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Nitrogen replacement value of alfalfa to corn and wheat under irrigated Mediterranean conditions

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Abstract

In crop rotations that include alfalfa (*Medicago sativa* L.), agronomic and environmental concerns mean that it is important to determine the N fertilizer contribution of this legume for subsequent crops in order to help to increase the sustainability of cropping systems. To determine the N fertilizer replacement value (FRV) of a 2-yr alfalfa crop on subsequent crops of corn (*Zea mays* L.) followed by wheat (*Triticum aestivum* L.) under irrigated Mediterranean conditions, two 4-yr rotations (alfalfa-corn-wheat and corn-corn-corn-wheat) were conducted from 2001 to 2004 in a Typic Xerofluvent soil. Corn yields were compared after two years of alfalfa and a third year of corn under monoculture and wheat yields were also compared after both rotations. Corn production after alfalfa outyielded monoculture corn at all four rates of N fertilizer application analyzed (0, 100, 200 and 300 kg N ha^{-1}). The FRV of 2-yr alfalfa for corn was about 160 kg N ha^{-1}. Wheat grown after the alfalfa-corn rotation outyielded that grown after corn under monoculture at both the rates of N studied (0 and 100 kg N ha^{-1}). The FRV of alfalfa for wheat following alfalfa-corn was about 76 kg N ha^{-1}. Soil NO_3^--N content after alfalfa was greater than with the corn monoculture at all rates of N fertilizer application and this higher value persisted during the second crop after alfalfa. This was probably one of the reasons for the better yields associated with the alfalfa rotation. These results make a valuable contribution to irrigated agriculture under mediterranean conditions, show reasons for interest in rotating alfalfa with corn, and explain how it is possible to make savings when applying N fertilizer.

Additional key words: crop rotations, fertilizer equivalent, FRV, maize, N contribution, N credit.

Resumen

Valor de sustitución del nitrógeno procedente de la alfalfa para el maíz y el trigo en regadío en la zona mediterránea

En las rotaciones que incluyen alfalfa (*Medicago sativa* L.), ésta aporta a los cultivos siguientes una cantidad de N que conviene cuantificar como medida de sostenibilidad. Para determinar el N equivalente o valor de sustitución de N (FRV) de una alfalfa de dos años en el maíz (*Zea mays* L.) cultivado posteriormente y el trigo (*Triticum aestivum* L.) subsiguiente en los regadíos mediterráneos, se estudiaron dos rotaciones de 4 años (alfalfa-alfalfa-maíz-trigo y maíz-maíz-maíz-trigo) entre 2001 y 2004 en un suelo Typic Xerofluvent. Se comparó el rendimiento del maíz con dos precedentes distintos: a) 2 años de alfalfa y b) 2 años de maíz, y, posteriormente, el rendimiento del trigo en ambas rotaciones. Las producciones de maíz después de alfalfa superaron las del maíz en monocultivo en las cuatro dosis de fertilizante estudiadas (0, 100, 200 y 300 kg N ha^{-1}). El FRV de una alfalfa de 2 años para el maíz se evaluó en unos 160 kg N ha^{-1}. El trigo después de la rotación alfalfa-maíz dio mayores rendimientos que el producido después del monocultivo de maíz para las dos dosis ensayadas (0 y 100 kg N ha^{-1}). El FRV de la alfalfa para el trigo que siguió a la alfalfa-maíz se estimó en unos 76 kg N ha^{-1}. El contenido de N-NO_3^- del suelo, mayor después de la alfalfa que en el monocultivo de maíz, persistió en el segundo cultivo después de la alfalfa y podría explicar los mejores rendimientos asociados a la rotación con alfalfa. Estos resultados, válidos para los regadíos mediterráneos, muestran el interés de cultivar alfalfa en rotación con maíz y su contribución al ahorro en fertilizante nitrogenado.

Palabras clave adicionales: contribución N, FRV, N equivalente, rotaciones de cultivos.

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Abbreviations used: FRV (fertilizer replacement value); N-FRV (nitrogen fertilizer replacement value).

Introduction

The beneficial effects of the cultivation of legumes on the productivity of subsequent crops have been recognized for centuries. Increases in yield of the order of 10 to 50% have been observed for non-legume crops grown after legumes, as opposed to non-legume monoculture (Hesterman, 1988; Triboi and Triboi-Blondel, 2004). It is also generally accepted that at least a part of this increase in productivity can be attributed to the N contribution from legumes. Their plowdown also helps to: break disease cycles, reduce pests, and control weed infestation, as well as contributing to the accumulation of soil organic matter and improving soil structure (Bullock, 1992; Varvel and Wilheim, 2003).

