An *in situ* incubation technique to measure the contribution of organic nitrogen to potatoes

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Abstract

Field experiments which consisted of the incubation of soil within polyvinylchloride (PVC) tubes inserted in glass jars previously buried in potato crop rows were conducted in order to measure the contribution of soil organic matter and organic amendments to the N nutrition of the crop. The experiments were carried out in Bragança, NE Portugal, in the summer seasons of 1996-1998. Five treatments including farmyard manure, poultry manure, municipal solid wastes, urea and the control were used. Manures and urea were applied in rates which correspond to 100 kg N/ha. Nitrogen released from soil organic matter and manures was checked through crop N recovered and petiole nitrate concentrations. In the plots of urea treatments 80.1, 68.4 and 98.8 mg NO_3-N kg^{-1} were released during the entire growing seasons of 1996, 1997 and 1998, respectively. In the control treatments 64.1, 41.5 and 55.4 mg NO_3-N kg^{-1} were recorded. The mean values of NO_3-N yielded from amended plots were not statistically different than control, excluding the plots of poultry manure in the initial sampling dates at the start of incubations. The measured amounts of inorganic N mineralized in the field from native soil organic matter were five to eight times higher than previous laboratory estimates from soil analysis. These results demonstrated that soils with low levels of organic matter could release significant amounts of inorganic N during a cropping season. Soil N availability estimated from the incubation technique was confirmed by petiole nitrate concentrations and closely related to crop N recovered. However, in the plots of urea treatments some inconsistencies were found, probably originated by the leaching of urea as molecular form to layers below the limit of soil coring. Soil N balance showed that more than 82 % of inorganic N released from organic matter came from the 14 cm soil surface layer.

Introduction

Fertilizer-N recommendation systems maintain a strongly empirical nature across the world since it has not been easy to establish soil N availability indices which could satisfactorily predict the contribution of the mineralization of organic matter to the N nutrition of crops [5, 39]. In addition, it is well known that crop response to the applied N could greatly vary from field to field and among cropping seasons, depending on the natural soil N availability [7, 25]. Thus, the adjustment of N supply to crop needs still remains a very uncertain exercise.

Most of the Portuguese laboratories of soil analysis use soil organic matter as the main indicator of potentially available N to the crops, although additional information regarding topography, soil depth and cropping history is required from the farmers. The model considers an empirical mineralization rate which ranges between 1 and 3 % depending on the soil type and general crop growth conditions, irrespective of the soil organic matter level [34]. Thus, the higher the level of soil organic matter the higher the estimates of soil N availability. This approach has as a main limitation the fact that the organic matter is not necessarily a reliable soil N availability index [11, 15, 17, 21]. On the other hand, several annual crops (winter wheat, rye, maize, sunflower, potato,…) are cultivated in inland regions of Portugal with or without irrigation on soils with low levels of organic matter. Climatic conditions, particularly warm temperatures during most of the year, and frequently excessive soil tillage promote the mineralization of organic substrates. Thus, laboratory estimates for the contribution of these soils to the N nutrition of crops are often negligible. Crop N recovered associated to yield goal is practically the only quantitative variable used for estimating fertilizer-N rates. This approach is also environmentally problematic since it could lead to the calculation of excessive N rates by underestimating the soil N-supplying capacity.

When organic amendments are used, which is usual in potato crop, the difficulties in making fertilizer N recommendations increase, because it is also necessary to predict their contribution to the N nutrition of crops. Several researchers have been involved in searching for indices that could predict the rate and/or the extent of organic materials mineralization [4, 6, 27, 35], but the success has not been better than the search for indices of soil N availability. The C/N ratio has been probably the most widely used index for assessing N availability from organic amendments. However, even this index has not always provided reliable results [20, 23].

In situ incubations are techniques which permit to measure the mineralization of soil organic matter under field conditions, since the soil is incubated close to its natural environment. These techniques had great improvement after the initial work done by Eno [8], who incubated soil cores within buried polyethylene bags. Since then, many researchers have used field methods to quantify soil N flows in agricultural fields [2, 3, 36, 37, 38], forestry [1, 10, 29] or grassland [14, 18, 22] ecosystems. Since the work of Eno [8] the methodologies have progressed in order to better simulate real field conditions with methods which minimize soil disturbance [1, 29], or maintaining the presence of roots [18] or earthworms [36].

In this study an *in situ* soil incubation that includes aspects from both Eno [8] and Raison et al. [29] techniques was used. The objectives of this work are (i) to measure the contribution of soil organic matter and organic amendments to the N nutrition of potato crop, (ii) to check the accuracy of the fertilizer-N recommendation program and (iii) to evaluate the accuracy of the incubation technique.

Material and Methods

Study site, climate and soil – The experiments were conducted on Sta Apolónia farming located in Bragança, NE Portugal (41º 49' N, 6º 46' W), during the summer seasons of 1996 to 1998. The climate is mediterranean type, dry and warm in the Summer. Mean annual precipitation is 730 mm, but 86 % of precipitation falling out of the crop growth period. Successful growth of potato is only possible under irrigation. Mean annual temperature is 11.9 ºC. However, high temperatures over the summer season are considered the most limiting factor to crop growth [32]. Maximum daily temperatures that were reached in each one of the growth seasons were: 34.2 ºC (6 July, 1996), 35.0 ºC (3 August, 1997) and 36.5 ºC (9 August, 1998). The soil was classified as eutric Cambisol [9]. Some other important characteristics of soil fertility are presented in table I.

