Nitrogen-use efficiency and economic efficiency of slow-release N fertilisers applied to irrigated turfs in a Mediterranean environment

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Abstract The effect of three fertilisers that delay the bioavailability of nitrogen (N) in the soil was compared with ammonium nitrate and a zero N control in two irrigated turfs in NE Portugal. The fertilisers used were: Floranid permanent 16-7-15 (slow-release, IBDU/Isodur fertiliser); Basacote plus 9M 16-8-12 (controlled-release fertiliser, copolymer ethylene acrylic); Nitroteck 20-8-10 (stabilized fertiliser, dicyandiamide as nitrification inhibitor + coating with polyterpene) and Nitrolusal (ammonium nitrate, 20.5% N), applied all at a rate of 120 kg N ha^{-1}. Nitrolusal was split into two fractions of 60 kg N ha^{-1}. Phosphorus (P) and potassium (K) rates were balanced among treatments by using superphosphate (18% P_2O_5) and potassium chloride (60% K_2O). The turf dry matter (DM) yield and N concentration in dry material were determined from several cuts of biomass throughout the growing season. Based on DM yield, N concentration in dry material and fertilisation costs, indices of N use efficiency and economic efficiency were estimated. Soil nitrate levels were monitored by using anion exchange membranes inserted directly into the soil. Basacote gave significantly lower DM yields than the other fertilised treatments. The apparent N recovery of Basacote was also the lowest. The results showed that Basacote released less N than that required for an adequate plant growth in the beginning of the growing season, hampered the flush of spring growth. Furthermore, the release period of this Basacote formulation, in the environmental conditions of these experiments, seemed to be longer than the length of the growing season. Nitroteck and Floranid yielded similar or even higher DM and apparent N recovery values than did Nitrolusal. The indices of economic efficiency ordered the fertilisers as Nitroteck > Nitrolusal > Floranid > Basacote or Nitrolusal > Nitroteck > Floranid > Basacote, if the costs of P and K fertilisers used to balance the P and K rates in the experimental design were, respectively, taken or not taken into account.

Keywords Controlled-release fertilisers · Economic efficiency of fertilisation · N-use efficiency · Slow-release fertilisers · Stabilized fertilisers · Turfgrass

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Introduction

Urban green spaces have seen a huge increase worldwide in the last few decades. They beautify the landscape and are used for recreation, important aspects for the well being of urban dwellers. Green spaces also bring several other important ecological benefits such as air cleansing, carbon sequestration and stormwater retention. However, the social and ecological benefits of urban green spaces can be lessened by inappropriate management regimes, for instance with regard to nitrogen fertiliser applications. An unbalanced N fertilization program may lead to water and atmospheric pollution due to nitrate leaching and green house gas emissions.

A wide range of fertiliser products are sold under the commercial advertisement that they can improve N use efficiency by matching nutrient release to crop demand. These kind of fertilisers are commercially classified in two main groups: slow-release fertilisers, obtained as condensation products of urea and urea aldehydes; and controlled-release fertilisers, products containing a conventional fertiliser whose nutrient release in the soil is regulated by sulphur or/and polymer coatings (Trenkel 2007). A third group is classified as stabilized fertilisers, those which are modified during the production process with a nitrification inhibitor (Trenkel 2007). The stabilized fertilisers delay the oxidation of NH_4^+ to NO_2^- during the nitrification process in the soil. While nitrate is freely mobile in the aqueous soil medium, ammonium may be adsorbed in the negatively charged clay-humic complexes, being more protected from leaching. Nitrification and urease inhibitors can also be sold separately to apply over a soluble fertiliser, such as urea, or spread directly on the soil surface.

The use of slow and controlled release fertilisers and/or stabilized fertilisers have been successfully used in several agro-environmental conditions, particularly in rice (Carreres et al. 2003; Tang et al. 2007), containerized nursery tree plants (Walker and Huntt 1999; Fernández-Escobar et al. 2004; Oliet et al. 2004; Girardi et al. 2005) and in agricultural and horticultural crops, especially on sites with a high precipitation rate, intensive irrigation and/or light sandy soils (Pasda et al. 2001). Other studies demonstrated their potential to reduce environmental pollution, in regards to N_2O emissions (Delgado and Mosier 1996; Shoji et al. 2001) and nutrient runoff (Emilsson et al. 2007). Abundantly demonstrated also is the positive effect of the use of nitrification inhibitors alone in reducing N_2O emissions from several agrosystems (Majumdar et al. 2000; Serna et al. 2000; Macadam et al. 2003; Zaman et al. 2009) and even other air pollutants, such as methane (Pathak et al. 2003).