Growing corn (*Zea mays* L.) after alfalfa (*Medicago sativa* L.) is common practice in several areas of the world, including the Ebro Valley (NE Spain), where irrigated intensive corn and alfalfa are two of the main field crops. The effects of growing alfalfa on subsequent corn production have mainly been studied and quantified in the US Midwest (Munson, 1978; Baldock and Musgrave, 1980; Bruulsema and Christie, 1987; Hesterman *et al.*, 1987; Fox and Piekielek, 1988; El-Hout and Blackmer, 1990; Harris and Hesterman, 1990; Bundy and Andraski, 1993) and in parts of The Netherlands and France (Spiertz and Sibma, 1986; Justes *et al.*, 2001). In N fertilizer trials involving the cultivation of corn after alfalfa, it has been observed that maximum corn yields are often achieved with the addition of little or no extra N fertilizer (El-Hout and Blackmer, 1990; Peterson and Russelle, 1991; Bundy and Andraski, 1993; Kelling *et al.*, 1993).

However, although cultivating alfalfa has a positive effect upon subsequent corn crops, with a clear reduction in the amount of N fertilizer required and with greater yields than in monoculture, many producers are apparently still hesitant to fully accept that N is supplied by previous alfalfa crops (Peterson and Russelle, 1991). Producers' profits are reduced by not taking into account this N contribution from alfalfa, while significant amounts of N may also be lost to the environment (Bundy and Andraski, 1993). It is difficult to understand why N fertilizer recommendations do not usually refer to these credits and why producers do not take them into account. As a result, corn grown after alfalfa is more likely to be over-fertilized than corn grown after other crops (Blackmer, 1989). In some areas, the practice of adding extra fertilizer as insurance against possible yield losses is considered a good practice and the mark of a good producer (Bundy and Andraski, 1993).

Similar observations have been reported in Spain. A survey conducted in the main irrigated alfalfa growing areas showed that 90% of producers believed that growing alfalfa increased subsequent corn yields, although only 25% of these farmers subsequently reduced their rates of N fertilization (Álvaro and Lloveras, 2003). This could have been due to the lack of data available for scientists and farmers working under Mediterranean conditions. Given the importance of irrigated crops in the region, the high doses of irrigation often applied, and the environmental problems associated with over fertilization involving N in some areas (Berenguer *et al.*, 2008), this information could be useful for farmers and help to promote more sustainable agricultural practices.

A traditional way to estimate the value bestowed on subsequent crops by alfalfa is the fertilizer N-equivalent or N-fertilizer replacement value (FRV or N-FRV): the amount of fertilizer N required to achieve the same yield in continuously cultivated corn attained by non-N-fertilizer corn grown after a legume crop (Lory *et al.*, 1995a; Varvel and Wilheim, 2003). This FRV value can, however, change according to the growing conditions. Reported values range from 0 to 187 kg ha^{-1}, depending on such factors as the location, duration and quality of the alfalfa crop (Sutherland *et al.*, 1961; Munson, 1978; Baldock and Musgrave, 1980; Kurtz *et al.*, 1984; Bruulsema and Christie, 1987; Fox and Piekielek, 1988; Kelling *et al.*, 1993). FRV can also, quite predictably, depend on irrigation efficiency.

The alfalfa N contribution effect may last for more than one year (Harris and Hesterman, 1990; Gault *et al.*, 1995). Fox and Piekielek (1988) reported that the residual effect of fertilizer N equivalence from alfalfa to a second year corn crop ranged from 67 to 89 kg ha^{-1}, whereas according to Kurtz *et al.* (1984), the influence of alfalfa on the second crop grown after corn was equivalent to a reduction in N application of from 22 to 56 kg N ha^{-1}. To the best of our knowledge, no previous studies have assessed the N-FRV of alfalfa, either for the first subsequent crop or for the second under Mediterranean conditions.

The results of the above research show that soil nitrate concentrations increased with the age of the alfalfa (Blackmer, 1989). However, the amount of N added to the soil by alfalfa due to its N-fixing capabilities varies cording to the weather, soil conditions and crop management system employed (CASC, 2000). As a rule of thumb, about 66% of the N content of the alfalfa crop is harvested as aboveground biomass, whereas 33% is left in the soil and is theoretically available to the following crop (Munson, 1978). According to Gault *et al*. (1995), alfalfa contributed at least as much fixed N to soil as was removed as harvested hay. It is clear that alfalfa contributes substantial quantities of N to subsequent grain crops, but there is uncertainty concerning the amounts involved (Morris *et al*., 1993).

As indicated by Power (1990), when making N fertilizer recommendations for the USA, the credit system used for legumes has generally been estimated on a state by state basis. This could be because of the amount of variation in potential N input by legumes, but it is also likely that the scientists issuing recommendations could be biased by their own data.

Furthermore, Baldock *et al*. (1981) and Bullock (1992) concluded that rotations involving legumes do not provide as much N as most calculations of fertilizer replacement suggest and that much of the yield benefit which has been credited to the N contribution is actually due to other factors. However, in an evaluation of alfalfa N-FRV under homogenous conditions, with N treatment as the sole variable, greater yields tend to be mainly related to legume contribution and the importance of other factors is minimized.

The objective of this study was to determine the FRV associated with the short term cultivation of alfalfa under irrigated Mediterranean conditions and its influence on subsequent first and second crops, corn and wheat (*Triticum aestivum* L.), respectively. This would be a valuable contribution to existing data, but needs to be adapted for the climate and irrigation system conditions of the Mediterranean area, where alfalfa-corn is a common rotation.