Experimental design – The field experiments were arranged as a randomised block design with three replicates (3 blocks). Five treatments involving three organic amendments, urea and the control (without N) were used. Individual plots measured 33 m^2, consisting of 7 rows of potatoes (5.25 m^2) with 18 plants each (6.30 m^2). Urea and organic amendments were applied in variable rates in order to equal to 100 kg N ha^{-1}.

Organic amendments – Three different kinds of organic amendments frequently used and available in the region were included in the experiments: a composted municipal solid waste, commercialized with the trade name of fertor; fresh poultry manure, obtained from commercial poultry farms of the region; and farmyard manure produced by the cattle of Sta Apolónia farming after being composted during four months. The composition of the organic materials is presented in table II.

Crop management – The potato was inserted into a triennial rotation with silage maize (Zea mays L.) and silage sorghum (Sorghum bicolor [L.] Moench) as summer crops. Triticale (Triticosecale Wittm.) was grown as a winter cover crop, mowed in May for cattle fodder. Thereafter, the soil was ploughed (35 cm) and scarified (14 cm) to complete soil preparation for potato planting. Phosphorus (superphosphate, 18 % P_2O_5) and potassium (KCl, 60 % K_2O) rates were applied according to pre-plant soil analysis. Urea and organic amendments were applied as was defined in experimental design. All pre-plant fertilizers and amendments were broadcast and incorporated in 0-14 cm soil horizon with pre-planting tillage. The crop was machine-planted on 28th, 28th and 21st May in 1996, 1997 and 1998, respectively. Whole pre-sprouting tubers (cv. Désirée) within the size 28-45 mm (1996) and 45-60 mm (1997 and 1998) were used. Seed rate was 44 000 tubers/ha, arranged at a 32 cm spacing in rows 70 cm apart. During the season the crop was sprinkle-irrigated and protected against weeds, late blight (*Phytophthora infestans*) and beetle (*Leptinotarsa decemlineata*).

In situ incubation technique – A technique which include aspects close to the methodologies of buried polyethylene bags [8] and PVC tubing [29] was used. Within crop rows two glass jars (1 L) per plot were buried after potato planting. Only the lid remained free at soil surface. Six soil samples were randomly collected across each field plot with PVC tubes (140 mm high and 32 mm diameter), that are filled by pushing them into the *solum*. Soil samples were incubated within the glass jars (3 tubes per jar) for periods of approx. 14 days in a sequential procedure during the entire growth season. Adjacent to each sampling point six other soil cores were collected to compose 2 samples with three sub-samples and taken to the laboratory for analysis without incubation. Glass jars were sealed and covered with inverted white plastic dishes, secured with stones, to prevent the incidence of light and excessive diurnal increase in temperature. The PVC tubes were perforated with 8 holes (7.5 mm diameter) evenly spaced along the body of the tubes. Every new incubation period started 24 to 36 hours after irrigation or any rainfall to ensure soil moisture close to field capacity.

Soil inorganic N content – Incubated and non-incubated soil samples were field-moist sieved (6 mm mesh) and stored frozen until analysis. The samples (20 g) of moist soil were extracted with 2 *M* KCl (40 ml), shaken for 1 hour and centrifuged at 6000 rpm during 10 minutes. The extracts were analysed for NO_3-N and NH_4-N. Nitrate-N concentrations were determined by the Griess-Ilosvay reagent after reduction in a Cd column and NH_4-N by Berthelot reaction [19]. Both of the ions were analysed by molecular absorption spectroscopy in a segmented flow analysis system. Gravimetric water content of soil samples was determined on the remaining soil dried in a forced air oven at 65 ºC.

Nitrogen nutrition index – Petiole nitrate content was used as N nutrition index. Thirty of the youngest fully mature leaves per plot were used for analysis. Petioles were separated from blades, dried and ground. The extracts were prepared by adding 50 ml of distilled water to 1.0 g of tissue sample. The mixtures were shaken for 1 hour and filtered. Nitrate-N concentrations were determined as was referred for soil extracts.

Tuber yield and N recovered – Tuber yields were obtained from 18 plants per plot. The tubers were manually uprooted with a hoe, washed, air dried and weighed. Sub-samples of 800-1000 g of tubers were cut into small pieces, dried at 65 ºC and the percentages of dry matter recorded. The samples were ground and their N content determined. Total Kjeldahl N was determined in a Kjeltec Auto 1030 Analyzer.

Nitrogen recovered by tubers was estimated from tuber dry matter yield and its N content.

Statistical analysis – The analysis of variance of soil NH_4-N and NO_3-N, net N mineralization, accumulated NO_3-N and petiole nitrate concentrations was performed by SYSTAT 5.0. The means with significant differences (P=0.05) were separated by Fisher's LSD test.

Results and Discussion

Soil water lost during incubation

To ensure soil moisture close to the field capacity each incubation period started 24 to 36 hours after irrigation or rainfall events, as was referred. There was some water loss during the incubations. However, soil moisture at the end of the incubation periods was on average only 4.2 % (w/w) lower than initial values. Thus, soil moisture conditions seem to have been appropriate for microbial activity.

