REGULATING PLANT-NITROGEN REMOVAL IN SEWAGE AND INDUSTRIAL WASTEWATER CUT & CARRY LAND TREATMENT SYSTEMS TO MINIMISE NITROGEN LEACHING

Selva Selvarajah

ENVIROKNOWLEDGE® LTD, Dunedin, New Zealand
Corresponding author Email: selvarajah@enviroknowledge.co.nz

ABSTRACT

Keywords: land treatment system, plant-N removal, wastewater-nitrogen, cut & carry, nitrogen leaching, groundwater nitrate

It is commonly known among the land treatment experts that optimally managed cut & carry systems are the best wastewater treatment systems environmentally, economically and culturally. However, most such systems require discharge permits for sewage and industrial wastewater discharges under the Resource Management Act (RMA) from the regional authorities. The critical factors encountered in the consent application, consent process and compliance performance management are the determination and regulation of suitable wastewater nitrogen (N) loading and the regulation and management of potentially leachable N in cut & carry land treatment systems.

The use of models that are not fit for purpose to determine wastewater-N loading, N leaching and groundwater nitrate contamination, may result in excessive regulation of the cut & carry systems with exorbitant pre-treatment of irrigated wastewater or the demise of the cut & carry system altogether by resorting to direct discharge to water. At the 2019 Land Treatment Collective conference I discouraged the use of models that are not fit for regulatory purposes and proposed the use of plant-N uptake to determine wastewater-N loading and to minimise nitrogen leaching.

This technical paper assesses the feasibility of using plant-N removal as a critical factor to determine and regulate wastewater-N loading rate for sewage and industrial wastewater discharge consenting and compliance performance monitoring purposes. I have concluded that annual potential plant-N removals rates (APPNRR) derived from the past agronomic field trials could be used conservatively to set wastewater-N and plant-N removal limits and managing cut & carry systems under optimal conditions to minimise nitrogen leaching.

INTRODUCTION

Cut & carry wastewater irrigation systems are the most effective land treatment systems and arguably the best wastewater treatment systems to treat small to medium scale wastewaters under well-managed environments with little or no nitrate leaching and impacts on the receiving water quality. Despite the above, most such systems require discharge permits from the regional councils under s15(1)(b) and (d) of the Resource Management Act (RMA) for industrial and sewage discharges. One of the critical factors encountered during the discharge permit application, consent process and permit compliance performance management is the

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determination of suitable wastewater-nitrogen loading and estimating or managing potential or actual nitrogen (N) leaching.

Provided specific and accurate soil-plant system/nutrient models exist to assess N leaching losses from land treatment systems and are validated frequently and well calibrated, models can be used to assess potential leaching of N and set wastewater-N loading limits. However, models predicting groundwater nitrate contamination must integrate vadose zone and groundwater attenuation processes or models with soil-plant system/nutrient models. Vadose zones are complex, highly variable and could contain spatially variable flows (Onsoy et al. 2005) hence difficult to model. Despite the difficulty in accessing fit for purpose models, there has been emerging practice among the RMA practitioners and land treatment specialists using farm nutrient models such as Overseer.

The use of models that are not fit for wastewater regulatory purposes could result in onerous regulation of cut & carry treatment systems and in many cases substantial reduction in wastewater-N loading warranting costly and high energy use pre-treatments to reduce wastewater N and/or conversion of discharge medium from land to water.

At the 2019 NZ Land Treatment Collective conference I presented a paper (Selvarajah 2019) discouraging the use of unvalidated and not fit for purpose nutrient model such as Overseer for consenting or compliance monitoring industrial and sewage wastewater discharge to land. As an alternative I proposed the use of plant uptake of wastewater-N to determining or managing wastewater-N loading and to reduce the potential for nitrate-N leaching. This technical paper assesses the feasibility of using plant-N removal as a critical factor to determine wastewater-N loading rate for wastewater discharge consenting and compliance performance monitoring purposes and optimising the performance of the cut & carry systems to minimise N leaching.