Material and methods

Irrigated field experiments were conducted over four growing seasons (2001-2004) at the University of Lleida (UdL)-IRTA research fields at Torregrossa (41°34’51”N, 0°50’27”E), Spain. Mean monthly temperatures and total rainfall for the four growing seasons and long-term averages are presented in Table 1. The soil was a Typic Xerofluvent (SSS, 1975) and the plow layer (0-30 cm) had a loam texture (304 g kg^{-1} sand, 457 g kg^{-1} silt and 239 g ka^{-1} clay), a 10.2 g kg^{-1} organic matter content and a pH of 8.4. Initial concentrations of available K (NH_4Ac) and available P (Olsen method) in the upper part of the profile were 162 and 14 mg kg^{-1}, respectively. The soil depth was about 120 cm, with an initial NO_3^--N concentration of 135 kg ha^{-1} (Table 2).

To evaluate the effect of the alfalfa on subsequent crops, a method for comparing monoculture corn with corn grown after two years of alfalfa but under the same conditions was designed. An alfalfa-corn rotation was established in 2001 with alfalfa being cultivated for two years and corn in the third year (2003); the corn

Table 1. Monthly air temperatures (T_m, °C) and rainfall (mm) for the experiments[a]

Month	2001		2002		2003		2004	
	T_m	Rainfall	T_m	Rainfall	T_m	Rainfall	T_m	Rainfall
January	5.9	9.2	6.3	4.6	8.5	93.8	6.5	96.0
February	8.2	14.6	9.0	4.0	6.2	5.8	8.9	1.0
March	12.2	1.4	10.2	0.2	9.9	12.4	12.4	3.6
April	14.2	0.6	13.0	19.0	12.9	39.6	14.1	31.2
May	17.8	27.7	17.1	12.2	16.6	29.0	17.2	49.8
June	21.9	1.6	20.2	9.0	21.2	62.4	20.2	77.2
July	26.5	6.6	25.6	0.0	23.5	7.0	22.4	10.0
August	25.6	0.8	23.3	10.4	22.8	14.8	23.8	39.6
September	18.5	76.2	18.2	39.6	19.4	13.8	20.6	26.4
October	14.8	111.2	17.2	3.2	14.4	43.2	17.7	20.0
November	9.9	4.6	11.1	11.4	9.7	80.8	6.6	18.0
December	5.4	4.6	6.7	73.8	7.5	91.0	6.6	16.4
Average temperature or total annual rainfall	15.4	259.1	14.0	187.4	14.1	493.6	15.1	389.2

[a] Long term (20 year) mean annual temperature and rainfall at Torregreossa were 14.7°C and 369 mm, respectively.

Table 2. Total soil nitrogen (kg NO_3^--N ha^{-1}) from depths of 0 to 120 cm, before fertilizer application and corn seeding at the beginning of the experiment (2001), for the second (2002) and for the third year (2003). Also analysis of variance for both rotations (alfalfa-corn rotation and monoculture corn)

Previous crop	Corn N rate (kg N ha^{-1})	2001 (14 April)	2002 (5 April)	2003 (15 April)
Corn	0	132	94	49
	100	123	99	46
	200	133	105	49
	300	154	111	49
Alfalfa		—	—	85
Corn N rate (Nc)		ns	ns	ns
Rotation (Rot)				**
Nc				ns
Nc × Rot				ns

** Significant at the 0.01 level. ns: not significant.

was planted after plowing under the alfalfa in winter. Simultaneously, a monoculture of corn was grown for three consecutive years (2001, 2002 and 2003) in the same field and on the same plots. As a result, a comparison of corn yields between the two systems (rotation alfalfa-corn *vs* monoculture corn) was possible in 2003. Every year, and in both systems, four N fertilization rates were tested for corn grown on the same plots: 0, 100, 200 and 300 kg ha^{-1}. In 2003, the possible greater yields due to the alfalfa effect were compared with N fertilization rates applied to corn crops grown under monoculture. The amount of N fertilization needed to obtain the same corn yield under monoculture as after an alfalfa crop without any N fertilization would be equivalent to the N-FRV of alfalfa to corn as first subsequent crop.

To evaluate the value bestowed by alfalfa on a second crop after corn, all the plots were planted with wheat in 2003-2004. The alfalfa-corn-wheat and corn-corn-corn-wheat (also referred to as a corn-wheat monoculture) rotations were then compared. Two N fertilization rates (0, 100 kg ha^{-1}) were tested in wheat. The greater wheat yields of 2004 related with a previous alfalfa crop were compared with N fertilization rates applied to wheat and also to previous corn crops. The N rate applied to wheat grown after the corn monoculture required to obtain the same yield as after the alfalfa-corn rotation with 0 kg N ha^{-1} was taken to provide an estimate of the N-FRV of alfalfa for the second subsequent crop.