Soil inorganic nitrogen

Soil NH_4-N levels in the upper 14 cm soil layer during the cropping season are presented in figure 1. Urea treatment originated significantly (P=0.05) higher soil NH_4-N levels than manures and control in the first sampling date of 1997 and in the 1st and 2nd dates of 1998. Rapid hydrolysis of urea, that occurs in warm and well aerated soils [12, 26], could justify the appearance of high amounts of NH_4-N in soil. On the first date of sampling, soil NH_4-N level was higher in 1998 than in 1997. The difference in the results is attributed to the temporal distance between fertilizer applications and the first sampling date (2 and 7 days in 1998 and 1997, respectively). In 1997 part of the applied urea could have leached below 14 cm before hydrolysis, in so far as the precipitation in this period reached 56 mm. In addition, part of the NH_4-N derived from urea hydrolysis could have already been nitrified at the first sampling date of 1997, seven days after the application of urea. Significant differences in soil NH_4-N levels among amendment treatments and control were not registered in any sampling date. Soil NH_4-N levels were low and quite similar over the season. The high dynamic of NH_4-N pool in soils with good conditions for microbial processes (immobilization, nitrification,…) [24, 30] and crop uptake could not have permitted NH_4-N accumulation.

The levels of soil NO_3-N, in the surface 14 cm of soil, over the growth seasons are presented in figure 2. On the first three dates of sampling of 1997 significantly higher soil NO_3-N levels in the plots of urea treatments were registered. The rapid hydrolysis of urea followed by nitrification justifies the result. The subsequent decrease in soil NO_3-N levels is attributed to crop uptake and NO_3-N leaching below surface 14 cm soil layer, due to precipitation (37 mm between the 1^{st} and 2^{nd} sampling dates) and irrigation water.

In the poultry manure plots of 1996 and 1997, soil NO_3-N levels in the first three sampling dates were higher than in other manures and control plots, despite mean values of no statistical significance (figure 2). The high Kjeldahl-N and inorganic-N content of the poultry manures justify the appearance of high amounts of NO_3-N in soil surface. Thereafter, leaching below 14 cm soil surface and crop uptake led soil NO_3-N to a basal level which was similar among all the treatments.

On the first sampling date of 1996 and 1998 high values of NO_3-N in soil derived from urea were not recorded, since only two days before urea application had elapsed. Soil nitrate levels on the 2nd date of sampling of 1998 were unexpectedly low if they were compared with the values of 1997. However, between the 1st and the 2nd dates of sampling of 1998 the rainfall exceeded 90 mm with 40 mm of water falling in one day (1st July, 12 days after crop emergence). Thus, nitrate leaching justifies the result. I have no strong arguments to justify the low soil NO_3-N levels recorded on the 2nd sampling date (13 days after planting) of 1996. However, I could report that after potato planting the weather was particularly dry. Taking into account that nitrification is severely inhibited under dry soil [16], and crop irrigation only started after crop emergence, that could explain the low levels of soil NO_3-N in the urea plots on the 2nd sampling date. On the 3rd date of sampling (23 days after planting) there were also no evidences of the presence of nitrates derived from urea. Nitrate leaching below 14 cm, due to crop irrigation, and crop uptake could be used to explain the result.

After the 3rd sampling date, crop uptake and irrigation water maintained soil NO_3-N in a basal level similar for all the treatments and years. Close to the end of the cropping seasons soil levels seem to increase, particularly in 1998 and 1996. The end of irrigation and crop uptake with continuous mineralization of organic substrates would have permitted NO_3-N accumulation.

Nitrogen mineralization rates

Net N mineralization rates were estimated from the temporal variation in NH_4-N + NO_3-N in incubated soils, dividing the difference between final and initial values of each incubation period by the number of days. The mean values of the treatments are plotted on X-axis at the middle point of each incubation period (figure 3). In the first sampling dates of 1998, significantly higher net N mineralization rates were recorded on plots of urea comparatively to the other treatments. The urea hydrolysis is fast with an increase in soil solution of inorganic N. The effect of urea on net N mineralization was not observed in 1997. In this year, the incubations started seven days after urea application and during this period 56 mm of rainfall was recorded. Considering the high solubility of the molecule of urea, its leaching below 14 cm soil layer could explain the differences between the years. In addition, after 7 days any easily mineralizable substrate would not remain in soil due to the fast urea hydrolysis.

Regarding amended and control plots, net N mineralization rates were low in the first period of incubation for both the years. Probably, the balance of mineralization/immobilization was dominated by the presence of triticale stubble, incorporated with pre-planting tillage few days before the start of the incubations. After the first two dates of sampling, in the course of the growing season, net mineralization rates increase slightly and were quite similar throughout treatments. When comparing the results between the years they are also similar, reflecting the stability of the cropping system.

The recorded values of net N mineralization rates ranged from 0.1 to 1.2 mg kg^{-1} d^{-1}. If one only took into account the control plots the values registered were 0.6 to 1.0 mg kg^{-1} d^{-1}. Much research has been published regarding the rates of net N mineralization or nitrification on natural ecosystems or agricultural fields [2, 10, 22, 36]. However, the differences in agro and/or natural ecosystems and in methodologies render useless any comparison.

Nitrate-N accumulation

Nitrogen nitrified during the growing season within the incubation tubes represents the amount of N available to the crop, since in well aerated soils and with favourable pH values, nitrate is the stable and predominant form of inorganic-N in the course of microbial N transformations. On the other hand, the incubation technique prevents leaching, denitrification and crop uptake and the sequential coring limits the inhibitory effect on nitrification by the reaction products. The amounts of NO_3-N yielded during the course of the growing seasons are presented in figure 4. In the plots of urea treatment 80.1, 68.4 and 98.8 mg NO_3-N kg^{-1} were accumulated in 1996, 1997 and 1998, respectively. The higher values of 1998 in comparison to the other years for urea treatment as well as the higher difference in that year between the urea results and the results of the other treatments seem to be in agreement with preceding evidence that in 1996 and 1997 a significant part of urea would not have been hydrolysed in the surface 14 cm of soil. Thus, the 14 cm of soil coring could be considered a limitation of the incubation technique, but only when N forms with great mobility in soils were used.