KEY NITROGEN TRANSFORMATION PROCESSES AFFECTING IRRIGATED WASTWATER-NITROGEN IN CUT & CARRY SYSTEMS

In the past 100 years, soil N transformation processes have been studied extensively by soil & plant scientists in the context of fertiliser-N application to promote crop production. Consequently, soil-N processes such as ammonia volatilisation, N-immobilisation and mineralisation, nitrification, denitrification and leaching and plant-N processes as N uptake and symbiotic N fixation have been recognised as main N transformation processes.

Of the above processes plant-N uptake has been recognised as the greatest N-flux followed by N immobilisation and mineralisation under most conditions. Nitrogen immobilisation which is also referred to as microbial assimilation is a process where mineral-N is utilised as nutrient by soil microbes for their growth and metabolism. A reverse microbial process, mineralisation comprises of ammonification and nitrification thus the end products are ammoniacal-N and nitrate-N.

Accurate soil-N immobilisation studies warrant the use of ^{15}N stable isotope techniques to trace the N pathways in various soil and plant N pools hence are complex, laborious and limited which in turn have resulted in relatively sparse studies compared to that of ammonia volatilisation, N leaching and denitrification. Consequently, nutrient models such as Overseer are unable to account for N-immobilisation thus resorting to arbitrary and blanket default apportion. On the other hand, soil organic-N mineralisation is intricately linked with N immobilisation dynamics hence despite numerous studies even mineralisation remains beyond accurate or sensible prediction by sophisticated or simple models and stubbornly difficult to replicate by laboratory methods.

In the past several decades, soil scientists have attempted to predict soil-N mineralisation on numerous occasions. After evaluating 10 different laboratory methods on 295 Canterbury cropping surface (0-15 cm) and field moist soil samples, Selvarajah et al. (1987) recommended 7-day anaerobically mineralizable-N and boiling KCl hydrolysable-N as more reliable methods. To date, the 7-day anaerobically mineralizable-N method has been used widely in New Zealand, but the data obtained is difficult to use to quantify soil-N availability for plant growth over a growing period.

On the other hand, as I identified at the 2019 NZLTC conference (Selvarajah, 2019), despite extensive consent monitoring of the cut & carry systems in New Zealand, only few peer reviewed papers had been produced which assessed N processes affecting soil applied wastewater-N. From the limited studies undertaken (e.g., Cameron et al. 2002 and Barton et al. 2005), it is evident that N immobilisation, plant uptake and leaching of N are the key factors affecting the soil applied wastewater-N processes in soil, of which a larger proportion of the N flux occurring via plant uptake. Based on the above concept, I presented a diagrammatic representation of the N fluxes (Selvarajah, 2019) which are likely in a cut & carry land treatment system (Figure 1).

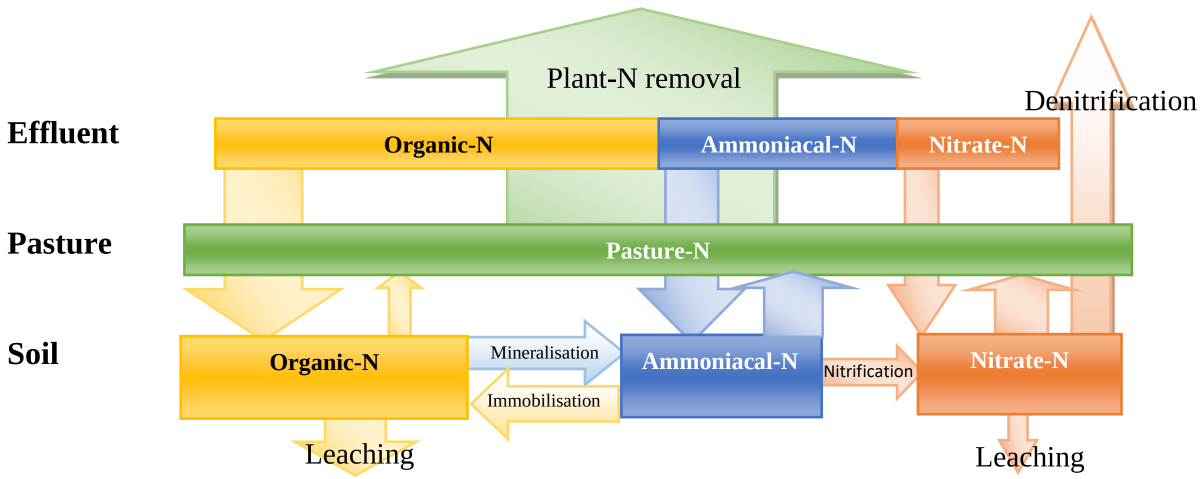

Figure 1. Diagrammatic representation of the industrial and municipal wastewater-N fluxes in cut & carry systems (Selvarajah, 2019)