In practice, however, the use of slow and controlled release fertilisers and/or stabilized fertilisers is mainly increasing in greenhouses, golf courses, professional lawn management, as well as by consumers (home and garden) and landscape gardeners (Trenkel 2007). In general agriculture, they are used to a much lesser extent mainly due to their cost/benefit ratio (Trenkel 2007) and also due to the insufficient demonstration of their real advantages over conventional fertilisers (Cartagena et al. 1995; Guertal 2000; Rodrigues et al. 2010).

Sport pitches, turfs and other public and private green areas have increased in the last few decades. It would not be acceptable if these green spaces had any negative impact on the environment. However, soil testing, for instance, is not a usual procedure to establish the fertilisation program for these particular spaces. Instead, the marketing strategies of the companies that sell the fertilisers dictate the rules, since it is easy to stress the advantages of the slow release fertilisers over the conventional ones, at least theoretically. Thus, taking into account the wide range of fertiliser products with different slow release mechanisms, and also often their high cost, it is important to test this type of fertilisers in real field conditions. In this work three fertilisers with different slow-release mechanisms were tested in two turfs of the cities of Valpaços and Bragança in NE Portugal. They were compared with a conventional N fertiliser and a zero N control by using dry matter (DM) yield as an indicator of the health and condition of the turf, N uptake and indices of N-use and economic fertilisation efficiency.

Materials and methods

Site, climate, soils and turfs

Two field experiments were carried out in NE Portugal, one located in a turf grass of the town of Valpaços and the other located in a turf grass of the *campus* of the Polytechnic Institute of Bragança. The experiments of Valpaços and Bragança were, respectively, carried out in the growing seasons of 2008 and 2009. The climate in the region is of Mediterranean type with some Atlantic influence. Mean monthly

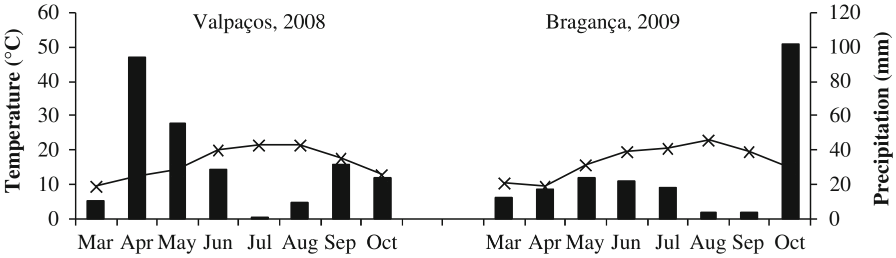


Fig. 1 Mean monthly temperature (*line*) and precipitation (*bars*) during the growing seasons of 2008 in Valpaços and 2009 in Bragança

temperature and precipitation throughout the growing seasons are presented in Fig. 1. Some physical and chemical properties of soils sampled shortly after the start of the experiments are presented in Table 1.

The experiment of Valpaços was carried out in a young turf grass sown 2 years before the trial start. The turf was established with a seed mixture of 50% tall fescue (*Festuca arundinacea*, cv. Eldorado), 30% perennial ryegrass (*Lolium perenne*, cv. Roadrunner) and 20% red fescue (*Festuca rubra*, cv. Rumba). The turf grass of Valpaços is a pleasant space that has been carefully managed by weeding out any spontaneous broadleaf species that emerged in the turf. The experiment of Bragança was carried out in an old garden (more than 15 years) of the Polytechnic Institute. It was not possible to find any reference to the type of seed used in the establishment of the turf. At present, the turf of Bragança is a mixture of different plants including many broadleaf species, since there has not been any strategy for selecting the species that are growing there. Both the fields were sprinkler-irrigated during the summer to maintain a regular plant growth. The amounts of water added were estimated in 420 and 350 mm, respectively for Valpaços and Bragança.

Experimental design and fertiliser treatments

The experiments included four different types of N-containing fertilisers and a zero N control, and were arranged in a randomized block design with three replications. The fertilised treatments were: Floranid permanent 16-7-15 (slow-release, IBDU/Isodur fertiliser); Basacote plus 9M 16-8-12 (controlled-release fertiliser, copolymer ethylene acrylic); Nitroteck 20-8-10 (stabilized fertiliser, DCD as nitrification inhibitor + coating with polyterpene) and Nitrolusal (ammonium nitrate, 20.5% N). All the fertilisers were applied at a rate of 120 kg N ha^{-1} in both the years. Floranid, Basacote and Nitroteck were basally applied and Nitrolusal was divided into two fractions of 60 kg N ha^{-1}. Phosphorus and potassium rates were balanced among treatments, including the control, by using superphosphate (18% P_2O_5) and potassium chloride (60% K_2O). The total amounts of P and K applied in each treatment were 35 kg P ha^{-1} and 93 kg K ha^{-1}. The fertilisers were applied to the ground on 11 March 2008 and 28 March 2009. The second fractions of ammonium nitrate were applied on 10 July 2008 and 14 July

