

Understanding nutrient cycling within agroecosystems

Dr Joann Whalen is shedding light on the soil interactions which govern nutrient flows. Here, she talks about her route into the field, and why this work is so valuable



Could you begin by outlining the focus of your research?

My research focuses on the fate of nutrients in fertilisers that are applied to agricultural soils. The work contributes to a larger effort amongst soil scientists and agronomists to understand how inorganic and organic fertilisers are utilised by crops, so we can minimise losses of excess nutrients such as N and P into the environment. Like other scientists working in the agricultural milieu, I am aware of the potential negative environmental consequences of improper fertiliser use.

What are the harmful effects of excess N and P being released into the environment?

Firstly, we are concerned about N and P causing eutrophication of lakes, rivers and oceans. The 'dead zone' in the Gulf of Mexico is a prime example of eutrophication that can be attributed to N and P runoff from agricultural land. Additionally, some gaseous forms of N are transported away from agricultural land and

are deposited on natural areas, which results in unintentional fertilisation of native grasslands and forests, leading to changes in the botanical composition of the plant communities and their associated fauna and flora. On top of this, one of the gaseous N by-products is nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance. The majority of N_2O emitted to the environment comes from agricultural soils, and this is a concern to me and other agricultural scientists.

How did you develop an interest in soil ecology? Could you summarise your career trajectory and explain how it led you to where you are today?

During the final year of my BSc in Agricultural Chemistry, we had to do an Honours project on an applied research question. I chose soil chemistry over food chemistry, and that led me to complete an MSc in soil biochemistry and a PhD in soil ecology. Soil ecology was just emerging in North America in the mid-1990s; I had never heard of the discipline during my undergraduate studies – in those days, we studied the traditional soil sciences like soil chemistry, soil physics and soil fertility. I had a lot to learn during my PhD, and it was like stumbling into a new world. Instead of focusing on a traditional discipline, we were trying to integrate concepts that transcended established categories and view the soil as a holistic system, looking at how the plants, soil microorganisms and soil fauna interact in a 3D setting that has certain physical structures and supports a vast number of chemical and biochemical reactions to achieve ecological functions like nutrient cycling and primary production.

Why is it important to gain a deeper understanding of N cycling within agroecosystems?

I think the main reason we need to understand N cycling in agroecosystems is because they receive substantial N inputs from fertilisers every year – sometimes several times during a growing season – and they are extremely inefficient at retaining the added N. Most researchers agree that agroecosystems are very 'leaky' in terms of N retention, and we would like to be able to predict how much N is available to the crop from naturally-occurring processes of decomposition and N mineralisation that are mediated by the soil microorganisms and associated soil fauna. This is especially important for grain and oilseed crops that have high reliance on N fertilisers to achieve profitable yields. Our overall vision is to develop tools that will help us predict N release by the soil food web, so we will know when and how much N fertiliser is needed for N-demanding crops. Better N fertiliser recommendations could help us to reduce the N input, lowering costs for producers and reducing the environmental risk.

What role do soil microorganisms play in N cycling in agroecosystems?

Soil microorganisms are responsible for virtually all of the N transformations in agroecosystems. Firstly, capture of gaseous dinitrogen (N_2) from the atmosphere is done by symbiotic N_2 -fixing bacteria that inhabit nodules in roots of legume plants; secondly, decomposition and the transformation of organic N in soil organic matter and crop residues to plant-available forms is mediated by bacteria, archaea and fungi; and, thirdly, the reduction of NO_3^- to a series of gases, including N_2O and N_2 , is primarily catalysed by bacteria. Thus, the activity of soil microorganisms is almost solely responsible for gains and losses of N within the agroecosystem.

Reducing our reliance on harmful fertilisers

Ongoing research at **McGill University** in Montreal, Quebec, Canada is exploring diverse and novel methods for enabling crops to absorb fertilisers more efficiently, reducing the release of damaging excess nutrients into the environment

IN THE FACE of a growing global population and the rising demands for essential foodstuffs, the need to sustain high levels of crop production is more pressing than ever. Yet, increasing amounts of chemical compounds such as CO_2 , N_2O and CH_4 are having a negative effect on the global climate, and large quantities of these pollutants are being inadvertently released into the environment by agricultural practices. In addition, agricultural land is responsible for the runoff of a diverse array of other contaminants.

It is clear that a holistic solution is required, which can simultaneously reduce the unnecessary release of nutrients and help agricultural practices become more efficient and high-yielding. Promisingly, a groundbreaking study within the Department of Natural Resource Sciences at McGill University in Montreal, Quebec is seeking to do just that. Led by Dr Joann Whalen, a Field Leader in soil ecology, the research is taking great strides towards increasing the efficiency of fertiliser utilisation, and developing novel methods for reducing the quantity of nutrients that are inadvertently released into waterways and the atmosphere. In doing so, the work undertaken by Whalen and her colleagues is expected to result in a number of significant environmental, economic and social benefits.

A MULTI-SCALE APPROACH

Significantly, this research is unique in its combination of multiple scales of study. From the nanoscale to a system-wide perspective, nutrient cycling in agroecosystems is considered at every level to ensure all parameters are included. The other advantage of approaching the study of nutrient cycling in this way is that it allows Whalen and her team to rigorously test hypotheses and answer questions regarding small-scale processes, with a priori knowledge of larger scale interactions. "The capacity to link

processes between scales," Whalen confirms, "is exclusive to the work we are conducting at McGill, and it is where the key strength of my research group lies".

