± 0.10	1.01 ± 0.20	0.95 ± 0.05
Organic matter (%)	1.37 ± 0.06	1.80 ± 0.18	1.67 ± 0.16	1.74 ± 0.36	1.70 ± 0.20

Table 2. F – ratios and their significance levels for two way ANOVA with repeated measures for soil pH, mineral-N, N-mineralization, nitrification, ammonium oxidizers, nitrite oxidizers and soil moisture for the sole crops and intercropped ratios, where sampling time was treated as a repeated measure. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns = not significant. n = 90.

Parameters	Source of variation		
	Between subject	Within subject	
	Cropping pattern (CP)	Time	Time x CP
pH	27.74 ***	ns	4.04 ***
Mineral – N	26.84 ***	47.37 ***	6.97 ***
Nmineralization	14.76 ***	0.903 ns	2.23 ns
Nitrification	0.89 ns	2.16 ns	1.47 ns
Ammonium oxidizers	429.44 ***	146.07 ***	76.88 ***
Nitrite oxidizers	12.33 ***	9.28 ***	1.38 ns
Soil moisture	27.53 ***	220.05 ***	4.84 ***

Table 3. Cropping season averages of soil organic C to total N ratio, ammonium- N, nitrate-N and ammonium-N and nitrate-N ratios. Values are cropping season averages, n = 18.

Treatment	Organic C/ Total N	Ammonium-N ($\mu g\ g^{-1}$ dry soil)	Nitrate-N ($\mu g\ g^{-1}$ dry soil)	NH_4N / NO_3N
Wheat SC	12.15	4.39 ± 1.51	3.39 ± 1.43	1.29
IC 4 : 2	14.45	3.66 ± 0.61	0.90 ± 0.17	4.06
IC 3 : 3	13.82	3.93 ± 1.21	1.59 ± 0.67	2.47
IC 2 : 4	12.25	3.74 ± 0.95	1.41 ± 0.18	2.65
Lentil SC	10.52	7.87 ± 1.87	1.61 ± 0.43	4.88

SC = sole cropping, IC = intercropping.

rate of mineralization and recorded the changes in these quantities across the cropping season. Numerous mechanisms have been identified by which plants can alter the physical, chemical and biological properties of soils (Finzi *et al.* 1998a, b; Hobbie 1992). Many involve changes in the quantity, quality and / or timing of inputs of plant derived substrate, e.g. litter. Differences in soil properties can be associated with both natural and anthropogenic changes in plant species composition

Table 4. Cropping season averages of mineral - N, nitrification, N – mineralization rates, ammonium oxidizers and nitrite oxidizers in sole (SC) and intercropped (IC) plots. Values are cropping season averages ± SE, n = 18.

Parameters	Treatments				
	Wheat SC	Intercropping ratios IC			Lentil SC
		4 : 2	3 : 3	2 : 4	
Mineral N(μg g^{-1})	7.14 ± 2.21	4.83 ± 1.04	5.95 ± 1.71	5.08 ± 0.75	9.49 ± 2.21
Nitrification (μg $g^{-1}month^{-1}$)	0.91 ± 0.24	1.0 ± 0.13	1.24 ± 0.24	0.83 ± 0.21	0.92 ± 0.34
N – mineralization (μg $g^{-1}month^{-1}$)	3.35 ± 0.43	4.11 ± 0.78	5.86 ± 0.53	3.52 ± 0.66	3.63 ± 0.77
Ammonium oxidizers (MPN x 10^3 g^{-1} dry soil)	0.16 ± 0.02	0.30 ± 0.05	0.37 ± 0.06	0.25 ± 0.04	0.25 ± 0.06
Nitrite oxidizers (MPN x 10^3 g^{-1} dry soil)	0.09 ± 0.02	0.30 ± 0.05	0.21 ± 0.04	0.15 ± 0.02	0.14 ± 0.02