Table 1 Selected properties of soils of the gardens of Valpaços and Bragança shortly before the establishment of the field trials

Parameters Texture (USDA)	Valpaços Loamy sand	Bragança Loamy
pH (soil:water, 1:2.5)	6.7	5.7
Organic C (Walkley–Black) (g kg^{-1})	4.5	10.2
Extractable P (Egner-Rhiem) (mg kg^{-1})[a]	11.4	14.0
Extractable K (Egner-Rhiem) (mg kg^{-1})[a]	95.4	174.3
Exchang. bases (ammonium acetate, pH 7)		
Ca (cmol$_c$ kg^{-1})	3.86	14.21
Mg (cmol$_c$ kg^{-1})	0.46	8.38
K (cmol$_c$ kg^{-1})	0.64	0.53
Na (cmol$_c$ kg^{-1})	0.60	0.38

[a] Extracted by ammonium lactate plus acetic acid, buffered at pH 3.7

2009. The last cuts occurred on 30 September 2008 and 31 October 2009.

Field determinations and laboratory analysis

Dry matter yield was used as the main indicator of the performance of the fertilisers. Dry matter yield was evaluated by sequential cuts throughout the growing seasons. Samples of a square meter were cut, dried at 70°C, weighed and ground. Nitrogen concentration in the plant material was determined in a Kjeltec Autoanalyser 1030. Dry matter yield and tissue N concentration allowed the determination of N uptake by turf biomass.

Soil nitrate levels were monitored during the growing seasons by using anion exchange membranes (AEM), following the methodology reported by Rodrigues et al. (2006) in pot experiments. Strips of 1 × 2 cm of AEM were inserted 8–10 cm into the soil with a hard spatula and kept there for a week. Two AEM strips were buried in each plot. The AEM were tied with a coloured line allowing for easy identification and removal from the soil. The AEM strips removed from soil were rinsed with distilled water and nitrate ions were then eluted in flasks containing 30 ml of 0.5 N hydrochloric acid per each pair of AEM strips. The AEM strips were kept in the acid media for 1 h and 15 min as proposed by Qian and Schoenau (1995). Nitrate concentrations in the extracts were determined by UV–Vis. spectrophotometry. The strips were regenerated in 0.5 M $NaHCO_3$ before being reused.

Data analysis

Data analysis was carried out using JMP software. The comparison of DM yield, N concentration and N uptake among fertilizer treatments was provided by ANOVA. After ANOVA examination, the means with significant differences ($\alpha < 0.05$) were separated by the Tukey–Kramer HSD test. Mean confidence limits were also applied to the data presented graphically (Figs. 2, 3, 4 and 5) to allow an easy viewing and comparison among fertiliser treatments.

Based on turf DM yield and N uptake two indices of N use efficiency were estimated. Two indices of economic efficiency were also estimated based on the costs associated with each fertilisation treatment, considering the prices of all the fertilisers at the

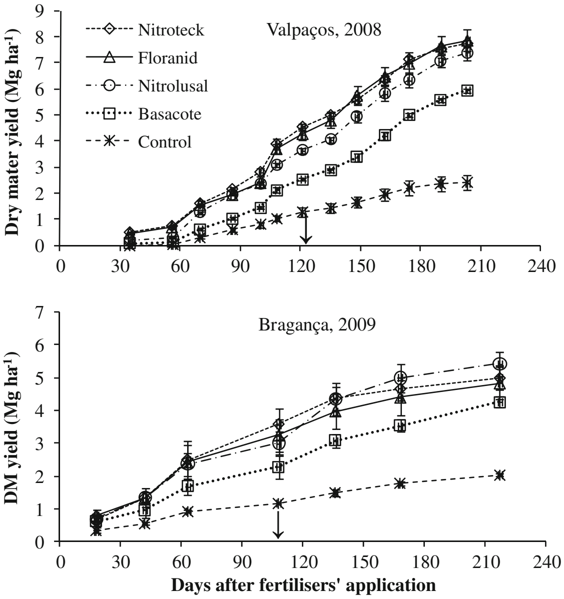


Fig. 2 Dry matter yield accumulated in the experiments of Valpaços (2008) and Bragança (2009) over the growing seasons. *Vertical bars* are the mean standard deviations. The *arrow* over the X-axis represents the date of the application of the second half of Nitrolusal