MICROBIAL INTERACTIONS

Whalen's utilisation of multi-scale enquiry is particularly beneficial when studying soil microbiology and N cycling. As a significant focus of her lab work, Whalen and her fellow researchers have studied, at great length, the reasons why certain soil environments are more prone to losing N than others. By analysing stable ^{15}N isotopes and using q-PCR amplification of *amoA*, *nosZ* and other relevant genes, they have been able to identify that fertiliser inputs from both manure and inorganic sources are cycled through soil microbial biomass within agroecosystems very rapidly. This results in poor retention of N and significant amounts of N lost in runoff or in gaseous forms to the atmosphere. Indeed, studies have shown that only around 60 per cent of the N applied to crops is effectively absorbed by plants, with the rest leaching or off-gassed from the soil profile.

Denitrifying microbes that inhabit the soil profile have the potential to drastically influence N_2O production. Yet, interestingly it has been demonstrated that microaggregates are the greatest 'hotspots'. Microaggregates are an essential component of healthy soils, but during rainfall events after fertiliser application, they can lead to the rapid release of N_2O emissions. Timing of fertiliser application is therefore key to ensure these events are prevented. Agricultural practices that build larger macroaggregates (> 250 micrometers), such as conservation tillage and organic fertiliser use, are also helpful in reducing the proportion of microaggregates. Due to the physical protection they afford to nutrients, larger aggregates should be encouraged in soils.

INTELLIGENCE

EARTHWORM-MICROBIAL INTERACTIONS CONTROLLING NITROUS OXIDE PRODUCTION IN PERENNIAL GRASS- AND LEGUME-BASED AGROECOSYSTEMS USING STABLE ISOTOPES AND MOLECULAR MARKERS

OBJECTIVES

To determine the temporal and spatial scales of earthworm's influence on nitrogen cycling that may lead to nitrogen loss from soils, thereby affecting fertiliser use efficiency and crop production in agroecosystems.

PARTNERS

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JOANN WHALEN is a Soil Ecologist who investigates nutrient cycling in the soil-plant system. She is interested in biomass production systems that increase soil carbon sequestration and improve nutrient use efficiency, and evaluates system performance with life cycle assessment.

A FIELD-SCALE ALGORITHM

Earthworms play an equally important role in the structure of the soil, creating burrows, casts and breaking down leaf litter. "Agroecosystems with perennial vegetation, such as grass- and legume-based hayfields, support large earthworm populations because soils are undisturbed by cultivation and senescing plant residues are a food source for earthworms," explains Whalen. She has already shown that such organisms create a habitat suited to microbial nitrifiers and denitrifiers on the small scale and now, with the establishment of a new algorithm, she may be able to extrapolate results at a larger scale. Testing N composition in isolation is far from ideal, so the ability to test the nutrient flux of an entire field can lead to more precise farming techniques and improved land management.

Further, the researchers designed the algorithm to be compatible with the long-established Soil and Water Assessment Tool (SWAT) model, allowing their new work to be subsumed into the nexus of calculations which predict hydrologic and nutrient fluxes at the watershed level.

Understanding the governing factors in soil structure and texture, combined with microbial interactions, allows Whalen to 'layer up' the data with abiotic variables such as management practices and climate change. With more and more data now available, the team is poised to make better predictions of N losses from agroecosystems, at the field and watershed scales, to document NO₃ leaching and net N₂O emissions for water quality improvement and Canada's Greenhouse Gas Inventory.

LEADING PRACTICE

The pioneering nature of Whalen's work, along with the considerable successes it has achieved, was formerly recognised in 2010 through a National Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant. The project, entitled 'Earthworm-microbial interactions controlling nitrous oxide production in perennial grass- and legume-based agroecosystems using stable isotopes and molecular markers' is ongoing, but aims to describe the nature and influence of

The work being carried out by the research team at McGill University is unique in its combination of multiple scales of study

earthworm-microbial interactions and identify whether earthworms can reduce or stimulate the loss of N₂O from a given agroecosystem.

Additionally, since receiving a further Discovery Accelerator Supplement from NSERC, Whalen has been able to diversify her team's expertise in two complementary fields: molecular analysis of the genes responsible for transforming the soil N cycle, and the development of a new algorithm for modelling macroporosity. The latter is of particular interest because macropores play a role in diffusing gas and aiding water movement through soil, and Whalen is confident that pursuing these avenues will significantly strengthen her lab's research profile. "Overall," she declares, "I believe that this work puts my lab at the forefront of efforts to describe the involvement of earthworms in the soil N cycle, and to link earthworm activities to N losses from soils".

Whilst the project is seeking to evaluate earthworm contributions to losses of gaseous N, the algorithm for macropore modelling is capable of enumerating the hitherto unquantified promotion by earthworm activity of NO₃ and particulate organic N losses through subsurface flow via leaching. The value of Whalen's work has also been recognised through sizeable funding from a multitude of agencies. By garnering such a diverse and impressive support network, Whalen has created an exceptional platform from which to pursue her work on N within the soil food web. With great optimism it is predicted that these studies will eventually succeed in reducing our reliance on commercial fertilisers, thus preventing large amounts of environmental pollution and making farming practices more economical and sustainable for future generations.