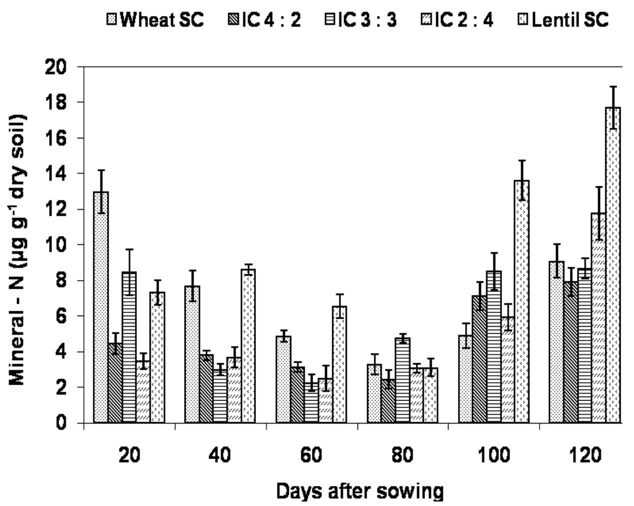

Fig. 1. Temporal changes in mineral N in the sole and plots planted to intercropped wheat and lentil in different ratios. Error bars represent standard error, n = 18 for each treatment. Wsc = Wheat sole cropping, Lsc = Lentil sole cropping, IC 4 : 2, IC 3 : 3, and IC 2 : 4 = wheat and lentil sown in the ratio of 4 : 2, 3 : 3 and 2 : 4 respectively.

(Binkley & Resh 1999). Differences in the capacity to absorb, translocate and utilize available N from soil may have resulted in the present differences as observed by Mengel (1983).

In the present investigation, mineral N concentration decreased during the cropping season. This rapid decline in the inorganic fraction during the early growing season can be ascribed to rapid plant uptake, immobilization into the microbial biomass, loss of nitrogen through nitrification denitrification reactions and possibly some transport across the barrier around the plots (Patrick & Reddy 1976). The NH_4^+ - N / NO_3^- - N ratio was always greater than 1 in the mineral N pool indicating efficient nitrate uptake by the plants and also observed by Jha *et al.* (1996).

In the present investigation different cropping patterns resulted in different rates of N mineralization. Plant species can influence nitrogen cycling through differences in litter quality (Hobbie 1992), and changes in a small fraction of soil organic matter can have large effects on ecosystem N dynamics (Wedin & Tilman 1990). The change in quantity and quality of litter is one of the likely mechanisms responsible for the changes in N mineralization and decreasing plant available N. Several other studies have also shown that mineralization rates vary in soils beneath different species (Finzi *et al.* 1998a; Wedin & Tilman 1990). A higher rate of N mineralization just at the beginning of the cropping season was probably due to mineralization of nitrogen from the decomposing farmyard manure.

Differences in the rate of nitrification among the treatments, in the present study may be attributed to the differences in the activity of the nitrifier population in different treatment plots. Vitousek *et al.* (1982) suggested that nitrification is controlled either directly or indirectly by the composition of the vegetation. Root dynamics may be a particularly important determinant of soil N distribution.

There have been few studies of changes in nitrifying bacterial population in soil under different plant species and even fewer under different cropping patterns. The population of ammonium oxidizers differed under different tree species within

Table 5. Cropping season averages of root biomass, dry matter yield and LER based on total dry matter yield in sole (SC) and intercropped (IC) plots. Values are means ± SE, n = 18.

Parameters	Treatments				
	Wheat SC	Intercropping ratios IC			Lentil SC
		4 : 2	3 : 3	2 : 4	
Root biomass of wheat (g hill^{-1})	0.73 + 0.25	1.37 + 0.57	2.08 + 0.87	0.82 + 0.27	–
Root biomass of lentil (g hill^{-1})		1.27 + 0.51	1.48 + 0.59	1.37 + 0.57	0.72 + 0.25
Dry matter yield of wheat (g hill^{-1})	6.17 + 2.07	11.03 + 4.11	8.75 + 3.05	6.5 + 2.16	–
Dry matter yield of lentil (g hill^{-1})		6.9 + 2.70	7.61 + 3.55	8.13 + 3.57	4.73 + 2.29
LER	1	1.52	1.69	1.55	1

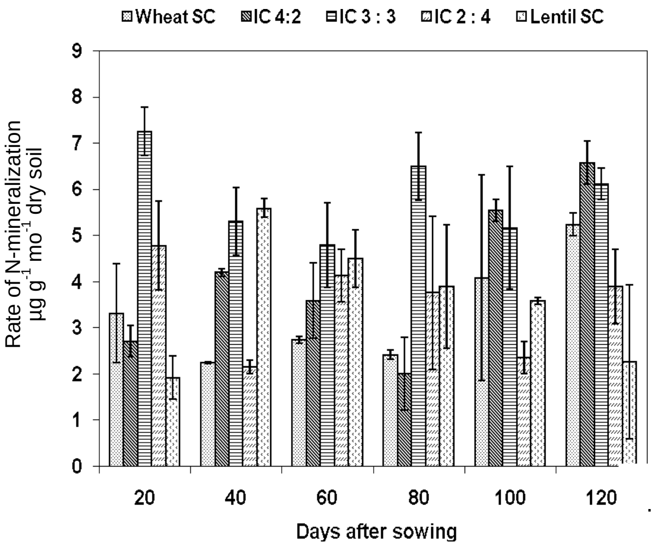

Fig. 2. Temporal changes in rate of N – mineralization in the sole and plots planted to intercropped wheat and lentil in different ratios. Error bars represent standard error, n = 18 for each treatment. Wsc = wheat sole cropping, Lsc = lentil sole cropping, IC 4 : 2, IC 3 : 3, and IC 2 : 4 = wheat and lentil sown in the ratio of 4 : 2, 3 : 3 and 2 : 4 respectively.