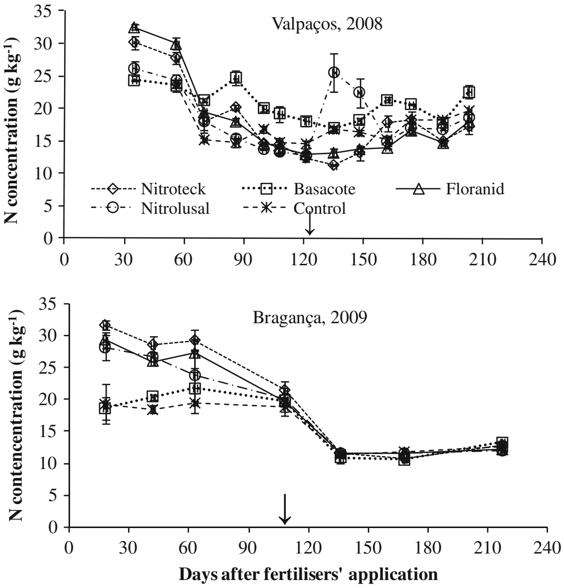


Fig. 3 Nitrogen concentration in turf dry matter in the experiments of Valpaços (2008) and Bragança (2009) over the growing seasons. *Vertical bars* are the mean standard deviations. The *arrow* over the X-axis represents the date of the application of the second half of Nitrolusal

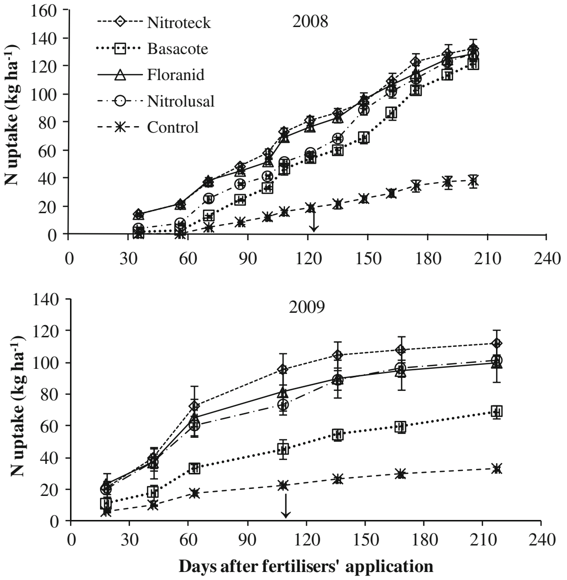


Fig. 4 Nitrogen uptake by the turf of the experiments of Valpaços (2008) and Bragança (2009) over the growing seasons. *Vertical bars* are the mean standard deviations. The *arrow* over the X-axis represents the date of the application of the second half of Nitrolusal

beginning of the experiment. The four indices were estimated as following:

Apparent N Recovery (ANR, %) = 100 × (N recovered in the fertilised treatments − N recovered in the control)/N applied as fertiliser;

Physiological Efficiency (PE, kg kg^{-1}) = (DM yield in the fertilised treatments − DM yield in the control)/(N recovered in the fertilised treatments − N recovered in the control);

Economic Efficiency of Total Fertilisation (EETF, kg $€^{-1}$) = (DM yield in the fertilised treatments − DM yield in the control)/Cost of fertilisation (including the fertilisers used to balance P and K in the experimental design);

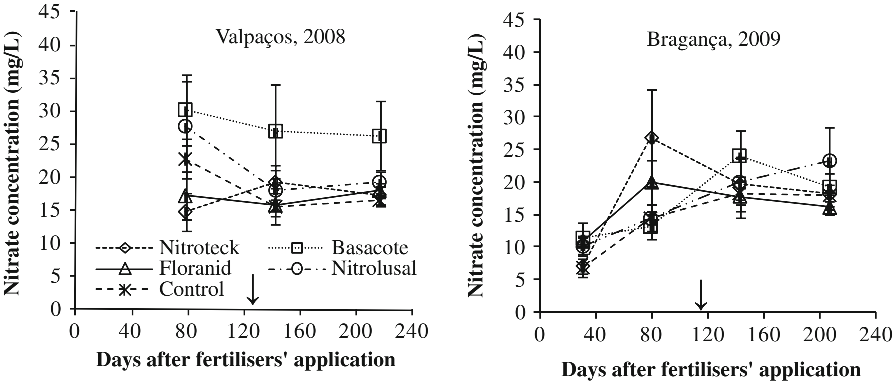
Economic Efficiency of N Fertilisation (EENF, kg $€^{-1}$) = (DM yield in fertilised plots − DM yield in the control)/Cost with the nitrogenous fertiliser.