Nitrogen budgets performed in a small US watershed using a spray irrigated municipal cut & carry system also recognised plant harvest contributed the greatest N output (Schreffler and Galeone, 2005). A controlled short-term glasshouse study involving high-rate simulated urine-N loading with wide ranging pasture species in disturbed and repacked soil pot trials showed much of the applied-N was apportioned mainly between leaching and plant uptake with increasing N application rates resulted increased plant-N uptake (Moir et al. 2012).

Whilst ammonia volatilisation is not illustrated in Figure 1, it is likely at varying emission rates and may be dependent on the alkalinity and the ammoniacal-N levels of the wastewater, the field evaporative conditions (Smith et al. 1996) and soil H^+ buffer capacity (Selvarajah et al. 1993). Also, nitrate-N is not expected to participate significantly in the immobilisation process unlike ammoniacal-N unless the ammoniacal-N availability is low. As can be seen in Figure 1, N leaching is possible from soil organic-N and nitrate-N (Barton et al. 2005 and Smith et al. 2016). Consequently, in this paper leaching is referred to as ‘N leaching’ rather than ‘nitrate leaching’.

PLANT-N REMOVAL IS EASY TO MONITOR AND REDCUES N LEACHING

Of the soil N transformation processes described in this paper, plant-N removal or plant-N uptake is the easiest N flux to monitor. In the context of cut & carry system, plant-N removal < plant-N uptake since not all plant assimilated N is removed from the land treatment system by harvest. Thus, the use of term ‘plant-N removal’ is more appropriate. Plant-N removal can be estimated from dry matter (DM) production per measured area multiplied by the N content of the harvested plant. Dry matter production can be monitored by direct or indirect methods.

In the case of pasture DM production estimate, *direct method* will require the use of quadrats (square or rectangular frames with known dimensions) to harvest grass manually by shearers or by mowing and obtaining herbage from defined land areas randomly from the paddock, drying the harvested grass at 70-80^{o}C for 17-24 hours and assessing the weight of the harvested material. Herbage-N% can be assessed for each representative sample of the harvested and dried material by assessing total-N in the laboratory. The DM and herbage-N% analyses obtained for a given area is extrapolated to a hectare to assess plant-N removal as kg N/ha.

Direct methods of assessing DM production of pasture are accurate and can be performed without extensive training. However, most farmers use indirect methods such as rising plate meter (RPM), C-Dax meter (CDM) attached to a vehicle or calibrated eye visual methods. There have been trials to use satellite data or land cover data collected by drones to estimate pasture production or animal ingested pasture. To monitor the performance of the cut & carry wastewater irrigation system I recommend the more accurate and reliable direct assessment of DM production.

Being the largest N-flux in cut & carry system regular plant-N uptake can be expected to reduce N accumulation in soil, thereby reducing N leaching potentials. It is not surprising although conducted under glasshouse conditions for short-term, trials involving wide ranging pasture grass species under simulated livestock urine-N loading have demonstrated a strong negative correlation between plant-N uptake and N leaching with increasing plant-N uptake resulting in reduced N leaching (Moir et al. 2012). The above effect was more pronounced under high N loading indicating good selection of cut & carry plant can optimise plant-N removal whilst reducing N leaching.

PLANT-N REMOVAL INTEGRATES OTHER FACTORS

Owing to its simplicity of the assessment and being the main N-flux there is compelling case to use plant-N removal to set wastewater-N loading limit and monitor the performance of the cut & carry wastewater treatment system. There are additional reasons for using plant-N removal as the key performance indicator of a cut & carry wastewater treatment system.

