CHALLENGES FOR LEACHATE MONITORING FROM ALLUVIAL SEDIMENTARY SOILS

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Abstract

Agricultural land use has intensified in recent times, heightening the risk of environmental nutrient contamination, arising mainly from increased use of synthetic fertilisers and irrigation, together with an increase in animal dung and urine returns. As regulatory authorities start to set limits on permissible nutrient losses from agricultural land, there is an urgent need to better understand and manage such nutrient losses from farms. Computer models are now commonly being used to simulate and forecast losses, but accurate measured data are also needed to test the models and ensure the reliability of the model predictions. In this paper we review the current methods available to monitor leaching on-farm and outline some of the challenges associated with making such leaching estimates, e.g. the sampling devices and issues relating to scale and spatial variability, as well as the wide variation in farm management practices. We identify research gaps and discuss options for measuring nutrient losses on-farm as well as make recommendations for future research. In addition, we present preliminary findings from a study where we have investigated the lower boundary condition in lysimeters, exploring whether there is a need to use suction at the base of lysimeters containing alluvial soils.

Introduction

Worldwide there are concerns about rising concentrations of nutrients in both ground and surface waters. Agricultural production systems have been identified as one of the key sources of leached nutrients, mainly from increased use of synthetic fertilisers and irrigation, as well as an increase in animal dung and urine returns (Di and Cameron 2002). Climatic variation, soil type and land management factors have been shown to be the main drivers influencing the overall amount of leaching. Generally leaching occurs if there is an accumulation of nutrients in the soil profile that coincides with or is followed by a period of high drainage.

Although the quantity of soil drainage is considered to be one of the most influential factors in nutrient leaching, it is notoriously difficult to measure in undisturbed soils (Webster *et al.* 1993). Because of this difficulty, a range of direct and indirect methods have been developed to quantify soil drainage. Indirect approaches include water balances (e.g. Jamieson *et al.* 1995), salt/ chloride balances (e.g. Snow *et al.* 1999), or the use of water content sensors (e.g. Fares and Alva 2000).

Drainage can also be directly measured using lysimeters, as reviewed by Goss and Ehlers (2009), as well as Allen *et al.* (1991). Both intact and repacked lysimeters have been used and the various methods of monolith extraction are reviewed by Derby *et al.* (2002) and Fuehr *et al.* (1997). A version of lysimeter that has been widely used is the passive wick lysimeter, with a number of reviews published (Zhu *et al.* 2002; Masarik *et al.* 2004; Gee 2005; Meissner *et al.* 2008), although to date no standard methods have been adopted for the direct measurement of drainage and leaching (Gee *et al.* 2009). Indeed Arauzo *et al.* (2010) concluded that currently there is no perfect system for monitoring drainage. The monitoring system needs to be chosen according to the objectives and specific field conditions (i.e. appropriate to soil type, climate and land use).

New Zealand, particularly the South Island, has widespread areas of river and stream deposited alluvial soils occurring on the floodplains, terraces and fans that are either currently used, or have the potential, for intensive land-use (Carrick *et al.* 2013). Leaching research on these soils has generally used either a combination of suction cups and a water balance drainage model to estimate leaching, or monolith (barrel) lysimeters to directly measure leaching. Here we review the challenges encountered when conducting such farm-scale monitoring and the limitations of the currently available leachate measuring methods.

Challenges of farm-scale monitoring

At the farm scale there are multiple factors that may cause variability in leaching. This variability may arise from management practices (e.g. cultivation, irrigation, crop and grazing rotations), as well as physical factors such as variability in land slope, soil water holding capacity, infiltration and soil wetness.

Leaching predictions by the OVERSEER® model are strongly influenced by the soil water holding capacity (Wheeler *et al.* 2011), and a number of studies have shown that this can vary significantly over short distances in alluvial soils (Hedley and Yule 2009; Dennis *et al*. 2010). The within-field variability of key soil properties has also been shown to have significant effects on predicted nitrate leaching (Lilburne and Webb 2002).

Irrigation affects water inputs, the quantity of drainage water, and therefore the potential for nutrient leaching. One farm may contain several different irrigation systems, applying water at different depths, intensities and timings, while depth and intensity can even vary within a single irrigator. The average depth applied depends on management, and can range from as low as 4 mm (centre pivot; Thomas *et al*. 2006), to 100 mm (border dyke; Wells and Barber 1998), to as high as 215 mm (moveable pods; Hawke *et al*. 2001). Within the one irrigator, the actual amount of water applied to any point on the paddock will vary depending on the irrigator's uniformity. A moveable pod system may have a lower quartile distribution uniformity (DU), as low as 0.44 (Thomas *et al*. 2006) – i.e. a quarter of the paddock receives less than half the average application depth, while other areas receive considerably more. Even a centre pivot can have considerable variation in depth (e.g. 0.74 DU; Thomas *et al*. 2006).