The plots amended with poultry manure yielded 75.8, 59.5 and 74.9 mg NO_3-N kg^{-1} in the three consecutive years, and were the higher values among organic amendments. The lower values of C/N ratio and the higher inorganic-N content (table II) justify the results, since these are characteristics of manures that usually tend to promote net mineralization. The amounts of NO_3-N yielded from the plots amended with municipal solid waste in 1997 and 1998 were higher than control and lower in 1996. However, the difference between the mean values obtained with farmyard manure, municipal solid waste and control treatments has no statistical significance. Control treatments accumulated 64.1, 41.5 and 55.4 mg NO_3-N kg^{-1} in 1996, 1997 and 1998, respectively.

The differences among the years must be justified with the differences in native soil N availability.

Crop nitrogen nutrition status

To check the accuracy of the incubation technique in predicting the contribution of soil and organic amendments to the N nutrition of plants, petiole nitrate concentrations, the most sensitive N indicator in potato plants [13], was used. The results are presented in figure 5. Urea treatments originated the highest petiole nitrate concentrations in the three years of study. This aspect could only partially be explained by the incubation technique, since some of the urea would have been hydrolysed below the surface 14 cm of soil.

Poultry manure released significantly more inorganic-N than the other organic materials in all the years. This aspect was previously detected with the incubation technique, but the significance of the differences on results was more evident with this index due to its high sensitivity to soil N status (figure 5). Farmyard manures and municipal solid waste originated identical results as control treatment. Nitrogen use efficiency of the farmyard manures and municipal solid waste was very poor. In general, the behaviour of organic amendments in soil is uncertain but in other studies similar results have been found. Pomares-Garcia and Pratt [28] verified that a manure obtained from a commercial cattle feedlot, with 1.53 % of total N and 0.0027 % of inorganic N, released 4.2 % of the total N in 2.5 months and only 17 % in ten months. Rodrigues and Coutinho [33] in a two years field experiment applying several commercial manures on potato crop registered apparent tuber N recoveries lower than

25 % of the applied N. In 1997, the lesser NO_3-N formation, detected by the incubation technique, was also clearly confirmed with tissue testing.

Crop N recovered

Crop N recovered is the best field method to evaluate the release of N from soil and fertilizers as well as check the accuracy of the *in situ* incubation technique. The relationship between NO_3-N accumulated during the season in the field incubation and N recovered by tubers is presented in figure 6a. A significant (P=0.001) linear relationship with a coefficient of determination of 0.59 was found. Thus, the result seems to validate the incubation technique as a reliable method to predict soil N availability during the growing season. However, some problems occurred with urea treatments in so far as if they were excluded the coefficient of determination improves to 0.67 (figure 6b). Above-mentioned reasoning was: the mobility of molecular urea-form in the rizosphere; and the rapid hydrolysis of urea followed by nitrification which enhances the susceptibility of N to be leached as nitrate-ion.

Soil N balance

The incubation technique could not provide information about the contribution of soil below 14 cm to N nutrition of plants. In order to understand what happened in the entire arable layer it was necessary to establish the soil N balance. In order to achieve it, the data of the control treatments were used since N losses from these plots are minimal. The components of the equation of N balance in the rizosphere (0-60 cm) are:

Net N mineralized (< 14 cm) = N uptake – Net N nitrified (0-14 cm) – Inorganic-N in irrigation plus rainfall water – Tuber yield total-N – Δ soil residual inorganic-N (0-60 cm).

Nitrogen uptake was estimated from N in tubers at harvest increased by a N harvest index (= 0.85) which took into account N lost due to crop senescence from the peak of maximum N in whole plants (aboveground + tubers) to harvest time [31]. Net N nitrified (0-14 cm) is NO_3-N accumulated in field incubations and represents inorganic-N available to the crop during the growth season, in so far as crop uptake, leaching and denitrification are expected to be negligible. Nitrogen introduced by water was estimated after periodic analysis of the inorganic-N concentrations of rainfall and irrigation water, and considering the amount of water involved. Nitrogen added by seed tubers was estimated from seed rate and N concentration in seed tubers. Δ soil residual inorganic-N (0-60 cm) represents the difference in the amount of inorganic-N in soil profile at the time of planting and harvest. The values estimated for all the components of the equation are summarized in table III.

Tuber N recovered accounted for a total of 110 kg/ha as a mean value of the three years of study. Nitrogen nitrified in the upper 14 cm of soil reached 82 % of the total N available from soil. Biological activity that promotes the mineralization of organic substrates appears to be high only in the well-aerated upper layer. Therefore, 14 cm of soil coring seems to be sufficient for studying *in situ* N transformations with influence in crop N nutrition, as long as mobile N forms were not used as fertilizer.

Nitrogen available from the mineralization of native organic matter was lower in 1997 than in the other years. Petiole nitrate, tuber N recovered and N nitrified in incubated soils furnished that evidence. Here, the result is also emphasized with net N mineralized below 14 cm of soil obtained from the equations of N balance. Otherwise, petiole nitrate and tuber N recovered reflect what happened in the rizosphere, not only in 14 cm soil surface.

The laboratory estimates of N available from native soil organic matter based on pre-plant soil analysis were 12, 9 and 18 kg N/ha, respectively for 1996, 1997 and 1998. The results were obtained using a constant net N mineralization rate of 3 %, considering 4 months as the length of the cropping season and using other information contained in table I (bulk density, fine separates and soil organic matter) [34]. Measured values in field incubation accounted to 83.2, 53.2 and 69.7 kg N/ha in 1996, 1997 and 1998, respectively, even if only the surface 14 cm of soil was considered (table III). Thus, the estimates of the laboratory were comparatively low and significant amounts of N seem to become available without being taken into account in N recommendations.