Plant-N removal also integrates and indirectly monitors the performance of other factors affecting the cut & carry performance indirectly. The following factors can be considered as affecting plant-N removal except for seasonal factors such as soil/ambient temperature and solar radiation:

- Soil moisture levels
- Soil structure and porosity
- Soil and plant nutrient status including micronutrient levels in soil
- Soil pH
- Frequency and timing of plant harvest
- Soil toxicity or anaerobiosis caused by contaminant accumulation (e.g., heavy metals) and heavy hydraulic/BOD loading respectively
- Plant type and variety/breed
- Plant population density

I have deliberately avoided soil biomass (or soil microbial/biological) activity and soil types in the above list of factors affecting plant N removal. Typically, soil biomass or soil enzymic activities have been reported as high in wastewater treated soils (Sparling et al. 2001, Speir 2002 and Wafula et al. 2015), which may not necessarily manifest into higher plant performance.

Equally, free draining or loamy soils or good soil types may be conducive to good plant performance however, the listed factors are more critical despite selecting a site with good soil type. Studies have shown soil type is not critical in the extent of plant uptake of nutrients instead found crop types affecting nutrient uptakes (Thippeswamy and Manjunath, 2015).

RELATIONSHIP BETWEEN DM AND HERBAGE-N%

Increasing N loading has been shown to increase DM yield and plant-N removal (Di and Cameron, 2007) and herbage-N% in pasture species (Moir et al. 2012). However, increased herbage-N% may not necessarily result in high plant-N removal. It is crucial to understand that whilst plant-N removal can be assessed from DM production and herbage N%, the above two factors are not related linearly. Whilst we are aware the DM production is highly variable, herbage-N% can also fluctuate substantially. For example, high DM production may not result in high herbage-N% even when soil-N supply and soil moisture are not limited.

When the above phenomenon was studied under non-limiting N and soil moisture conditions, a reduction in herbage-N% was observed as DM yield accumulated for vegetative crops (Mills et al. 2009) (Figure 2). Thus, from the perspective of effective N removal from soil, the combined performance of DM and herbage-N% is critical, ideally targeting high herbage-N%. For example, 8 t DM with 4.5% herbage-N would have removed similar N mass (i.e., 360 kg N) as 12 t DM with 3% herbage N.

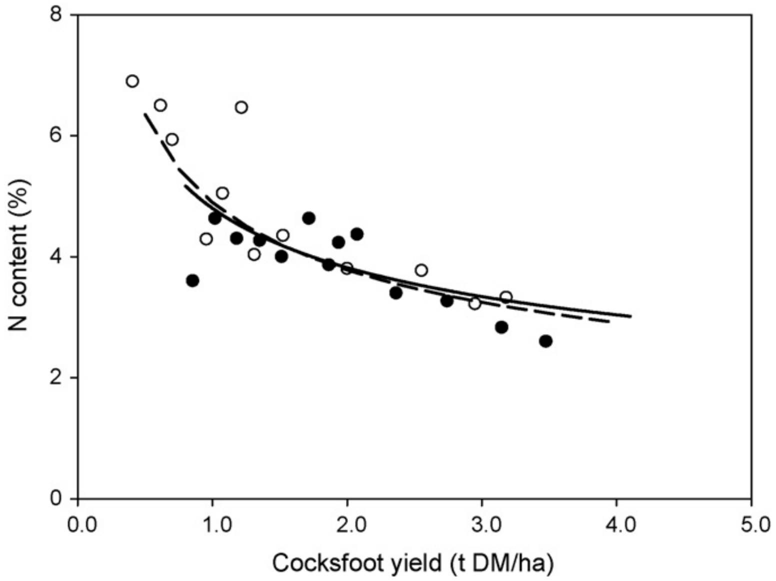

Figure 2. N dilution curve for cocksfoot under unlimited N and soil moisture from Mills et al. (2009) (● 2003/2004 trial ○ 2004/2005 trial) (Solid line from Lemaire et al. 1989)

PLANT TYPE IS A KEY FACTOR AFFECTING PLANT N REMOVAL

Based on the preceding section, the selection of plant type in a cut & carry system need not necessarily be based on the highest herbage-N% and can also be based on the following factors:

- Ease of management
- Compatible with specific situation (e.g., high soil moisture or high sodium tolerant)
- High financial returns (monetary value of the harvested product or profitability)
- Deep rooted to reduce N leaching and resilient to unplanned soil moisture deficits (e.g., lucerne)
- Nutritious or environmental benefits (e.g., plantain can improve milk solid production whilst reducing N leaching)

If plant type is selected primarily to treat wastewater-N, in addition to considering other benefits, it is critical to consider the N removal potential of a plant type under optimal conditions. Table 1 shows a compilation of the N removal potential of a range of plants based on past field agronomic trials involving fertilisers and irrigation which can be used in cut & carry wastewater treatment systems.