The experimental design consisted of a split-split-plot design with four replications. The main plots were used for the rotations of alfalfa-corn-wheat or monoculture corn-wheat, whereas four N fertilization rates were applied for corn on the subplots. For the alfalfa-corn rotation, the different N fertilizer rates were only applied in the third year, when corn was planted after alfalfa. For the monoculture corn crops, on the other hand, these N rates were applied for three consecutive years on the same plots. In the fourth year, each experimental subplot of corn was split in two sub-subplots on which two different N fertilizer rates were randomized at tillering of wheat.

Alfalfa cv. Aragon was seeded on 7 April 2001 with a seed rate of 30 kg ha^{-1} and was plowed under on 16 February 2003. The crop was harvested four times in the first year and six in the second. The plot dimensions were 6 × 39 m. Pre-sowing fertilization consisted of applying 60, 87 and 250 kg ha^{-1} of N, P and K, respectively, whereas annual fertilization applied, which was applied in winter, involved 87 kg ha^{-1} of P and 200 kg ha^{-1} of K. Appropriate herbicides and insecticides were used to control weeds and pests, as required. Alfalfa forage production was estimated by harvesting two central strips of the whole plot using a plot harvester (Haldrup, Løgstor, Denmark). A 200 g sample of herbage was collected from each plot at each harvest in order to determine the dry matter content.

Corn was sown on 14 April 2001, 18 April 2002, and 26 April 2003, with a row distance of 75 cm and at a plant density of 75,000 plants ha^{-1}. The 'Juanita' variety (Pioneer Hi-Bred) was used, which had previously been ranked among the most productive in the area in variety tests. The size of each subplot was 6 × 9 m for the corn crop. The pre-seeding fertilizer for the corn crop contained 87 kg ha^{-1} of P and 166 kg ha^{-1} of K, respectively. The nitrogen fertilization rates applied in the tests were based on ammonium nitrate (33% N), half of which was applied at pre-seeding and the other half as side-dress at stage V6, in order to increase the efficiency of N use. Herbicides and insecticides were applied to ensure that crop productivity was not adversely affected by weeds or pests.

Both the corn and alfalfa plots were flood irrigated at the same time, and at 12-15 day intervals, depending on the irrigation turns applicable in the area in question. Irrigation started 15 days before the seeding of corn, in order to prepare the soil, and had finished by mid September. A total of about 6,500 m^3 ha^{-1} of water in 2001, 7,000 m^3 ha^{-1} in 2002, and 8,000 m^3 ha^{-1} in 2003 were applied, according to local irrigation turns and water availability.

In the case of wheat, the 'Cartaya' cultivar was used and was sown on 14 November 2003. The seeding rates were 450 seeds m^{-1} with an inter-row spacing of 15 cm. For the wheat crop, the size of each sub-subplot was of 3×9 m. The two N treatments tested, which were smaller than the rates usually applied in the area (120-150 kg N ha^{-1}; Sisquella *et al.*, 2004) were chosen to asses a yield response to the soil N level. In the 100 kg ha^{-1} treatment, N fertilization was based on ammonium nitrate (33%), which was applied after tillering. The wheat was irrigated twice and according to established irrigation turns; the crop received a total of about 1,500 m^3 ha^{-1} of water.

The corn was harvested by 3 October 2001, 28 September 2002, and 23 October 2003, while the wheat was harvested by 15 July 2004. The grain yield of the corn was evaluated by harvesting the three central rows of each plot using a Nurserymaster Elite Plot Combine adapted for corn (Hege, Wintersteiger, Ried, Austria). The wheat yield was evaluated by harvesting a 1.5 m-wide central strip with a Nurserymaster Elite Plot Combine. Grain moisture was measured from a 300 g sample (GAC II, Dickey-John, Auburn, Ill, USA) taken from each plot and grain yield was adjusted to 14% moisture.

Every year, corn residues were not removed from the fields, but plowed under before the next crop; this is common practice in the study area (Sisquella *et al.*, 2004).

To determine soil nitrate concentrations, soil samples were collected from each plot at various different times: before seeding and after plowing under the alfalfa, and twice (before seeding and after the harvest) during each growing season, on both the corn and wheat plots. Ten soil samples were taken from depths of 0 to 30 cm, and two samples were taken from depths of 30 to 60 cm, 60 to 90 cm and 90 to 120 cm on each experimental plot. Soil samples were taken using Edelman cylindrical augers. These samples were combined to produce a composite sample per depth and experimental plot. Soil nitrates were extracted with water (1:1 soil/water ratio solution; Bremner, 1965) and colorimetrically analyzed for NO_3^- using an Autoanalyzer (Anasol, ICA instruments, Paris, France).

The N-FRV of alfalfa for both subsequent crops were evaluated applying the traditional N credit method (Lory *et al.*, 1995a; Varvel and Wilhelm, 2003). The third year (2003) yield equation was adjusted in line with the response curve of growing corn for both systems relating to N fertilization rates. Substituting corn yields after alfalfa with no subsequent N application into the adjusted equation for third year corn under monoculture gave a N rate equivalent to N enrichment in soils associated with alfalfa crops. Following the same procedure, wheat yields in 2004 were used to adjust equations relating to the first crop in the rotation and to wheat N fertilization. For the evaluation of the N-FRV of alfalfa for the second crop after, wheat yields for 0 N fertilization after alfalfa-corn-wheat rotation was substituted into the adjusted equation for the wheat response to N rate under the monoculture of corn-wheat.