Conclusions

The experiments showed that soils with low organic matter content could supply significant amounts of N. Measured values are five to eight times higher than the recommended fertilizer-N doses estimated by our laboratory from pre-plant soil analysis. The organic amendments released little N even the poultry manures. These results stress the difficulties of proper manure management due to the uncertainty relating to the amount and timing of N released. The incubation technique apparently yielded good estimates of N released from soil organic matter and manures considering their close relationship with crop N recovered. The reason for the good performance certainly is the similarity of conditions for microbial activity with the surrounding soil. The diurnal changes in soil temperature could occur; soil moisture along each incubation period was adequate; glass jars prevented nitrate losses by diffusion, leaching and crop uptake; denitrification was prevented by controlling excess moisture and permitting some aeration (tube holes); and sequential analysis avoided the inhibitory effect of nitrate accumulation in nitrifying organisms. In addition, insect damage was not a problem and the process of putting in and taking out the soil cores from the jars could not be easier.

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References

[1] Adams M.A. and Attiwill P.M., Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. II. Indices of nitrogen mineralization, Plant Soil 92 (1986) 341-362.

[2] Bhogal A., Hatch D.J., Shepherd M.A. and Jarvis S.C., Comparison of methodologies for field measurements of net nitrogen mineralization in arable soils, Plant Soil 207 (1999) 15-28.

[3] Boone R.D., Soil organic matter as a potential net nitrogen sink in a fertilized cornfield, South Deerfield, Massachusetts, USA, Plant Soil 128 (1990) 191-198.

[4] Castellanos J.Z. and Pratt P.F., Mineralization of manure nitrogen-correlation with laboratory indexes, Soil Sci. Soc. Am. J. 45 (1981) 354-357.

[5] Dahnke W.C. and Johnson G.V., Testing soils for available nitrogen, in: Westerman R.L. (ed.), Soil Testing and Plant Analysis. Book Series 3, 3rd ed. SSSA, 1990, pp. 127- 139.

[6] Douglas B.F. and Magdoff F.R., An evaluation of nitrogen indices for organic residues, J. Environ. Qual. 20 (1991) 368-372.

[7] Engels T. and Kuhlmann H., Effect of rate of fertilizer on apparent net mineralization of N during and after cultivation of cereal and sugar beet crops, Z. Pflanzenernähr. Bodenk 156 (1993) 149-154.

[8] Eno C.F., Nitrate production in the field by incubating the soil in polyethylene bags, Soil Sci. Soc. Proc. 24 (1960) 277-279.

[9] FAO/UNESCO, Soil Map of the World. Vol. 1, Paris, 1974.

[10] Fisk M.C. and Schmidt S.K., Nitrogen mineralization and microbial biomass nitrogen dynamics in three Alpine tundra communities, Soil Sci. Soc. Am. J. 59 (1995) 1036-1043.

[11] Fox R.H. and Piekielek W.P., Field testing of several nitrogen availability indexes, Soil Sci. Soc. Am. J. 42 (1978) 747-750.

[12] Giroux M., Comparison of urea and ammonium nitrate as N-fertilizer sources for potato, Am. Potato J. 61 (1984) 522-523.

[13] Gupta A. and Saxena M.C., Evaluation of leaf analysis as a guide to nitrogen and phosphorus fertilization of potato (*Solanum tuberosum* L.), Plant Soil 44 (1976) 597-605.

[14] Hall J.M., Williams B.L. and Killham K., Investigation of N mineralization-immobilization dynamics in blanket peat to optimize the N economy of improved grass pasture, Eur. J. Agron. 3/4 (1994) 317-320.

[15] Harmsen G.W. and van Schreven D.A., Mineralization of organic nitrogen in soil, Adv. Agron. 7 (1955) 299-398.

[16] Harris P.J., Microbial transformation of nitrogen, in: Wild, A. (ed.) Russell's Soil Conditions and Plant Growth, 11th ed., Longman Scientific & Technical, New York, 1988, pp. 608-651.

[17] Hong S.D., Fox R.H. and Piekielek W.P., Field evaluation of several chemical indexes of soil nitrogen availability, Plant Soil 123 (1990) 83-88.

[18] Hook P.B. and Burke I.C., Evaluation of methods for estimating net nitrogen mineralization in a semiarid grassland, Soil Sci. Soc. Am. J. 59 (1995) 831-837.

[19] Houba V.J., van der Lee J.J., Novozamsky I. and Walinga I., Soil and Plant Analysis. Part 5 - Soil Analysis Procedures, Wageningen, 1989.

[20] Kanamori T. and Yasuda T., Immobilization, mineralization and the availability of the fertilizer nitrogen during the decomposition of the organic matters applied to the soil, Plant Soil 52 (1979) 219-227.

[21] Keeney D.R. and Bremner J.M., Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability, Agron. J. 58 (1966) 498-503.

[22] Mazzarino M.J., Oliva L., Nuñez A., Nuñez G. and Buffa E., Nitrogen mineralization and soil fertility in the dry Chaco Ecosystem (Argentina), Soil Sci. Soc. Am. J. 55 (1991) 515-522.

[23] McKenney D.J., Wang S.-W., Drury C.F. and Findlay W.I., Denitrification, immobilization, and mineralization in nitrate limited and nonlimited residue-amended soil, Soil Sci. Soc. Am. J. 59 (1995) 118-124.

