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Characterising the within-field scale spatial variation of nitrogen in a grassland soil to inform the efficient design of in-situ nitrogen sensor networks for precision agriculture

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ABSTRACT

The use of in-situ sensors capable of real-time monitoring of soil nitrogen (N) may facilitate improvements in agricultural N-use efficiency (NUE) through better fertiliser management. The optimal design of such sensor networks, consisting of clusters of sensors each attached to a data logger, depends upon the spatial variation of soil N and the relative cost of the data loggers and sensors. The primary objective of this study was to demonstrate how in-situ networks of N sensors could be optimally designed to enable the cost-efficient monitoring of soil N within a grassland field (1.9 ha). In the summer of 2014, two nested sampling campaigns (June & July) were undertaken to assess spatial variation in soil amino acids, ammonium (NH_4^+) and nitrate (NO_3^-) at a range of scales that represented the within (less than 2 m) and between (greater than 2 m) data logger/sensor cluster variability. Variance at short range (less than 2 m) was found to be dominant for all N forms. Variation at larger scales (greater than 2 m) was not as large but was still considered an important spatial component for all N forms, especially NO_3^-. The variance components derived from the nested sampling were used to inform the efficient design of theoretical in-situ networks of NH_4^+ and NO_3^- sensors based on the costs of a commercially available data logger and ion-selective electrodes (ISEs). Based on the spatial variance observed in the June nested sampling, and given a budget of £5000, the NO_3^- field mean could be estimated with a 95% confidence interval width of 1.70 μg N g^{-1} using 2 randomly positioned data loggers each with 5 sensors. Further investigation into "aggregate-scale" (less than 1 cm) spatial variance revealed further large variation at the sub 1-cm scale for all N forms. Sensors, for which the measurement represents an integration over a sensor-soil contact area of diameter less than 1 cm, would be subject to this aggregate-scale variability. As such, local replication at scales less than 1 cm would be needed to maintain the precision of the resulting field mean estimation. Adoption of in-situ sensor networks will depend upon the development of suitable low-cost sensors, demonstration of the cost-benefit and the construction of a decision support system that utilises the generated data to improve the NUE of fertiliser N management.

1. Introduction

Improving nitrogen (N) use efficiency (NUE) remains one of the key challenges for global agriculture (Cassman et al., 2002; Robertson and Vitousek, 2009) and is essential for the success of sustainable intensification (Tilman et al., 2011). The deleterious environmental effects and economic costs of diffuse N pollution from farmland in Europe, where N has been applied in excess of crop requirement, are well documented (Sutton et al., 2011).

One often-cited approach to reduce N losses and improve NUE, is to ensure synchronicity of N supply with crop demand (Shanahan et al., 2008; Robertson and Vitousek, 2009), although, achieving this in practice is challenging due to the complex nature of the soil-plant system. Precision agriculture (PA) attempts to address this issue by reducing uncertainties surrounding the measurement of key variables to determine optimum N fertiliser management (Pierce and Nowak, 1999; Dobermann et al., 2004). Temporal variations in growing conditions, both within and between seasons may lead to considerable differences in optimum N fertiliser requirement and hence, inefficiencies in N fertiliser-use if temporal variations are not considered (Lark and Wheeler, 2003; McBratney et al., 2005; Shahandeh et al., 2005; Shanahan et al., 2008; Deen et al., 2014). However, conventional soil sampling

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techniques, coupled with laboratory analysis is expensive, labour-intensive, and time-consuming and cannot provide real-time data of sufficient resolution to accurately inform PA management (Sylvester-Bradley et al., 1999; Kim et al., 2009).

A number of different approaches have been used to address this issue. Crop canopy sensing techniques, for determination of plant N status, are now in commercial use and can be used to inform variable rate fertiliser application (e.g. wheat, maize; Raun and Johnson, 1999; Diacono et al., 2013). Whilst the advantages of this approach in some situations have been evidenced (Diacono et al., 2013), plant N status and yield is the product of many variables and may not always correlate with soil mineral N status. On-the-go soil sampling for NO_3^-, using electrochemical sensor platforms attached to agricultural vehicles have been developed (Adsett et al., 1999) and, for the case of pH, commercialised (Adamchuk et al., 1999). The results have been used to develop field nitrate maps (Sibley et al., 2009) which could be used to define within-field management zones and to calculate variable fertiliser application rates. On-the-go sampling is generally more spatially intensive than manual field sampling, allowing better spatial resolution, although key information on how soil mineral N varies over small spatial scales may not be obtained. This can lead to increased uncertainties of interpolative predictions, especially if the sample volume is small (Schirrmann and Domsch, 2011). Furthermore, increasing the temporal resolution of this approach requires additional economic costs and as both these approaches rely on reactive management, crucial changes in soil mineral N status may be missed.