In the context of wastewater-N removal and land availability, the ideal outcome may be high DM x high herbage-N% combination. Whilst legumes such as red clover and lucerne can remove high quantities of N from soils, they are also known to fix atmospheric N_2 in root nodules which can be transported to the foliage thus exaggerating plant-N removal from the irrigated wastewater-N. There has been little or no assessment of biological N fixation (BNF) in land treatment of wastewater in New Zealand. However, from fertiliser-N trials it is well known that increasing N supply in soils can reduce BNF (Ledgard et al. 1999). Studies also showed livestock urine deposition had prolonged effect on reducing BNF in ryegrass-white clover pasture (Menneer et al. 2003).

Table 1. Annual potential plant-N removal rate (APPNRR) for selected plants under optimal conditions (i.e., trials held under irrigation and with N fertiliser applications)
(some Herbage-N% derived from crude protein values converted to total-N)

Plant	DM yield (t/ha/year)	Herbage N%	APPNRR (kg/ha)	Product end use	Reference
Lucerne ('Grassland Kaituna') (*Medicago sativa*)	17-28	4.6%	780-1280	Hay/silage	Brown and Moot (2004)
Red clover ('Grassland Pawera) (*Trifolium pratense*)	13-20	4%	520-800	Hay/silage	Brown and Moot (2004)
Chicory ('Grassland Puna) (*Cichorium intybus*)	13-20	2.8%	360-560	Hay/silage	Brown and Moot (2004)
Cocksfoot ('Grassland Wana') (*Dactylis glomerata*)	22	2.7-3.4%	590-750	Hay/silage	Mills et al. (2006)
Maize (Hybrid CF1) (*Zea mays*)	20	1.1-1.2%	220-240	Silage	Villaver, 1996
Plantain ('Ceres Tonic') (*Plantago lanceolata*)	13-16 (at extended leaf height 450 mm)	3% (derived from young stem & leaf)	390-480	Hay/silage	Lee et al. 2015
[1]Ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*)	14	3.5 % (derived from 2.6 to 5.4)	490	Hay/silage	Thomas et al. 2014

[1]Derived from NZ dairy pasture national average hence not considered as plant-N removal under optimal conditions. Ryegrass/clover has greater plant-N removal potential under optimal conditions.

Most wastewater related overseas studies on BNF in legumes relied on the extent of root nodulation hence may not be reliable. Whilst not fully accurate BNF studies using natural ^{15}N abundance ($\delta^{15}N$) or labelled ^{15}N are more reliable. Most studies focused on the impacts of heavy metals on BNF, rather than the effects of N loading rates.

Studies which used soil inoculation with BNF bacteria emphasised the need to inoculate the soils, however, there was no significant difference between N uptake by legumes grown in inoculated soil and normal soil irrigated with sewage wastewater despite a good correlation between plant-N accumulation and nodule numbers (Carvalho et al. 2012).

Other studies have shown soil inoculation is critical to BNF under zero fertiliser-N input and the absence of inoculation could cause no BNF and poor plant performance (Berenji et al. 2015). Combined with the fact N addition and soil inoculation can decrease and increase BNF respectively, it can be assumed under high N loading wastewater irrigation and zero soil inoculation the extent of BNF could be low hence legumes can be used as cut & carry plants.

When selecting any plants, it is critical to note that within a plant type there is high variation between hybrids or cultivars in DM yield which may affect the ultimate plant-N mass removal. For example, in the same field trial it was shown annual yield of Bronsyn cultivar of ryegrass was14,150 kg DM/ha whilst PG31 yielded 10,900 kg DM/ha (Easton et al. 2001). Annual species as Italian ryegrass (e.g., *L. multiflorum*) could uptake substantially more N than perennial ryegrass (e.g., *L. perenne*) at high N loading rates (Moir et al. 2012). For the above reason where applicable cultivars/hybrids must be specified as in Table 1.