The results were subjected to analysis of variance using the General Linear Model procedure of Statistic Analysis System (SAS Institute, 1989). Yield equations were adjusted by applying TableCurve 2D V2.03 (Jandel Scientific, 1994).

Results

The fertilizer replacement value of alfalfa for corn grown after alfalfa

Regardless of the N fertilization rate, the soil NO_3^--N content at seeding decreased with continuous corn cultivation (Table 2): in 2001, at a depth of 120 cm, the average N rate was 135 kg ha^{-1}, while in 2002, the corresponding concentration was 102 kg ha^{-1}. Finally, before corn seeding in 2003, the NO_3^--N content in the soils was around 48 kg ha^{-1} on the monoculture plots, but 85 kg ha^{-1} after the alfalfa crop. The relatively high rainfall from December 2002 to March 2003 (Table 1) could partially explain these low soil NO_3^--N values.

The yields for corn grown for three years under monoculture for the different N fertilization treatments and alfalfa yields previous to rotation are presented in Table 3. Nitrogen fertilization up to an application rate of 100 kg N ha^{-1} increased corn yields in 2001 and 2002, but there was no response to N applied at higher rates. However, in the third year, there was a greater response to N application. In this last corn growing season, the maximum yield under monoculture was obtained at the application rate of 300 kg N ha^{-1} (Fig. 1).

Corn yields in 2003 associated with the different N fertilization treatments under monoculture and yields obtained after cultivating alfalfa can be compared in Figure 1. It can be clearly seen that the corn grown after alfalfa outyielded the monoculture corn for all N fertilization rates. Even so, there was significant interaction

Table 3. Alfalfa (dry matter) production and corn grain yields (kg ha^{-1}) and analysis of variance for the three years of corn monoculture production

Crop	Fertilizer treatment (kg N ha^{-1})	2001	2002	2003
Alfalfa	—	7,974	22,738	—
Corn	0	7,443^b	9,162^b	8,162^c
	100	10,213^a	13,104^a	11,574^c
	200	10,357^a	12,484^a	13,527^b
	300	10,359^a	12,521^a	15,273^a
Corn N fertilization		*	**	**

**,*: respectively significant at the 0.01 and 0.05 levels. ns: not significant. Means followed by the same letter in the columns 2001, 2002 and 2003 are not significant at $p < 0.05$.

between the previous crop in the rotation and the N rate, while the differences in corn yield between the two crop rotations decreased with increasing N rates. The observed differences in yield between continuous corn and corn following alfalfa ranged from 4,737 kg ha^{-1} at 0 kg N ha^{-1} to about 900 kg ha^{-1} when corn was fertilized with 300 kg N ha^{-1}.

The third year corn yield under monoculture adjusted very well to a quadratic-plateau model (Fig. 1). Corn yields after alfalfa adjusted equally well to a quadratic-plateau model (Fig. 1).

The traditional credit method was considered for evaluating the N-FRV of alfalfa and corn yields after growing alfalfa with an application rate of 0 kg N ha^{-1} (12,899 kg ha^{-1}). Substituting this quantity in the adjusted equation for the response curve for growing corn under monoculture ($Y = 8{,}174 + 40.28\ N - 0.0664\ N^2$; where N is the N fertilization rate) would correspond to a N fertilizer application rate of 159 kg ha^{-1}. This would probably be the N-FRV or N-fertilizer equivalent to the effect of a 2-yr alfalfa crop on a subsequent corn crop under the experimental conditions.

The N-FRV of alfalfa for a second year crop following alfalfa

The effects of alfalfa on the rotation were still significant in the second crop (wheat) after the alfalfa (Table 4). On average, wheat grown after the alfalfa-corn rotation yielded 6,434 kg ha^{-1} whereas that grown after corn cultivated under monoculture yielded 5,197 kg ha^{-1}. Wheat yields did, however, increase when N fertilizer was applied to the crop at rates of 0 or 100 kg ha^{-1}. The significant interaction Rotation * Wheat N rate showed that the N rate effect on wheat depended on the first crop in the rotation. For the 0 kg ha^{-1} N fertilizer applications, wheat yields were 4,105 kg ha^{-1} for a previous monoculture corn crop and 5,773 kg ha^{-1} after the alfalfa-corn-wheat rotation. Similarly, when 100 kg ha^{-1} N were applied, wheat grown after monoculture corn yielded 6,289 kg ha^{-1}, and 7,096 kg ha^{-1}