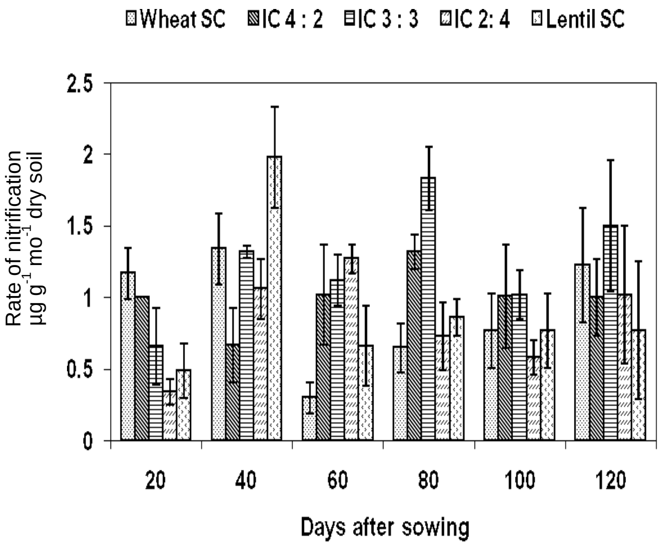

Fig. 3. Temporal changes in rate of nitrification in the sole and plots planted to intercropped wheat and lentil in different ratios. Error bars represent standard error, n = 18 for each treatment. Wsc = wheat sole cropping, Lsc = lentil sole cropping, IC 4 : 2, IC 3 : 3, and IC 2 : 4 = wheat and lentil sown in the ratio of 4 : 2, 3 : 3 and 2 : 4 respectively.

a single forest community (Lodhi 1978). Grayston *et al.* (2001) indicated that the presence of plants and plant species is a significant factor governing the resident microbial community structure (size and composition). The ammonium oxidizer population was strongly correlated with rates of N mineralization. This supports the contention that enhanced microbial activity is responsible, at least partially, if not entirely for the observed N mineralization. There was a strong correlation of ammonium oxidizers with nitrite oxidizers. This confirms the fact that both processes carried out by these bacteria are coupled (Woldendorp & Laanbroek 1989).

Thus the intercropping systems enriched the organic C and total N and resulted in increased nitrifier population and enhanced the processes of N mineralization and nitrification.

The total root biomass of individual crop plants tended to increase in the IC plots compared to SC plots. Surface proliferation of roots in IC plots was also observed. Kirby & Rackham (1971) also recorded similar observations, for which they reasoned that increased competition for soil resources and an accompanying shift in allocation of resources was the major factor. They also observed that at high plant densities roots tended to be increasingly concentrated in the upper part of the soil profile. Higher root biomass of the crops under IC in the present study compared to SC indicated a potential improvement in the search of nutrient sources.

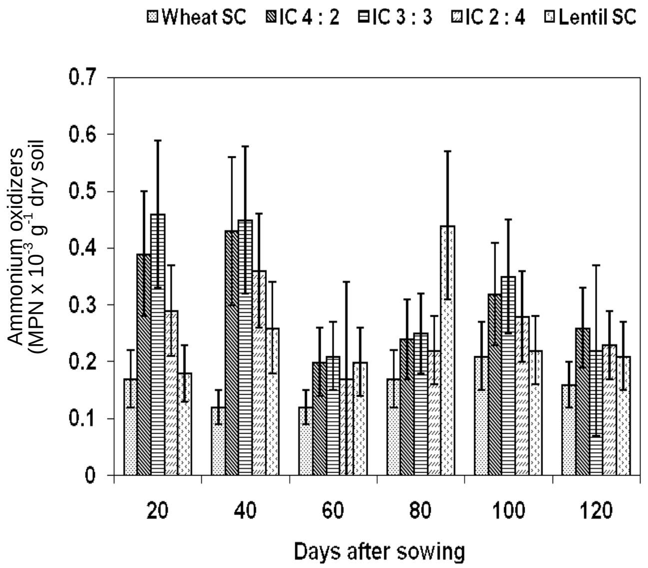

Fig. 4. Temporal changes in ammonium oxidizer population in the sole and plots planted to intercropped wheat and lentil in different ratios. Error bars represent standard error, n = 18 for each treatment. Wsc = wheat sole cropping, Lsc = lentil sole cropping, IC 4 : 2, IC 3 : 3, and IC 2 : 4 = wheat and lentil sown in the ratio of 4 : 2, 3 : 3 and 2 : 4 respectively.