PRINCIPLES IN SETTING WASTEWATER-N LOAD LIMITS AND OTHER NECESSARY LIMITS

Given numerous cut & carry systems have been consented and are currently operational in New Zealand, plant-N removal data (ideally with herbage-N% and DM production data) can be gathered from the above consents which can be used to determine realistic plant-N removal rates. Owing to widely varying consent conditions, wastewater quality and the management of the land treatment systems any interpretation of N removal efficiency would demand extensive data collection, collation, assessment and interpretation which will require considerable amounts of resources.

Even if the above exercise was performed, the derived plant-N removal rates must be used in association with the respective management conditions of the land treatment systems which may not be practical. For the above reasons, the best available option is to use *annual potential plant-N removal rates* (APPNRR) determined from the past documented field trials. Plant-N removal determined from several such trials are illustrated in Table 1.

The scientific logic behind the above approach is to adopt conservative philosophy in manging potential N leaching losses. The assumption is, if wastewater-N is applied below the APPNRR, the potential for N leaching loss is reduced or avoided if the *actual annual plant-N removal rate* (AAPNRR) is similar or closer to the annual wastewater N loading.

Several assumptions have been made to arrive at the above rationale:

- Wastewater treatment site soil has not been disturbed recently to accumulate excessive mineral-N,
- Wastewater applied has sufficient BOD to immobilise any soil based mineralizable-N,
- Small gaseous losses via ammonia volatilisation and denitrification are inevitable, and
- For much of the time soil moisture level is managed within field capacity.

Setting actual N removal rate at the optimal removal rate is, however, risky unless there is confidence in managing factors affecting *targeted* plant-N removal under optimal conditions consistently. Thus, one of the safest ways to overcome any N leaching losses because of excessive wastewater-N loading or soil-N accumulation is to maintain annual wastewater-N loading below that of the potential removal rate. Thus, such a system can be expected to be slightly N deficient.

There may be situations with plants not being able to access much of the wastewater-N irrigated. It could be caused by high proportion of the wastewater applied-N being organic or high immobilisation of the applied-N as identified by Cameron et al. (2002). Apart from high available-C in the wastewater, soils with high C:N ratio may also reduce plant-N removal because of competition with soil microbes to secure mineral-N. Gerber (2000) found sewage wastewater applied to three grass species had 63% of the applied-N in the herbage in the second year of the wastewater application. I believe the above issue was probably caused by high soil C:N ratio of 13.2.

Despite the potential gaseous N losses and N immobilisation of the applied wastewater-N, a conservative approach is sensible since it is difficult to achieve optimal plant-N removal conditions annually in all-year-round wastewater irrigation systems and any immobilised-N has the potential to mineralise during the lifespan of the treatment system. Based on 75% of the potential plant performance owing to less-than-ideal soil and seasonal conditions, I propose 25% reduction in wastewater-N loading as a conservatory approach. This means, as in Table 1, if red clover annual N removal is 520-800 kg N/ha, I will recommend an annual wastewater-N loading of 390 kg N/ha, which has been derived by multiplying 0.75 with the lower range of potential plant N removal of 520.

If a single limit control such as annual wastewater-N loading is regulated, N leaching must be monitored, which is onerous and costly. If N leaching is monitored a suitable N leaching threshold limit must be set which is not easy. Models cannot be used to set N leaching unless they are validated as fit for purpose. However, if plant-N removal limit is also regulated along with wastewater-N loading, there is no need to regulate or monitor N leaching.

In cut & carry systems avoiding N leaching, annual plant-N removal must be lower than the annual-N input. Thus plant-N removal limit cannot be set as the wastewater-N loading limit. Owing to gaseous-N losses and immobilisation, a trigger plant-N removal level can be set conservatively based on 75% of the applied annual wastewater-N loading. Owing to plant performance and plant-N removal is also affected by annual climatic variations, I recommend the use 3 year rolling average to monitor compliance with set annual plant-N removal. The above approach will also promote adaptive management of soil, plant and wastewater to improve plant performance when plant-N removal drops below the required annual target.