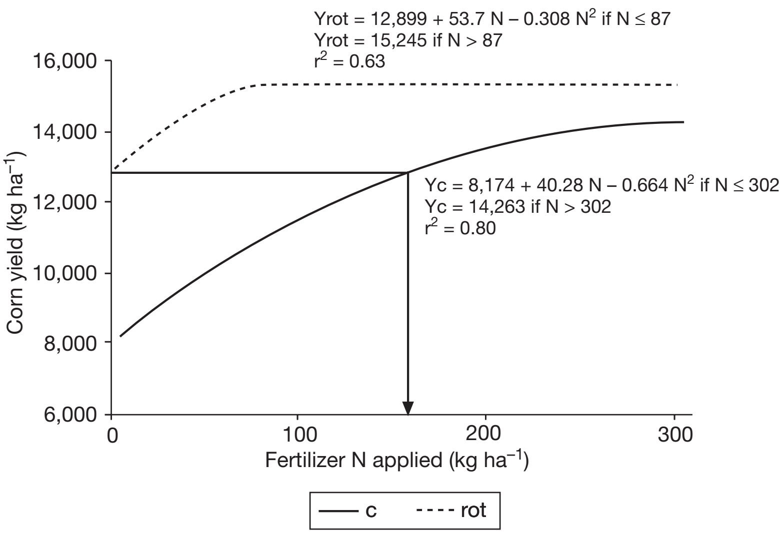

Figure 1. Grain yield (Y) of corn grown after alfalfa (rot) or under monoculture (c) at different N rates (N) in 2003. Quadratic-plateau response models and estimated N-FRV value are presented.

Table 4. Total soil NO_3^--N (depths of 0-120 cm) before (initial) wheat seeding and after (residual) wheat harvest and wheat yield, according to the first crop in the rotation (corn of alfalfa) and to the N application rates for corn and wheat

Corn N rate (kg ha^{-1})	Wheat N rate (kg ha^{-1})	Soil initial NO_3^--N (kg ha^{-1})		Soil residual NO_3^--N (kg ha^{-1})		Wheat yield (kg ha^{-1})	
		Corn	Alfalfa	Corn	Alfalfa	Corn	Alfalfa
0	0	23	35	39	41	4,219	5,065
0	100			38	50	6,114	6,807
100	0	24	37	40	43	4,266	5,379
100	100			44	60	6,623	7,728
200	0	23	41	35	49	3,908	6,339
200	100			40	59	6,184	7,003
300	0	25	51	38	47	4,027	6,307
300	100			44	57	6,235	6,845
Rotation (Rot)		**		ns		**	
Corn N rate (Nc)		**		ns		ns	
Rot × Nc		*		ns		ns	
Wheat N rate (Nw)				**		**	
Rot × Nw				*		*	
Nc × Nw				ns		ns	
Rot × Nc × Nw				ns		ns	

**,*: respectively significant at the 0.01 and 0.05 levels. ns: not significant.

when it was grown after alfalfa. Finally, the N fertilization rates for previous corn crops did not influence wheat yields.

The soil nitrate content of the previous wheat crop was influenced by the first crop in the rotation and also by the corn N rate (Table 4). After corn grown under monoculture, the N fertilization rate for corn did not affect the initial soil nitrate content. However, when the first crop in the rotation was alfalfa, the level of corn N fertilization increased in line with the initial soil nitrate content. The quite high rainfall registered at the beginning of November 2003 (Table 1), a flood irrigation system, and quite a sandy soil, may all have contributed to large amounts of nitrate being leached and may also explain the low soil NO_3^--N values registered before the wheat crop.

After the wheat crop, the soil nitrate content was not influenced by either the first crop in the rotation or by the corn N rate, but it increased in line with the rate at which fertilizer was applied to wheat. Furthermore, the greater soil nitrate content related with higher rates of wheat N fertilization depended on the first crop in the rotation. In the 0 kg ha^{-1} N fertilizer applications, there were similar soil nitrate contents with both the previous crops, but when 100 kg ha^{-1} N were applied, there were 41.5 kg ha^{-1} NO_3^--N after corn cultivated under monoculture, and 56.5 kg ha^{-1} NO_3^--N after the alfalfa-corn-wheat rotation.

Substituting 5,773 kg ha^{-1}, which was the wheat yield for 0 N fertilization in the alfalfa-corn-wheat rotation, in the linear equation (Yield = 4,106 + 21.83 × N) used to adjust for the response to N fertilization under a corn-wheat monoculture gave an equivalent N fertilizer concentration of 76 kg ha^{-1}.

Discussion

The fertilizer replacement value of alfalfa for corn grown after alfalfa

The grain yields obtained in the experiment were similar to the average yields for the area: between 11,000 and 14,000 kg ha^{-1} (Villar *et al.*, 2002; Dauden and Quilez, 2004). The lower grain yields in 2001 were due to a lack of water in the irrigation system by the end of the growing cycle. In the first two years, there was sufficient N already in the soil (Table 2) and the highest yield was obtained with only 100 kg ha^{-1}. However, when soil N was depleted (2003), the highest yield was obtained at a greater N rate. The results show that, even in irrigated areas, the usual N recommendation rates of 250-300 kg ha^{-1}, which are based only on plant yield and do not consider soil nitrate content, are not always needed.