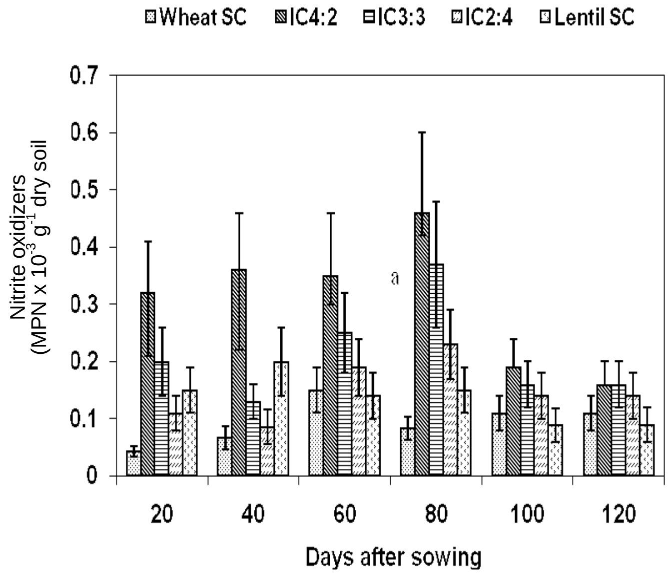

Fig. 5. Temporal changes in nitrite oxidizer population in the sole and plots planted to intercropped wheat and lentil in different ratios. Error bars represent standard error, n = 18 for each treatment. Wsc = wheat sole cropping, Lsc = lentil sole cropping, IC 4 : 2, IC 3 : 3, and IC 2 : 4 = wheat and lentil sown in the ratio of 4 : 2, 3 : 3 and 2 : 4 respectively.

Total dry matter yield in IC plots was higher as compared to SC plots as also observed by Peters *et al.* (1997). LER values greater than one indicated more efficient utilization of plant growth factors by intercrops compared to sole crops (Willey 1979). LER for the present study ranged from 1.52 to 1.69, indicating 52 to 69 % more efficiency than sole cropped plots. Some successful intercropping combinations reported are as follows: corn - beans in Mexico with LER = 1.33 (Lepiz 1971), corn - peanuts in Tanzania with LER 1.48 (Evans 1960), sugarcane - cowpeas in Brazil with LER = 1.24 (Dalal 1974) and corn - pigeon peas in Trinidad with LER = 1.82 (Hunter & Camacho 1961). These examples show that a hectare of intercropping produced from 24 to 82 % more than two half - hectares of single crops. The yield advantages of successful intercropping systems have been related to minimizing interspecific competition for light, water and nutrients. A greater value of land equivalent ratio reported from a finger-millet - pigeon pea intercropping system indicated greater biological efficiency of crops grown in association and was probably due to temporal and spatial complementarity effect, there by giving corresponding yield advantages (Singh & Arya 1999). Temporal asynchronies in growth rates are possibly among the other factors that contributed to the intercropping performance.

The results also indicate that spacing of crop species is crucial in agro-ecosystems. The optimum spacing regime for the present study was IC 3 : 3, where the available land was used most effectively to produce the greatest yield. It might be possible that a more efficient spacing for crops may exist than the ones used in this experiment, which would produce a greater yield.

Lentil is a good mixing partner and is suitable for intercropping with wheat and the addition of 50 % of its monocrop population to 50 % wheat can be recommended on the basis of soil nitrifier population and N transformation rates in soil and LER. Campbell (1978) demonstrated that meadow - based multiple crop rotations are more beneficial than monocropping systems with respect to crop production, and soil health. The traditional practice of intercropping of wheat with lentil is a good practice and should be encouraged for higher productivity coupled with greater risk coverage under rainfed condition in central Himalaya. Priority should be given to improve the IC composition and the sowing ratio selection to improve the nutrient use efficiency of the intercropping system involving several other popular crops.

Acknowledgements

We thank all members of Scientific Advisory Committee and the Director, GBPIHED.

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(Received on 20.01.2010 and accepted after revisions, on 06.09.2011)