[24] Mengel K., Dynamics and availability of major nutrients in soils, Adv. Soil Sci. 2 (1985) 65-131.

[25] Neeteson J.J. and Wadman W.P., Assessment of economically optimum rates of fertilizer N on the basis of response curves, Fert. Res. 12 (1987) 37-52.

[26] Overrein L.N. and Moe P.G., Factors affecting urea hydrolysis and ammonia volatilization in soil, Soil Sci. Soc. Amer. Proc. 31 (1967) 57-61.

[27] Paul J.W. and Beauchamp E.G., Nitrogen availability for corn in soils amended with urea, cattle slurry, and composted manures, Can. J. Soil Sci. 73 (1993) 253-266.

[28] Pomares-Garcia F. and Pratt P.F., Value of manure and sewage sludge as N fertilizer, Agron. J. 70 (1978) 1065-1067.

[29] Raison R.J., Connell M.J. and Khanna P.K., Methodology for studying fluxes of soil mineral-N *in situ*, Soil Biol. Biochem. 19 (1987) 521-530.

[30] Recous R., Machet J.M. and Mary B., The fate of labelled ^{15}N urea and ammonium nitrate applied to a winter wheat crop, Plant Soil 112 (1988) 215-224.

[31] Rodrigues M.A., Influência da Fertilização Mineral e Orgânica na Cultura da Batata: Eficiência de Utilização do Azoto. MSc. Thesis, ISA, Portugal, 1995.

[32] Rodrigues M.A., Gestão do Azoto na Cultura da Batata. PhD. Thesis, ISA, Portugal, 2000.

[33] Rodrigues M.A. and Coutinho J.F., Efficiency of uptake and utilization of N from mineral and organic sources by potato crop, Proc. of 4th ESA-Congress, Veldhoven-Wageningen, 1996, pp. 368-369.

[34] Santos J.Q., Fertilização – Fundamentos da Utilização dos Adubos e Correctivos. Publ. Europa-América, Mem Martins, Portugal, 1996.

[35] Serna M.D. and Pomares F., Indexes of assessing N availability in sewage sludges, Plant Soil 139 (1992) 15-21.

[36] Subler S., Parmelee R.W. and Allen M.F., Comparison of buried bag and PVC core methods for *in situ* measurements of nitrogen mineralization rates in an agricultural soil, Commun. Soil Sci. Plant Anal 26 (15 & 16) (1995) 2369-2381.

[37] Vinther F.P., Nitrogen fluxes in a cropped sandy and loamy soil measured by sequential coring, Eur. J. Agron. 3/4 (1994) 311-316.

[38] Westermann D.T. and Crothers S.E., Measuring soil nitrogen mineralization under field conditions, Agron. J. 72 (1980) 1009-1012.

[39] Walley F., Yates T., van Groenigen J.-W. and van Kessel C., Relationship between soil nitrogen availability indices, yield, and nitrogen accumulation of wheat, Soil Sci. Soc. Am. J. 66 (2002) 1549-1561.

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Table II – Selected characteristics of organic amendments.

Table III – Soil N balance for control treatments (values in kg/ha).

Figure 1 – Soil NH_4-N levels in the upper 14 cm layer along the cropping season. Data from fresh soil samples taken up at the start of each new incubation period. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each sampling date. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

Figure 2 – Soil NO_3-N levels in the upper 14 cm layer along the cropping season. Data from fresh soil samples taken up at the start of each new incubation period. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each sampling date. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

Figure 3 – Daily net mineralization rates for each incubation period along the growing season. The data are plotted in the middle point of the incubation periods. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each incubation period. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

Figure 4 – Cumulative NO_3-N yielded in incubated soils during the growing season. The data represent the contribution of each incubation period for total NO_3-N release. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each sampling date. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

Figure 5 – Petiole NO_3-N concentrations as a function of treatment and year. Petiole sampling dates were 20, 15 and 18 days after crop emergence in 1996, 1997 and 1998. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste. For each year, means with the same letter do not differ by Fisher's $LSD_{.05}$ test.

Figure 6 – Relationship between cumulative soil NO_3-N yielded in incubated soils during the entire growing seasons and crop N recovered: a) using the data of all the treatments; b) excluding the data of urea treatments.

Table I – Soil properties of field plots

	1996	1997	1998
pH (H_2O)	6.2	6.0	6.5
pH (KCl)	5.1	4.3	5.4
[§] Organic-C (mg g^{-1})	0.60	0.50	1.01
[‡]Available P (mg P_2O_5 kg^{-1})	102	46	112
[‡]Available K (mg K_2O kg^{-1})	128	101	180
Bulk density (g cm^{-3})	1.20	1.16	1.18
Topsoil texture	sandy loam	sandy loam	sandy loam
Coarse fragments, > 2 mm (%)	22.7	21.1	23.8

[§]Walkley-Black and [‡]Egner-Rhiém methods [34].

Table II – Selected characteristics of organic amendments.