The observed lack of response in terms of corn yields at N application rates above 100 kg ha^{-1} in 2001 and in 2002 (Table 3) was probably due to high soil NO_3^--N values prior to seeding (Table 2), as shown by Boixadera *et al.* (2005). The soil NO_3^--N content decreased with continuous corn cultivation and this probably explains the larger response of corn to N fertilization in the third year than in the two previous seasons.

Corn in rotation with alfalfa presented greater yields than corn grown under monoculture for all the N rates applied (Fig. 1). This kind of response, with greater corn yields after cultivating alfalfa or soybeans, has also been reported by other authors (Hesterman, 1988; Bundy and Andraski, 1993; Varvel and Wilhelm, 2003) working in the Midwest of the USA.

Some authors also reported that in the first year of corn cultivation after alfalfa, grain yields either did not increase as a result of the application of N, or they were maximized by the addition of reduced amounts of N, such as 30-50 kg N ha^{-1} (Fox and Piekielek, 1988; Bundy and Andraski, 1993; Kelling *et al*., 1993; Morris *et al*., 1993; Aflakpui *et al*., 1994; Lory *et al*., 1995b). In the experiment, the rate of N fertilization applied associated with the greatest corn yields after alfalfa was 100 kg N ha^{-1}, but it is possible that a lower rate of N application could have registered also maximum yields. The optimum N rate, according to the quadratic-plateau model for corn grown under monoculture, would be that stated in Figure 1, where the maximum yield was produced at a rate of 87 kg N ha^{-1}.

The differences between the yield responses in the experiment (at rates up to 100 kg N ha^{-1}) and those for the USA (30 to 50 kg N ha^{-1}) could have been due to the fact that corn yields under irrigated Mediterranean conditions tend to be higher. Other differences between the US Midwest and the Mediterranean region, such as the weather, soil type, soil depth and soil organic matter content (CASC, 2000), and the short duration of the alfalfa season (2 years) compared with older alfalfa crops, could also explain these differences. It has been relatively well established that as the age of alfalfa increases, so too does the total soil nitrogen in its root residue and hence the total mineralized nitrogen content (Munson, 1978; El-Hout and Blackmer, 1990).

A N-FRV value of 159 kg N ha^{-1} is greater than most of the levels cited in publications referring to the US Midwest, which credit alfalfa with N contributions of between 100 and 125 kg N ha^{-1} (Karlen *et al*., 1994). Bruulsema and Christie (1987) reported that legume plowdown supported corn yields equivalent to those achieved with the application of 90-125 kg ha^{-1} of N fertilizer in Ontario, which suggested concentrations of N availability from legume residue of between 65 and 71%. In Pennsylvania, Fox and Piekielek (1988) reported that 3-yr total N fertilizer equivalences for alfalfa were estimated to be 187 kg ha^{-1} and that average annual proportional contributions to total N were 70% in the first year, 20% in the second and 10% in the third. On the other hand, Baldock and Musgrave (1980), working in New York, concluded that growing alfalfa for two years contributed 135 kg N ha^{-1} to a corn crop. Kurtz *et al*. (1984) summarized some of these recommendations and reported N-FRV values ranging from 56 to 157 kg ha^{-1} for a good alfalfa crop, with specific values depending on the particular area and growing conditions. In contrast, under poor alfalfa growing conditions, they observed reductions in the N-FRV for corn and suggested values ranging from 0 to 56 kg N ha^{-1}. In France, Justes *et al*. (2001) considered that in the two years after alfalfa plowdown, about 100 kg N ha^{-1} could be saved by grain producers.

The N-FRV for alfalfa may be related to forage yields (Munson, 1978; Gault *et al*., 1995). Alfalfa yields are normally high under irrigated Mediterranean conditions (Lloveras *et al*., 1998, 2001) and this could explain why the values obtained in the investigation were generally greater than most of those cited above. Even so, the suggested N-FRV value could be considered rather conservative, as it was calculated from an alfalfa stand with only two years of production and with a total production of 31 t ha^{-1} (Table 3). This value would possibly have been greater if the alfalfa had been under production for four years, as is usual in the area. Under the Mediterranean conditions of this trial, a 4-yr alfalfa crop produces a total of 60-80 t ha^{-1} of dry matter (Lloveras *et al*., 1998).

On the other hand, Bullock (1992) noted that the widely used FRV methodology probably overestimates the N contribution of legumes when there is a crop rotation. Hesterman *et al*. (1987) have argued that the amount of N credited to legumes in a crop rotation in northern-central USA may be inflated by as much as 132% when applying the FRV method. According to Hesterman *et al*. (1987), Hesterman (1988) and Bullock (1992), yield increases after cultivating legumes are not only due to the effects of N fertilization, but also to other factors, such as reductions in insects and diseases or improvements in soil structure (Varvel and Wilheim, 2003) that could not be measured in the present study. These yield-enhancing effects that are not directly associated with the N contribution are referred to as the «rotation effect» (Bullock, 1992). Even if the trial design had tried to minimize this rotation effect as much as possible, it would still probably have contributed to the FRV for alfalfa. This effect can be evaluated from the quadratic-plateau response models of the two production systems, after both monoculture corn and following alfalfa, at the maximum N fertilizer rate. At this non-limiting fertilization rate, the yield difference of 982 kg ha^{-1} could be supposed to be related to the rotation effect. By removing this rotation effect on the corn yield after alfalfa for the application rate of 0 kg ha^{-1} N, the FRV for alfalfa, which is estimated at 159 kg ha^{-1}, could be recalculated as 115 kg ha^{-1}.