One approach, which has yet to be explored, is the use of in-situ sensors capable of monitoring soil mineral N in real time. At the time of writing, there are no such quasi-permanent field sensors in use commercially. However, potential for the development and deployment of such sensors exists (Shaw et al., 2014). For example, ion-selective electrodes (ISEs) have many characteristics suitable for soil sensing networks. They are relatively cheap, simple to use, require no mains electrical power supply and the concentration of the target ion can be easily calculated via a pre-calibration. Nitrate (NO_3^-) ISEs have previously been successfully deployed for monitoring streams and agricultural drainage ditches (Le Goff et al., 2002, 2003) as well as for on-the-go soil sampling of agricultural soils (Sinfield et al., 2010) and on-farm rapid tests for soil NO_3^- (Shaw et al., 2013). Similarly, ammonium (NH_4^+) ISEs have been used for water monitoring in a variety of situations (Schwarz et al., 2000; Müller et al., 2003). Direct soil measurement, which is essential for the success of in-situ monitoring, has been shown to be possible (Ito et al., 1996; Adamchuk et al., 2005), although improvements in accuracy and robustness of the sensing membrane are required. Increasing use of nano technologies for the construction of electrochemical sensors may result in significant advances in sensor performance (Arrigan, 2004; Atmeh and Alcock-Earley, 2011).

Using in-situ sensor networks may enable a step away from predetermined fertiliser N recommendations (Defra, 2010) to a more dynamic system that responds in real-time to changes in growing conditions. It potentially has many benefits compared to on-the-go soil sampling and crop canopy sensing. The data provided by in-situ sensors will be of significantly higher temporal resolution, negating the need for repeated sampling surveys throughout the year, which represent an economic cost to the farmer. Furthermore, this may enable more accurate timing of fertiliser application, reducing the risk of yield penalties caused by N-nutrition deficiencies, and the risk of N transfers to water and air as a result of excessive fertiliser N applications. It is also likely that the data generated at a high temporal resolution by in-situ sensor networks will increase knowledge of the controls of soil N processes and thus enable development of models which allow for a proactive approach to fertiliser N management. However, there is a trade-off to be made. The increase in temporal resolution gained from in-situ sensor networks may be offset by the costs of achieving sufficient spatial resolution.

It is, therefore, important that consideration is made as to how such sensor networks could be optimally designed to enable sufficiently precise estimates of mean field or management zone (MZ) soil N at minimum cost. Two factors complicate this. First, each sensor must attach to a data logger, over a relatively short distance. As data loggers cost more per unit than sensors, and one logger can support several sensors, then feasible networks will comprise sensor clusters, each associated with a logger. As such, sensor networks can be regarded as multi-scale sampling schemes with data loggers (primary units) and sensors (secondary units) randomly placed in an area around each data logger. Second, soil N is variable, at multiple scales. Efficiently designed sensor networks will have sufficient replication at the most variable scales, achieving this within the constraints of feasible clustered designs. As shown by de Gruijter et al. (2006), the optimum configuration of such a sampling scheme depends on the relative costs of additional primary and secondary units and the within- and between-primary unit variability.

The primary objective of this study was to address the above problem and to investigate how the design of a theoretical network of in-situ soil N sensors could be optimised on a cost-precision basis, to enable monitoring of soil N concentrations in a grassland field. As seen in the discussion above, the feasibility and optimal design of sensor networks depends on the variability of the target properties at different within-field scales. An effective way to collect such information is by spatially nested sampling, which has been used previously to characterise the spatial variation in a range of soil-related variables (Lark, 2011). In nested spatial sampling, sample sites are arranged in a nested hierarchical design which allows the partition of the variance of the measured variable into components associated with a set of pre-determined scales. At the highest level of the hierarchy sample, points are arranged in clusters associated with “mainstations” which may be at randomly-located sites or on nodes of a grid or transect. Within a mainstation, sample points may be divided between two or three stations at level 2 which are separated from each other by some fixed distance. Within each level-2 station, sample points may be ordered at further nested spatial scales.

As such, spatially nested sampling was performed at a range of scales to characterise the within-field spatial variability of amino acids, NH_4^+ and NO_3^-. These results were then used to explore the optimisation of a NH_4^+ and NO_3^- in-situ sensor network design on the basis of both cost and precision. Finally, the potential and challenges of implementing this approach within a PA framework are discussed.

2. Materials and methods

2.1. Field site and soil characteristics

The field used for this study is located within the Henfaes Research Station Abergwyngregyn, Wales, UK (53°14′N 4°01′W). The site has a temperate, oceanic climate, receives an average annual rainfall of 1250 mm and has a mean annual soil temperature at 10 cm depth of 11 °C. The field is roughly rectangular with a perimeter of 559 m and an area of 1.91 ha. It has an average altitude of 12.1 m asl with a slope of 1.5% in a northerly aspect. It is a semi-permanent sheep-grazed grassland, dominated by *Lolium perenne* L. The current ley was established by direct drill in April 2009 using a perennial and hybrid ryegrass mix. The field has been used for both all year round grazing and silage production since 2009,