	Poultry manure			Farmyard manure			Municipal solid waste		
	1996	1997	1998	1996	1997	1998	1996	1997	1998
Dry matter (%)	59	90	72	51	73	27	45	52	52
C/N ratio	4.7	6.9	7.6	11.8	10.2	11.0	14.4	21.3	12.1
N Kjel. (g kg^{-1})	39.9	35.2	30.1	11.8	16.6	19.4	17.3	11.9	14.0
NH_4-N (g kg^{-1})	1.431	1.891	0.283	0.119	0.152	0.122	0.057	0.691	0.164
NO_3-N (g kg^{-1})	0.006	0.429	0.027	0.204	0.413	0.995	0.180	0.027	0.019
Ca (g kg^{-1})	71.0	25.7	30.3	23.9	24.0	21.7	30.3	28.5	15.6
Mg (g kg^{-1})	5.4	7.6	4.3	4.3	3.7	1.6	2.9	3.6	3.3
K (g kg^{-1})	16.0	18.0	20.0	7.4	4.8	15.0	4.6	4.2	5.8
P (g kg^{-1})	15.2	11.8	11.0	3.9	6.0	6.4	4.8	5.4	5.1
S (g kg^{-1})	3.5	4.3	3.5	2.1	3.0	3.1	2.7	2.0	2.1
Fe (g kg^{-1})	1.8	4.9	2.7	38.7	26.7	15.7	11.9	8.7	7.6
Na (mg kg^{-1})	4.0	4.1	5.8	1.7	1.4	3.0	8.0	4.8	6.4
Zn (mg kg^{-1})	248	260	270	178	160	150	620	750	620
Mn (mg kg^{-1})	237	300	257	796	792	494	208	166	171
Cu (mg kg^{-1})	40	55	60	114	74	58	343	322	278

Table III – Soil N balance for control treatments (values in kg/ha).

	Crop N uptake	Net N_{nit} (0-14 cm)	N (irrig. + rainfall)	N in seed tubers	Δ inorg.-N (< 60 cm)	Net N_{min} (< 14 cm)
1996	130.8	83.2	5.6	5.0	18.4	18.6
1997	93.4	53.2	8.6	8.0	13.4	10.2
1998	105.8	69.7	6.2	8.0	6.3	15.6
Mean	110.0	68.7	6.8	7.0	12.7	14.8

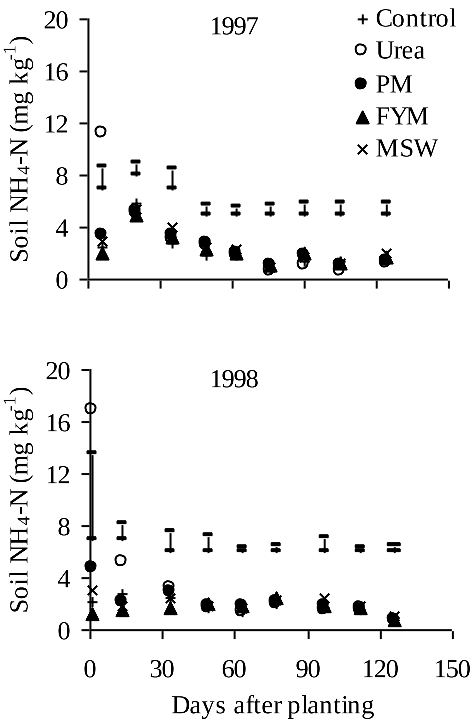

Figure 1 – Soil NH_4-N levels in the upper 14 cm layer along the cropping season. Data from fresh soil samples taken up at the start of each new incubation period. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each sampling date. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

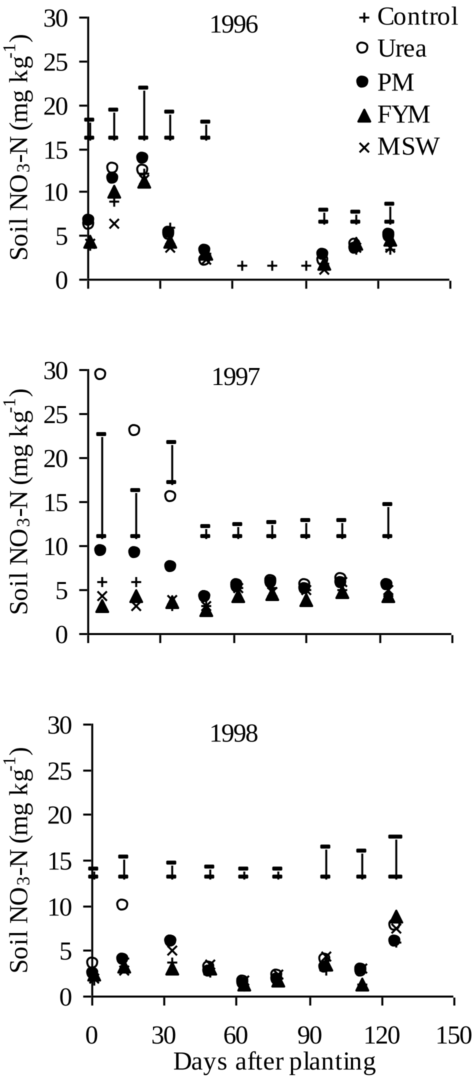

Figure 2 – Soil NO_3-N levels in the upper 14 cm layer along the cropping season. Data from fresh soil samples taken up at the start of each new incubation period. Vertical bars represent least significant differences (P=0.05) for comparing adjacent means in each sampling date. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