Results

Dry matter yield and plant N uptake

The accumulated dry matter yields were significantly lower in the control than that in the fertilised treatments in both the 2008 and 2009 experiments (Fig. 2). The accumulated DM yields in the Basacote plots were significantly lower than that recorded in the other fertilised plots for almost all the sampling dates. The mean DM yield accumulated in the Nitrolusal treatment was significantly lower than that observed in the Nitroteck and Floranid plots in 2008, at the time of the application of the second half of the N rate (10 July). In 2009, the mean DM yield immediately before the topdress N application was slightly lower in Nitrolusal than in Nitroteck and Floranid treatments, but the differences were not statistically significant. Thereafter, the DM yield increased faster in Nitrolusal than in Nitroteck and Floranid treatments due to the topdress N application. Thus, at the end of the growing seasons no significant differences were found in DM yields among Nitroteck, Floranid and Nitrolusal treatments. In the turf grass of Valpaços (2008) the accumulated DM yields at the end of the growing season were 7.9, 7.7, 7.4, 5.9 and 2.4 Mg ha^{-1}, respectively for Floranid, Nitroteck, Nitrolusal, Basacote and Control. In Bragança, the accumulated DM yields were 5.4,

Fig. 5 Nitrate concentration in AEM extracts in the experiments of Valpaços (2008) and Bragança (2009) over the growing seasons. *Vertical bars* are the mean standard deviations. The *arrow* over the X-axis represents the date of the application of the second half of Nitrolusal



5.0, 4.8, 4.3 and 2.0 Mg ha^{-1}, respectively for Nitrolusal, Nitroteck, Floranid, Basacote and Control. Thus, the turf of Bragança showed a lower yield potential in comparison to the turf of Valpaços, probably due to the presence of higher amount of broadleaf species. It is also important to note that the experimental variability was comparatively higher in the turf of Bragança.

In the first part of the growing seasons, Floranid in 2008 and Nitroteck in 2009 showed the highest N concentrations in the turf DM (Fig. 3). Basacote and Control showed the lowest N concentrations in DM in the first samplings. In 2008, after the fourth date of sampling, N concentrations in DM was the highest in Basacote, excluding the values recorded in Nitrolusal in the two dates following the application of the second half of N rate. In 2009, N concentration in DM increased from the first sampling date to the third in the Basacote treatment, but the values were lower than that of the other fertilised treatments. In 2009, in the second half of the growing season, N concentrations dropped to values close to 11–12 g kg^{-1}, without significant variation with time or with the fertiliser treatment, whereas in 2008 the N concentrations in tissues increased in the last sampling dates after a period of low values, between 120 and 150 days after the fertilisers' application.

Plant N uptake followed a similar pattern as DM yield (Fig. 4). Thus, N uptake was significantly lower in the control than in the fertilised treatments. Basacote showed the lower values among the fertilised treatments. In 2008, N uptake in Nitrolusal was significantly lower than in Floranid and Nitroteck treatments in the first part of the growing season. After the application of the second half of the N rate, N uptake in Nitrolusal reached similar values than that found in Nitroteck and Floranid treatments. In 2009, the differences in N uptake between Nitrolusal, Nitroteck and Floranid were not statistically significant from the beginning to the end of the growing season. In 2008, N uptake at the end of the growing season was higher than that found in 2009, as had been observed for DM yield. The mean values of N uptake in 2008 were 132.4, 129.0, 129.0, 121.4 and 38.2 kg ha^{-1}, respectively in Nitroteck, Floranid, Nitrolusal, Basacote and Control. In 2009, the mean values of N uptake were 112.2, 101.4, 100.0, 68.9 and 32.9 kg ha^{-1}, respectively in Nitroteck, Nitrolusal, Floranid, Basacote and Control.

The soil nitrate levels were monitored through the use of anion exchange membranes. In 2008, the mean nitrate concentration in AEM extracts seemed to be higher in the Basacote plots, in spite of the huge experimental variability, when the analysis started at 80 days after the fertilisers' application (Fig. 5). In 2009, the experimental variability was often high. In the second sampling date, the mean nitrate concentrations in AEM extracts were the highest in Nitroteck followed by Floranid. As the growing season progressed, the highest nitrate concentrations in the AEM extracts were recorded from the Basacote and Nitrolusal plots.

Indices of N-use and economic fertilization efficiency

The apparent N recovery was higher than 75% for Nitroteck, Floranid and Nitrolusal in 2008 (Table 2). In 2009, the apparent N recovery was lower than in 2008, and the values of Nitroteck, Nitrolusal and Floranid ranged from 55.9 and 66.1%. Basacote showed apparent N recoveries lower than that of the other fertilised treatments with the values 69.3 and 30.0%, respectively in 2008 and 2009. The physiological efficiency of N of the different fertilisers ranged from 42.3 to 60 g kg^{-1} in 2008 and 37.2 and 61.5 g kg^{-1} in 2009 (Table 2). Basacote showed values clearly out of the pattern of the other fertilised treatments. Basacote had the highest PE in 2009 and the lowest in 2008.