The intensity of water application will affect the amount of water that either infiltrates or runs off at an individual soil location (i.e. the effective application depth), and whether there is preferential flow of the infiltrated water within the soil. Intensity varies depending on the irrigator type and the position on the irrigator. A moveable pod irrigator may apply water as low as 2.2–9 mm/hr (Hawke *et al*. 2001), while a travelling gun may apply water at an instantaneous intensity of 630 mm/hr (Cook 1983). The intensity of a centre pivot also varies greatly from the centre to the end of the machine.

A single paddock being watered by a centre pivot together with a moveable sprinkler system (in areas where the centre pivot does not reach) may contain areas receiving greatly different water depths, at different timings, and at different intensities, meaning there may be no one point that is representative of the paddock as a whole.

There are multiple sources of nutrients across paddocks and farms, where nutrients can be applied relatively uniformly (e.g. fertiliser, effluent) or at point sources that could be located specifically (e.g. gateways, troughs) or randomly (e.g. urine patches). Uniform and specifically located point sources are easier to monitor leachate from as these sources can be identified, and the relative percentage of the farm area determined. Random point sources are the challenge, as demonstrated in recent research by Lilburne *et al.* (2012) using stochastic simulation to test the accuracy of using suction cups and barrel lysimeters to measure nitrate leaching from cow urine patches, randomly located in a paddock. Urine patches cover only 14–30% of a grazed pasture (Dennis *et al.* 2011; Moir *et al.* 2011). Lilburne *et al.* (2012) showed that even with 80 barrel lysimeters the poor interception of urine patches will mean that 23% of the time the estimate of leaching will not be within ±20% of the true value (Figure 1).

The nutrient application in an individual urine patch can also vary greatly. For instance, cattle urinations have been recorded to comprise 1.6–3.5 L of urine, containing 2.5–20.5 g N/L, and to wet 0.16–0.49 m^2 of soil (Doak 1952; Whitehead 1970; Williams *et al*. 1990; Bristow *et al*. 1992; Nguyen and Cook 1994). Taking the extreme values above, cattle urinations could theoretically apply anywhere between 82 and 4500 kgN/ha, although average values of between 500 and 1000 kgN/ha are assumed for most purposes. Sheep apply lower volumes of urine, resulting in lower N application rates per hectare, and a lower risk of nitrogen leaching loss (Williams and Haynes 1994).