Because of not regulating N leaching losses directly, groundwater nitrate must be monitored to assess any actual impacts of the cut & carry systems. This can be done by installing piezometers in areas with shallow groundwater and monitoring bores in areas with deeper aquifers upstream and downstream of the land treatment site. Whilst there is evidence for organic-N leaching, there has been little or no monitoring of the organic-N in groundwater. Organic-N has the potential to be mineralised in the upper most vadose zone (Holden and Fierer 2005), hence unlikely to enter groundwater unless substantial preferential flow pathways exist.

Ideally, groundwater quality parameters such as nitrate-N, ammoniacal-N, E.coli, pH, total-iron and total-P should have been monitored before applying for land discharge consents. This will allow groundwater nitrate-N trigger level to review consents or change management practices. Given excessive soil nitrate accumulation or leaching is possible following any soil disturbances of pastoral soils, any land disturbances must be avoided over the consent period. Any replanting must be performed by direct drilling.

MANAGEMENT OF THE KEY FACTORS AFFECTING CUT & CARRY SYSTEM PERFORMANCE

The key factors affecting cut & carry systems to treat and manage wastewater are like that of cut & carry systems managed for farming purposes. Such factors have been studied for more than 100 years and can be categorised broadly as soil and plant conditions. If both soil and plant conditions are maintained at optimum levels the plant N removal can be sustained at high level.

Table 2. Key plant-N removal factors and causes for poor performance and remedies

Plant-N removal factors	Causes for poor performance	Remedies
Soil oxygen	Saturated soil conditions	• Avoid saturated conditions. • Install and monitor soil moisture probes.
Soil moisture	Soil moisture deficiency	• Design wastewater irrigation system to avoid soil moisture deficiency.
Wastewater N quality	Nitrate leaching	• Minimise excessive nitrate in wastewater by manipulating pre-treatment or avoid using nitrate-based chemicals at the wastewater source. • Avoid nitrate in wastewater by pre-treatment over winter or when soil temperature is <10ºC. • Use suitable nitrification inhibitor to reduce nitrification
Soil structure & porosity	Excessive application of sodium (Na)	• Avoid excessive sodium application. • If high Na is due to the use of detergents reduce or avoid using Na-based detergents and replace with K based detergents. • Use SAR approach and monitor soil Na, Ca, Mg and K levels regularly. • If excessive Na levels in soil, to leach excessive soil Na, ○ Apply gypsum ($CaSO_4$) to soil with pH 6.5-7.5 ○ Apply lime ($CaCO_3$) if soil pH is <6
	Soil compaction	• Avoid soil compaction by large machineries in wet soils • Avoid plant harvest when soil is wet.
Soil nutrient levels (except for N)	Soil nutrient deficiency	• Monitor key plant and soil macro and micro nutrient deficiencies except for N. • Apply the deficient nutrients by using known fertilisers except for fertiliser N.
Soil pH	High or low pH wastewater use	• Maintain soil pH between 6-7. • If soil pH is <6, apply lime. • If soil pH is >7, apply $FeSO_4$.
Harvest frequency and timing	Premature or delayed harvest	• Avoid premature or delayed harvest.
Plant population	Low plant density	• Ensure correct population density at the outset.
Plant type	Wrong plant type	• Define goals for selection of plants (if the primary goal is N removal annual and deep and dense rooted grass species remove more N)
Soil toxicity	Wastewater with heavy metals or excessive BOD	• Avoid heavy metal accumulation above safe levels. • Reduce hydraulic loading when BOD is excessive. • When irrigating high BOD wastewater during wet conditions use more land area than usual.

As discussed before, given the absence of a reliable method to predict plant available N in soil, I have not recommended the assessment of available N for any nutrient deficiencies in Table 2. As recognised earlier, herbal N% may not be a reliable indicator for N removal efficiency since low dry matter yield could be associated with high herbal N% and vice versa. However, plant N removal estimated from the harvested cuts may be compared with that of the previous seasons to assess any declining N removal trends.

It is tempting to supplement any potential or actual N deficiencies limiting optimal plant performance with fertiliser-N or by increasing wastewater-N loading. Whilst high one-off N loadings (as urine-N) have been shown to increase plant-N removal and herbage-N%, N leaching losses can also increase (Di and Cameron, 2007 and Moir et al. 2012 respectively). Increasing wastewater-N and hydraulic loading have been shown to increase nitrate-N levels in soils (Geber 2000) indicating potential for N leaching. Addition of fertiliser-N can be problematic, particularly when the cut & carry system performance is monitored primarily by plant-N removal because it is not possible to distinguish between wastewater-N and fertiliser-N contribution to plant-N removal.