The economic efficiency of total fertilisation was the highest for Nitroteck and the lowest for Basacote in both the experiments of 2008 and 2009 (Table 2). The highest economic efficiency of total fertilisation was recorded in 2008 for Nitroteck with a value of 9.3 kg DM €$^{-1}$, whereas the lowest (0.8 kg DM €$^{-1}$) was recorded for Basacote in 2009. If the costs of phosphorus and potassium fertilisers used to balance the macronutrients in the experimental design were not taken into account, and the calculation included only the nitrogenous fertilisers, the highest economic efficiency was recorded for Nitrolusal for both the experiments of 2008 (19.2 kg DM €$^{-1}$) and 2009 (13.0 kg DM €$^{-1}$). Thus, the economic efficiency of total fertilisation order the fertilisers as Nitroteck > Nitrolusal > Floranid > Basacote. The economic efficiency of N fertilisation order the fertilisers as Nitrolusal > Nitroteck > Floranid > Basacote.

Table 2 Turf dry matter (DM) yield, N uptake, apparent N recovery (ANR), physiological efficiency (PE), economical efficiency of total fertilisation (EETF) and economical efficiency of N fertilisation (EENF) in the 2008 and 2009 experiments

Site (year)	Treatment	DM (kg ha^{-1})	N uptake (kg ha^{-1})	ANR (%)	PE (kg kg^{-1})	EETF (kg €$^{-1}$)	EENF (kg €$^{-1}$)
Valpaços (2008)	Nitroteck	7,732.5 a	132.4 a	78.2	56.5	9.3	12.7
	Floranid	7,854.8 a	129.0 a	75.7	60.0	4.4	4.7
	Basacote	5,929.0 b	121.4 a	69.3	42.3	1.2	1.3
	Nitrolusal	7,376.8 a	129.0 a	75.7	54.7	6.1	19.2
	Control	2,406.2 c	38.2 b	–	–	–	–
Bragança (2009)	Nitroteck	4,997.9 ab	112.2 a	66.1	37.2	5.2	7.1
	Floranid	4,820.4 ab	100.0 a	55.9	41.3	2.2	2.4
	Basacote	4,256.5 b	68.9 b	30.0	61.5	0.8	0.8
	Nitrolusal	5,412.8 a	101.4 a	57.2	49.2	4.1	13.0
	Control	2,045.5 c	32.9 c	–	–	–	–

In columns and for each year, means followed by the same letter are not statistically different by Tukey–Kramer HSD test ($\alpha < 0.05$)

Among the fertilisers with a slow release mechanism, both the indices of economic efficiency order the fertiliser as followed: Nitroteck > Floranid > Basacote.

Discussion

Agronomic performances of fertilisers

The turf produced significantly lower DM in the control than in the fertilised treatments and recovered also much less N. This means that N was an important limiting factor for the vegetation growth in both the turf grasses.

Basacote is a polymer-encapsulated controlled-release fertiliser, containing 7.4% NO_3–N and 8.6% NH_4–N, whose rate of nutrient release is regulated by a membrane of copolymer ethylene acrylic. The DM yield and the N uptake in the biomass were the lowest among the fertilised treatments, as well as the apparent N recovery. It was clear that a significant part of N contained in the fertiliser was not released until the end of the growing season. The data provided by the anion exchange membranes showed also that Basacote would release more N latter in the growing season, corroborating the results of DM yield and N uptake. Based on the curve feature of the accumulation of DM and N uptake during the growing season, as well as on tissue N concentration, it seems that Basacote did not release enough N for an adequate vegetation growth at the beginning of the growing season. Taking into account that the flush of spring is probably the higher demand period for nitrogen and is also decisive for the total accumulated DM, this may justify the poor performance of Basacote in terms of DM yield and N uptake.

There have been several studies with controlled-release fertilisers reporting a prolonged release period beyond the labelled rates specified by the manufacturers, whose results were justified with temperature. Since the diffusion of water into the membrane and the nutrient release is temperature dependent, as temperature increases, nutrient release of the controlled-release fertilisers also increases too (Huett and Gogel 2000; Haase et al. 2007; Du et al. 2008). The prolonged release period beyond the labelled rates usually found has been attributed to the fact that the release pattern of the polymer-coated fertilisers is determined in a water-leach test at constant temperature, typically 21–25°C (Haase et al. 2007), conditions that are quite different to that found in the field. The positive agronomic and environmental benefits that have been reported from the use of controlled-release fertilisers can be related to restrictions in soil nutrient availability, such as the improvement in N_2 fixation in flooded rice (Carreres et al. 2003), the reduction in nutrient concentration in runoff water from vegetated roofs (Emilsson et al. 2007), or the promotion of morphological values of containerized *Pinus halepensis* seedlings (Oliet et al. 2004). Poor results associated with controlled-release fertilisers have been reported when the release of significant amounts of nutrients was important for crop performance (Zebarth et al. 2007; Rodrigues et al. 2010). In this experiment, the apparent lack of available N in the Basacote plots, in particular in the colder months of March and April would mainly also be the result of the temperature regime throughout the growing season (Fig. 1). The manufacturer of Basacote indicates release periods of 9–10, 8–9 and 6–7 months if the soil temperature is, respectively, 15, 21 and 27°C. In these experiments, the estimation of the mean temperature for the growing seasons gave 16.5 and 17.4°C, respectively for Valpaços and Bragança. For these temperatures the release periods would be slightly higher than 9 months, which correspond to release periods longer than the duration of the field trials ($\approx$7 months). Thus, it seems that this Basacote formulation (Basacote 9M) was not adequate for the length and the environmental conditions of the growing season of these regions.