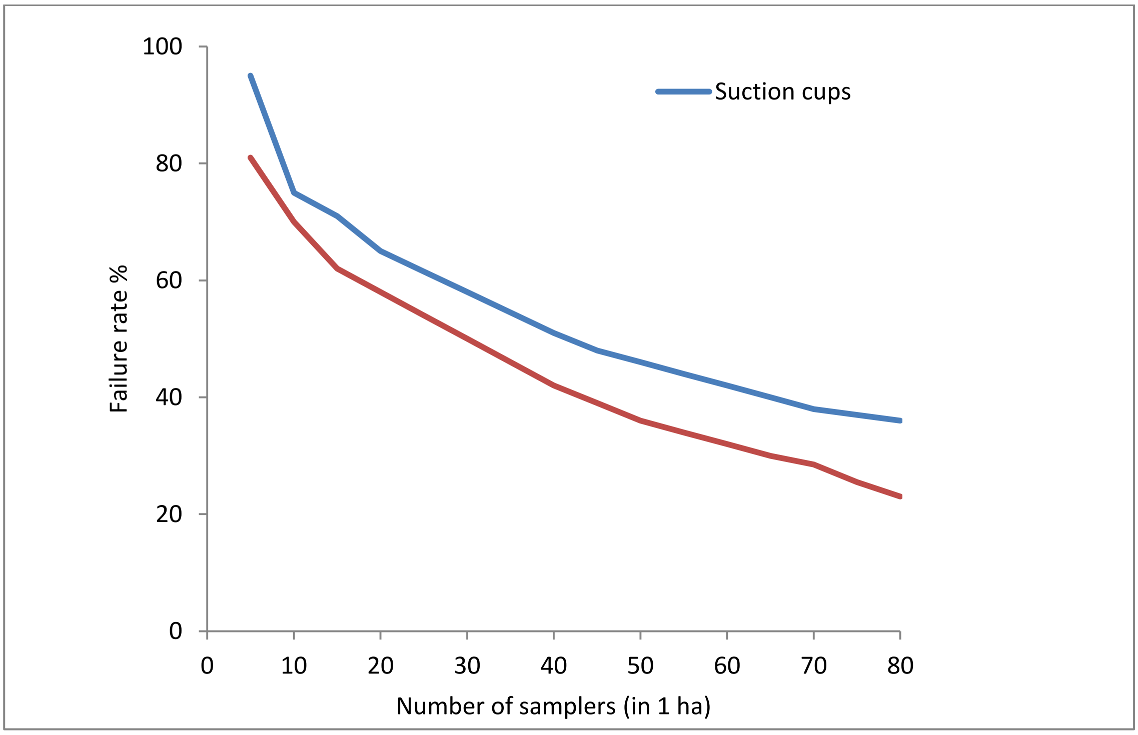

Figure 1 The accuracy of using suction cups or barrel lysimeters to measure nitrate leaching from urine patches on grazed pasture (redrawn from Lilburne *et al*. 2012). Failure rate is the percentage of times that the estimate of nitrate leaching fails to be with ±20% of the true value.

Strengths and weaknesses of suction cups and barrel lysimeters

Leaching research on alluvial soils in New Zealand has generally used either suction cups or barrel lysimeters. Although mole and tile drainage is widely used in the downlands, this method is limited to soils with a hard subsoil pan and sufficient land slope for the drains to work well, both of which are uncommon in alluvial soils.

The strengths and weaknesses of suction cups and barrel lysimeters have been reviewed in a number of recent papers (Weihermuller *et al*. 2007; Allaire *et al*. 2009; Fares *et al*. 2009). Suction cups are often used because they have a low capital cost, and are relatively easy to install. However, because of the small sampling area many replicates are needed to obtain a representative leachate sample at the paddock scale, resulting in a high operating cost. They are also difficult to install in stony soils, which are widespread in alluvial landscapes where Carrick *et al.* (2013) mapped 1.68 million hectares as having potential for intensive land use. The major criticism of suction cups is that they have a small sampling area, and therefore the ability to intercept a representative sample of the pore network is unknown (Weihermuller *et al*. 2007; Fares *et al*. 2009). Recent New Zealand research compared nitrate leaching from the same soil monolith measured by suction cups and barrel lysimeters, and concluded that suction cups were inappropriate to use for the two structured soils, but provided a representative measurement from the young sandy loam soils (Wang *et al*. 2012). This result is significant as structured soils are the norm, rather than the exception in New Zealand (McLeod *et al*. 2008). Suction cups also only measure leachate concentration and need to have adjacent lysimeter measurements of drainage flux to calculate the mass leached (Lilburne *et al*. 2012) unless an indirect water balance calculation approach is used (Jamieson *et al*. 1995).

Barrel lysimeters have been widely used in New Zealand research, typically at the scale of 50 cm diameter by 70 cm depth, although diameters can vary between 20 to 120 cm and lysimeter depth up to 120 cm. These lysimeters usually contain an undisturbed soil monolith, with the typical lysimeter size thought to contain a representative sample of the soil pore network for most New Zealand soils, although larger lysimeters may be needed for soils with very coarse structure (e.g. clay soils). Barrel lysimeters are preferred because leachate can be measured from a known soil volume and they enable the researchers to control nutrient inputs. However, as with suction cups, multiple replicates are needed to measure paddock-scale leaching, resulting in a high capital and operating cost that has tended to limit lysimeter use to purpose-built outdoor laboratories.

The major criticisms of barrel lysimeters are: (1) the sidewalls restrict lateral flow, (2) they are not suitable for areas with a high groundwater table, and (3) they are not connected to natural soil at the base. This artificial ‘free drainage’ boundary may create saturated conditions at the lysimeter base that would not occur in the undisturbed soil in the paddock, resulting in measurement artefacts in leaching (e.g. by inducing denitrification processes). This weakness can be minimised by applying an artificial suction to the lysimeter base to mimic that of the natural soil, but there has been debate about when this technique is needed as it adds complexity and cost to the lysimeter setup.

In a recent study we compared the response of a stony silt loam and stone-free deep silt loam, when either free drainage or suction was applied to the base of the same lysimeters under a 3-day irrigation cycle, (where 15 mm depth irrigation was applied at each irrigation event). Figure 2 shows that changing the suction at the lysimeter base had a clear effect on the lysimeter drainage and internal soil moisture status for the stone free deep silt loam, but not for the stony soil. These results indicate that it is necessary to apply suction to the lysimeter base of fine-textured soils by using either the wick lysimeter (Gee *et al*. 2009) or equilibrium tension methods (Brye *et al*. 1999; Masarik *et al*. 2004). However, the results also confirm that suction is not necessary for measuring leaching from the stony soils that are widespread in alluvial landscapes, and that traditional free-drainage lysimeters are suitable for stony soils.