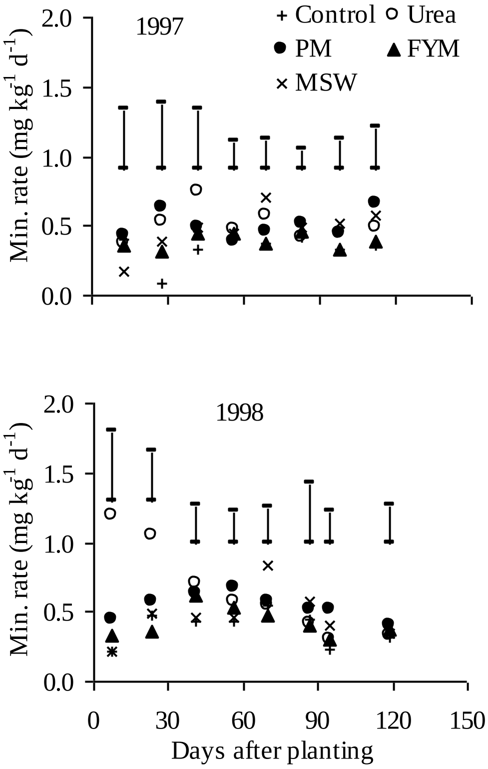

Figure 3 – Daily net N mineralization rates for each incubation period along the growing season. The data are plotted in the middle point of the incubation periods. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each incubation period. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

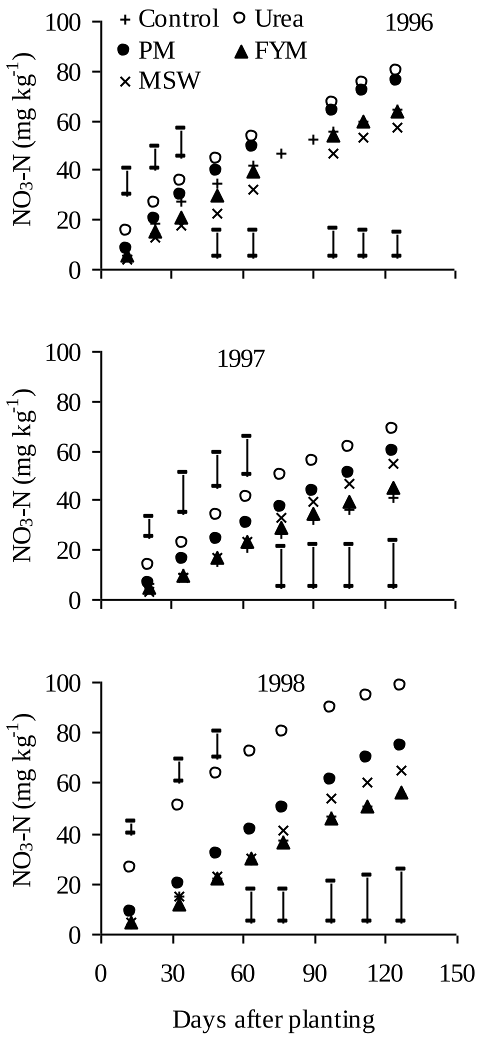

Figure 4 – Cumulative NO_3-N yielded in incubated soils during the growing season. The data represent the contribution of each incubation period for total NO_3-N release. Vertical bars represent least significant differences (*P*=0.05) for comparing adjacent means in each sampling date. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste.

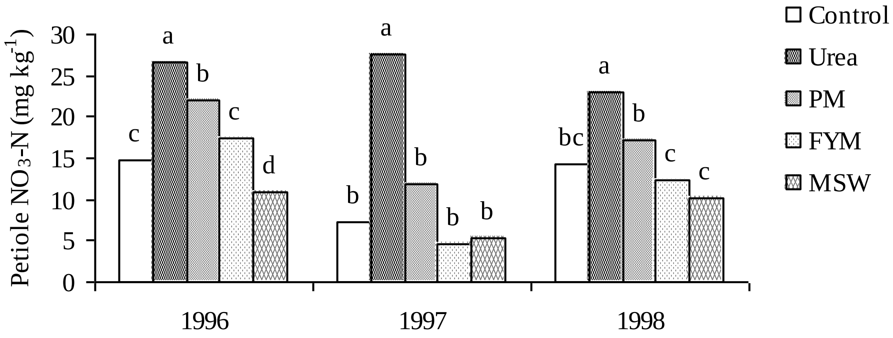

Figure 5 – Petiole NO_3-N concentrations as a function of treatment and year. Petiole sampling dates were 20, 15 and 18 days after crop emergence in 1996, 1997 and 1998. PM, poultry manure; FYM, farmyard manure; MSW, municipal solid waste. For each year, means with the same letter do not differ by Fisher's $LSD_{.05}$ test.

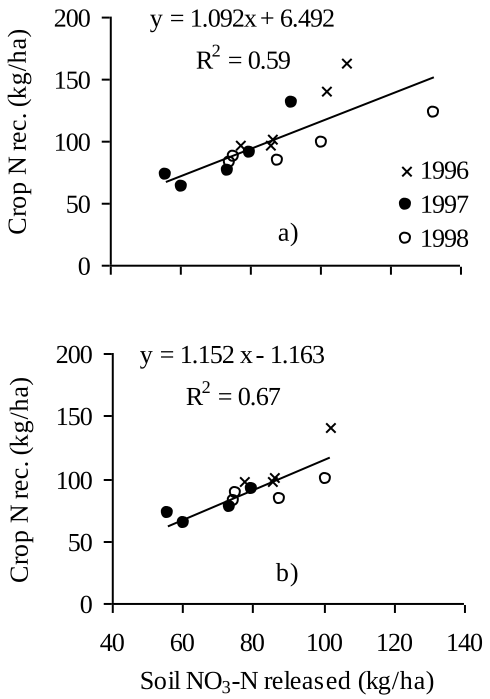

Figure 6 – Relationship between cumulative soil NO_3-N yielded in incubated soils during the entire growing seasons and crop N recovered: a) using the data of all the treatments; b) excluding the data of urea treatments.