Floranid is a slow-release fertiliser containing 2.1% NO_3–N, 7.9% NH_4–N and 6% N in the form of the single oligomer isobutylidene-diurea (IBDU). The nitrate fraction is immediately available for plant uptake after the fertiliser application, as well as the ammonium fraction, the latter being less vulnerable to leaching and denitrification, but susceptible to abiotic NH_4^+ fixation and biological immobilization. If not incorporated into the soil may lead to NH_3 volatilization. IBDU is a low solubility compound released slowly by hydrolysis, which is affected by soil moisture and temperature. Dry matter yield, tissue N concentration, N uptake and the indices of N use efficiency were very similar to those observed with Nitrolusal which was applied in two equal fractions in these experiments.

In some previous field studies, where a Floranid trade mark was included, no advantage was found in crop growth and yield over conventional N sources (Cartagena et al. 1995; Diez et al. 1997). Better results were reported by Fernández-Escobar et al. (2004), who found better growth of containerized olive nursery plants and reduced N losses by leaching by using Floranid in comparison with several soluble N sources. In all the afore-mentioned studies was used Floranid 32 (32% N), a fertiliser where almost all N is in the IBDU molecule. In the present study, the Floranid is a compound NPK fertiliser, containing 16% N, from which only 6% is IBDU-N. The relatively good performance of that fertiliser in these experiments would be due to the fact that the major part of N is available early in the season stimulating the flush of the vegetation in the spring, considering that plants can benefit if both the NO_3–N and NH_4–N forms are available in soil (Cao and Tibbitts 1993). No sign of significant slow release effect was observed from the agronomic parameters determined. However, NH_4–N and IBDU-N confer some protection to leaching and denitrification in the first weeks after the fertiliser application, which would benefit the agronomic performance of the fertiliser. Rodrigues et al. (2010) used this Floranid formulation in field experiments with tall cabbage and in pot experiments with tall cabbage and ryegrass. In the field experiments, the total N and petiole nitrate concentrations showed that there was a slow release effect which was comparable to the use of half of the N at preplant as urea and half of the N applied as topdress in the form of ammonium nitrate. In the pot experiments the slow-release effect was shortened by the rapid hydrolysis of IBDU, particularly enhanced by favourably higher temperature and soil moisture. Globally, Rodrigues et al. (2010) did not find significant differences in crop yields and N use efficiency between Floranid and the conventional urea/ammonium nitrate fertilization.

Nitroteck is a stabilised fertiliser with dicyandiamide as nitrification inhibitor, but it is also a controlled-release fertiliser, since it is encapsulated by a membrane rich in polyterpene. The fertilizer did not contain N in nitrate form. The N of the fertilizer is in the ammoniacal and amidic forms and also in the dicyandiamide molecule. The agronomic performance of Nitroteck was similar to that observed with Floranid and Nitrolusal. Based on DM yield, tissue N concentration and N uptake it seems that the fertilizer readily released enough nitrogen early in the growing season allowing for a good performance of the turf. The apparent N recovery was 78.2% in 2008 and 66.1% in 2009, which are values relatively high when compared to the values usually found in field conditions. The apparent N recovery in field crops is usually in the range of 40–60% (Boswell et al. 1985). The values were also similar or even slightly higher when compared to that of Nitrolusal in these experiments.

There have been few studies involving stabilized fertilizers, but the information on the use of dicyandiamide and other nitrification inhibitors is abundant. Dicyandiamide has a bacteriostatic effect in the *Nitrosomonas* bacteria, which delays the oxidation of NH_4^+ to NO_2^- during the nitrification process in soil. The inhibiting effect of dicyandiamide on

Nitrosomonas may last 6–8 weeks depending on the amount of N applied, soil moisture and temperature (Trenkel 2007). Dicyandiamide has been successfully used to reduce environmental contamination particularly with hazardous N gases. It has been shown that dicyandiamide applied to urea significantly reduced N_2O emissions in irrigated crops, such as spring barley (Delgado and Mosier 1996), rice (Majumdar et al. 2000) and wheat (Majumdar et al. 2002), in comparison to urea alone. The application of dicyandiamide was also effective in reducing N_2O emissions from pastoral soils subjected to cattle urine (Kelliher et al. 2008; Zaman et al. 2009). Pathak et al. (2003) also found a reduction in CH_4 emissions in a rice–wheat cropping system from the addition of dicyandiamide to urea. In this study, Nitroteck provided good agronomic results probably because part of the N is in the NH_4^+ form, which can be taken up by the plants and the combined effect of the nitrification inhibitor with the coating membrane improved N use efficiency by prolonging the period of N release which increases the opportunity for root uptake.