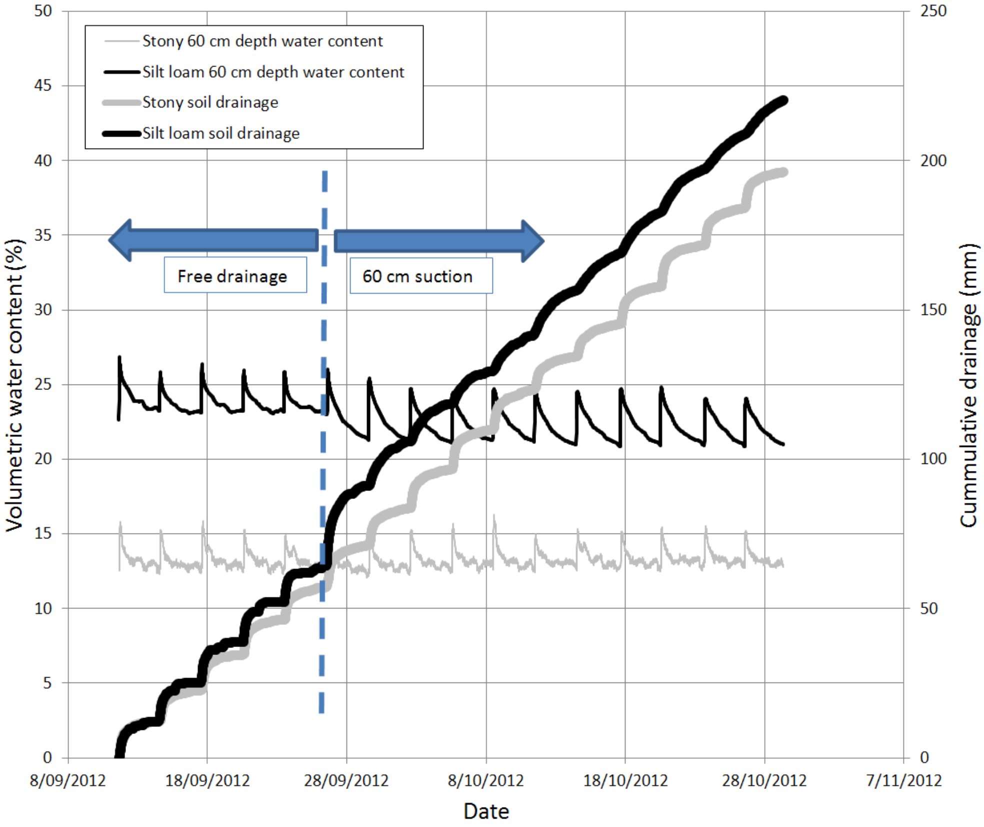

Figure 2 Comparison of the effect of changing the suction at the lysimeter base on the lysimeter drainage and internal soil moisture status for a deep silt loam, compared to a stony soil (40 cm of silt loam overlaying gravels). The lysimeters were irrigated with 15 mm irrigation depth every 3 days. The blue dashed line indicates the point when suction at the lysimeter base was changed.

Recommendations to improve farm-scale monitoring

It is clear that on-farm monitoring of nutrient leaching from alluvial soils has many challenges. However, it is also clear that on-farm leaching measurements are necessary to validate the predictions of models such as OVERSEER®. At present there are simply too few historical leaching studies in the alluvial soil landscape in relation to the vast area and significance of this landscape to the New Zealand economy (Carrick *et al*. 2013). The location and experimental setup of future farm-scale leaching reference sites will need careful planning to ensure the spatial relevance of the sites and to address the experimental challenges we have highlighted. Some recommendations to improve farm-scale monitoring in alluvial landscapes include:

1. All present sampling devices such as suction cups and lysimeters are limited in their suitability for use to measure on-farm leaching of alluvial soils since the soil types, management practices, or nutrient application (e.g. urine patches) are variable across a paddock, and because of the multitude of sampling replicates that would be required. There is a clear research need to develop much larger scale sampling devices that can integrate leaching over scales of at least 10's of metres.

2. Even where the spatial locations of nutrient inputs are known (e.g. controlled urine application) research indicates that suction cups need to be larger in size, otherwise they need to be limited in use to soils with fine, relatively uniform structure.

3. Where nutrient application is randomly located, such as with urine patches, the most viable option with present sampling technology is to use controlled applications above the sampling device. In the case of pasture this may involve using an electric wire over the lysimeters to allow grazing but to avoid urination, then urine can be manually applied at the average rate and percent coverage.

4. It may be more realistic to target measurement locations to cover the known variability and then use models to upscale the results to the farm scale, than to expect to directly measure the actual mean losses from a farm. Another option is to monitor hotspots, i.e. monitor the most likely worst-case locations on the farm, and not expect the result to reflect farm-scale losses.

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