The estimated level of FRV contrasts with observed differences in soil NO_3^--N at corn seeding, which were only about 37 kg ha^{-1}. Another possible explanation for the suggested high N-fertilizer equivalent was that part of the N could have come from the alfalfa roots and been made available in the course of the corn growing season (Justes *et al.*, 2001). As Varvel and Wilhelm (2003) observed, N from legumes does not become available until much later in the growing season and this makes its detection difficult using conventional soil-testing methods.

The practical value obtained for the legume contribution to subsequent crops could, however, be given to producers and, although often questioned, these FRV may help to reduce N applications and increase crop benefits while also helping to reduce possible water contamination due to the excessive application of N.

The N-FRV of alfalfa for a second year crop following alfalfa

The suggested FRV, or the N-fertilizer equivalent of 2-yr alfalfa for the second crop following alfalfa, would be about 76 kg N ha^{-1}. However, this value should be considered approximate because only two N rates (0 and 100 kg ha^{-1}) were used to adjust the response. The differences between wheat yield at 0 and 100 kg ha^{-1} N after alfalfa rotation were 1,323 kg ha^{-1} and 2,184 kg ha^{-1} after monoculture corn. This greater quantity after monoculture production could have been related with lower levels of soil N available for wheat at the 0 kg ha^{-1} rate compared with the non-limiting rate of 100 kg ha^{-1}. It is possible that an application of 50 kg ha^{-1} after a monoculture crop would have produced a yield closer to 100 kg ha^{-1} than to 0 kg ha^{-1} and that this would then have reduced the estimated level of N-FRV for the second crop. The results generally agree with those of several other studies. Munson (1978), Fox and Piekielek (1988), Peterson and Russelle (1991), Justes *et al.* (2001) and Triboi and Triboi-Blondel (2004) also reported residual effects of alfalfa in second year crops following cultivation of a legume. Their values ranged from 67 to 90 kg ha^{-1}. On the other hand, Kurtz *et al.* (1984) reported that recommended N adjustments for a second year corn crop after alfalfa should be between 22 and 56 kg N ha^{-1}.

The greater wheat yields obtained from the alfalfa-corn rotation with respect to wheat yields associated with the continuous corn-wheat rotation (Table 4) could be explained, at least in part, by the greater soil NO_3^--N content associated with the alfalfa rotation. Considering a similar amount of leached nitrate before the wheat crop in both systems, the different effect of the N rate on the wheat yield associated with the first crop in the rotation could be related with the N content of the alfalfa roots remaining in the soil. The mineralized N from their residues was probably gradually made available during the second growing season (Justes *et al.*, 2001) and measured in the soil at the end of the wheat crop. The soil NO_3^--N content at wheat harvest, which was greater after the alfalfa crop than after the monoculture corn (Table 4), would show that N from legumes became available later in the growing season (Varvel and Wilhelm, 2003).

The differences between rotations, in terms of soil nitrate content before the seeding of wheat, were of the order of 17 kg N ha^{-1}, whereas the FRV of alfalfa for the second crop after an alfalfa crop was approximately 76 kg N ha^{-1}. These differences between estimated N-FRV and soil nitrate content before wheat seeding also suggest that rotation effects probably contributed to the estimated value of FRV. For the corn crop, this suggested value of N-FRV for a second crop after alfalfa could be considered conservative. A longer period of alfalfa production would have probably improved N accumulation in the soil as well as the quantity of leguminous roots and the corresponding amount of mineralized N during the growing season.

According to this work, in flood irrigated mediterranean systems, corn grown after two years of alfalfa outyielded monoculture corn at all of the application rates for N fertilizer for corn used for comparison purposes: 0, 100, 200 and 300 kg ha^{-1}.

Under these experimental conditions, the FRV of alfalfa for the subsequent corn crop was about 160 kg N ha^{-1}. This quantity could have been even greater if the alfalfa crop had been grown for four years, as it usually is in this area, instead of for two, as in the experiment.

The effects of growing alfalfa persisted for at least two growing seasons, because wheat crop grown after corn were affected by previous alfalfa crops. The FRV of alfalfa for this second crop was estimated to be 76 kg N ha^{-1}.

These FRV were, at least, partially due to an increase in soil N content after the alfalfa crop for both the first and second crops. The N turnover from the alfalfa residues was greater than initially predicted. However, our results suggested that other factors, such as the rotation effect, could also have been involved in this process. The high FRV values for alfalfa show the advantages of including this crop in the rotation. If it fits in with the cropping system, it can help to reduce N applications and to increase crop benefits, while at the same time helping to reduce possible water contaminations due to excess N.

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