Nitrolusal is a widely used N fertiliser. Nitrogen in Nitrolusal is 50% NO_3–N and 50% NH_4–N. In this experiment Nitrolusal was applied basally and as topdress in two equal rates, in order to simulate the effect of a slow release N fertilizer. The DM yield and N uptake shortly before the topdress N application were lower than those recorded in Floranid and Nitroteck. At the end of the growing season DM yield, N uptake and apparent N recovery were similar to those observed in Floranid and Nitroteck. The result allows the conclusion that more than half of the N in Floranid and Nitroteck would be available in the first part of the growing season (first 3 months), which explain the good stimulus on the spring flush of the vegetation.

The turf grass of Valpaços showed a higher DM yield potential than the turf grass of Bragança, probably because of the difference in the plant species composition. In the higher productive turf, Basacote hampered the spring flush of the vegetation, due to the lack of available N in the soil. Nitrogen released later in the growing season increased N concentration in tissues and improved N uptake but was less effective in increasing DM yield. Thus, in 2008 the physiological efficiency was lower in Basacote in comparison to the other fertilised treatments, when it would be expected that the lower soil N availability would increase the physiological efficiency as observed in the experiment of 2009.

The anion exchange membranes provided results with high experimental variability. After being successfully used in monitoring N release from organic and slow-release fertilisers in pot experiments (Rodrigues et al. 2006, 2010), the results here presented were not so helpful. It was probably the surface application of fertiliser with an irregular diffusion of the ions in the soil profile and/or a deficient contact of the membrane with the soil in the short period of incubation impairing the full success of the methodology. More promising seemed to be the results of Davenport and Schiffhauer (2007) obtained with a similar methodology which consisted in monitoring plant available nutrients in cranberry by inserting a commercial ion-exchange membrane probe into the rooting zone in a low pH soil.

Economic considerations

The economic efficiency of total fertilisation is an index which includes the costs of the N fertiliser and also the P and K fertilisers used to balance the P and K rates among all the treatments in the experimental design. Since Nitrolusal is the only single N fertiliser, the costs of P and K were higher. Thus, this index penalizes Nitrolusal. The economic efficiency of N fertilisation considers only the cost of the N fertilisers. Since Nitroteck, Floranid and Basacote are compound NPK fertilizers, this index penalizes all of them in comparison to Nitrolusal, since their costs are higher in part due to their content of P and K.

Nitroteck was the cheapest solution among the fertilisers which have a mechanism to extend N availability in the soil. If the total costs of fertilisation were taken into account, Nitroteck gave the better result even including Nitrolusal. Contrarily, Basacote gave the worst result among all the fertilised treatments. The factors that favour Nitroteck were the high DM yield and the relatively low price of this fertiliser. In the opposite position was Basacote with a very high cost and a significantly lower DM yield.

Conclusions

The slow-release fertiliser Floranid permanent 16-7-15 and the stabilized fertiliser Nitroteck 20-8-10 emerged as suitable technical solutions for the irrigated turf grasses of the Mediterranean region. The results were equivalent or even slightly better than that of ammonium nitrate divided in two N rates during the growing season. The DM yield, a parameter that may reflect the health and good condition of the turf, was relatively high as well as the apparent N recovery. These fertilisers also allow the reduction in labour, since only a single basal application is required during the entire growing season. Nitroteck is also a suitable economic solution, since its cost is not much different from that of conventional compound NPK fertilisers with similar concentrations in N, P and K.

Basacote plus 9M 16-8-12 showed some limitations as a fertilization solution for the turfs grown in these environmental conditions. It seems that the N available in the soil in early spring was lower than that required for the optimum plant growth, which was reflected in an unsightly lack of greenness of the turf. The apparent N recovery of Basacote was also lower than that of the other fertilisers tested, revealing a release period longer than the duration of the growing seasons. Thus, for the environmental conditions of these regions it seems that if should be advised a Basacote formulation with a shorter release period as a mean to better match the N released with turf needs. The other disadvantage of Basacote is the cost, considerably higher than that of the other fertilisers used in these experiments.

The indices of economic efficiency ordered the fertilisers as Nitroteck > Nitrolusal > Floranid > Basacote or Nitrolusal > Nitroteck > Floranid > Basacote, if the costs of P and K fertilisers used to balance the P and K rates in the experimental design were, respectively, taken or not taken into account. Among the fertilisers with a slow release mechanism, both the indices of economical efficiency order the fertiliser as follows: Nitroteck > Floranid > Basacote.

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