Given the main objective of the cut & carry system is to reduce N leaching from land treatment system, managing slightly N deficient system in a growing season may not be critical. However, if the 3-year rolling plant N removal average declines substantially, this must be assessed against key factors and if N deficiency has been the cause, wastewater-N loading can be increased by consent variation provided hydraulic loading is compatible with soil and plant performance and potential for N leaching.

In temperate countries like New Zealand, in all year round cut & carry land treatment systems, plant-N removal rates during winter periods can reduce substantially owing to reduced plant growth. Thus, much of the annual potential plant N removal rate relies heavily on the plant performance during the remainder of the year, particularly summer. Provided hydraulic loading does not exceed field capacity or plant available water (PAW), irrigating wastewater with low or no nitrate levels will assist in reducing any direct nitrate leaching during winter.

Most municipal wastewater treatment plants tend to generate less nitrate over winter periods which is favourable to avoiding direct nitrate leaching. If wastewater-N is applied as organic-N and ammoniacal-N, any mineralisation and nitrification respectively will be relatively lower during winter thus applied N can accumulate in soil for peak summer plant uptakes. The potential for nitrate accumulation in soil is low over winter because saturated soil conditions can promote greater denitrification losses (Luo et al. 2007). If in doubt suitable nitrification inhibitors can be used minimise nitrate accumulation by nitrification (Table 2).

CONCLUSIONS

In the absence of cost effective and reliable N leaching monitoring systems and fit for purpose wastewater land treatment models, the most sensible interim approach is to use the most significant N flux in land treatment system such as plant-N removal to determine and regulate wastewater-N loading to manage cut & carry land treatment discharges effectively.

A wide range of options are available to select plant or crop to use in cut & carry land treatment system. Discharge permit wastewater-N loading limit can be set at 75% of the annual potential plant-N removal rate (APPNRR) to minimise long-term soil N accumulation and N leaching. The N removal effectiveness of the system can be assessed by regulating and monitoring plant-N removal rate and the site aquifer for groundwater nitrate. Groundwater nitrate trigger levels can be set based on background groundwater nitrate-N levels to trigger consent reviews or reductions in wastewater N loading or changes system management.

Performance monitoring against plant-N removal and groundwater nitrate levels will promote conducive and sustainable management practices favouring high plant/crop performance and adaptive management to correct poor plant performance regularly. Thus plant-N removal trigger approach is expected to result in effective cut & carry system management, less N leaching and less onerous consent conditions and monitoring.

Whilst cut & carry land treatments are considered as excellent wastewater treatment systems, their success is dependent on effects based and pragmatic consent conditions and monitoring. The contrary approach will result in increased adoption of high energy, high capital, high maintenance, high cost and fast depreciating conventional or advanced wastewater treatment systems to treat and discharge to waterways or discharge heavily treated wastewater to land.

RECOMMENDATIONS

Until cost effective and reliable nitrate leaching monitoring or fit for purpose and validated land treatment models are developed, I recommend that,

1. the consent authorities
    a. limit and monitor cut & carry land treatment wastewater N based on 3-year rolling average plant-N removal and set and monitor plant-N removal targets.
    b. set groundwater nitrate-N trigger levels based on the background values and require monitoring of the groundwater quality for nitrate-N upgradient and downgradient to the land treatment site and
    c. if warranted co-ordinate the collation of technically defensible annual wastewater-N loading rates and plant-N removal triggers based on plant-N removal potentials for a range of cut & carry plants/crops by peer reviewed expert desktop research (e.g., Envirolink),
2. the consent holders must,
    a. promote and adopt economically attractive and environmentally sustainable cut & carry land treatment systems to manage wastewater effectively and generate income and
    b. ensure key factors affecting plant performance are managed under favourable conditions over the term of the consent and
3. the researchers must develop,
    a. fit for purpose wastewater land treatment models based on technically defensible long-term field trials for wide ranging plant types and wastewaters,
    b. cost effective and technically defensible N leaching monitoring systems and
    c. suitable nitrification inhibitors to minimise land treatment nitrate leaching.

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