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The role of riparian buffer management in reducing off-site impacts from grazed dairy systems

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Abstract

Agriculture in general and intensive animal production in particular can degrade the environment, especially as a consequence of the overuse of nutrients. Intensively grazed dairy systems, defined by the presence of foraging animals in the landscape, are often considered a more benign approach to dairy production with perceived smaller impacts due to the reduced requirement for manure disposal. However, grazing dairy cows contribute nutrients and pathogens in excreta, and sediment through landscape deformation. These impacts can dramatically increase in parts of the farm such as feeding, watering and sacrifice areas, laneways and night paddocks where animals are concentrated and spend a disproportionate amount of time. Other practices such as the disposal of dairy shed or dairy factory effluent and cultivation of fodder crops can also pollute the environment. A common approach to reduce nutrient, pathogen and sediment losses from dairy farms is to establish buffer zones in riparian areas that act as an interface between upland land use and waterways. This is generally done by fencing riparian areas to exclude stock and revegetating with understory and overstory species, with the aim of increasing infiltration, trapping sediment and decreasing contaminant losses from upland pastures. However, poorly designed and managed riparian areas may themselves contribute to further environmental degradation. Rarely is an integrated approach, including factors such as animal behavior and dairy farm management practices, as well as an analysis of landscape and riparian hydrology used in developing riparian management recommendations for individual farms. This paper reviews the threats posed by intensively grazed dairy systems, approaches to improve riparian zone management and recommends future research needs.

Key words: nutrients, phosphorus, nitrogen, fecal organisms, sediment, filter strips, watershed

Introduction

Milk production per cow, farm size and herd numbers continue to increase in most of the dairy-producing regions of the industrialized world despite declines in farm numbers[1]. This intensification of the dairy industry has been in large part due to greater use of inputs such as fertilizer and feed supplements which have contributed in many instances to nutrient surpluses on farms[2–5]. These on-farm nutrient surpluses can have negative consequences for the environment, including emissions through various nutrient transport pathways[6,7]. The factors attributed to intensification of the dairy industry and the consequences of the intensification are in general similar for grazing and confinement systems[8]. Manure management of housed animals is a priority in most confinement dairy systems. However, despite the perception that grazed dairy systems are more environmentally benign than confinement systems[9,10], animals defecating and urinating across the landscape will result in different pollutant sources and propensity to degrade waterways.

As a mitigating measure farmers are actively encouraged to improve riparian management, firstly by fencing these areas to exclude stock, and also by revegetating fenced areas to reduce contaminant delivery to streams and improve native biodiversity attributes. However, livestock movement and management, both within the riparian area and across the broader landscape, challenge traditional approaches to riparian management.

This review describes the impacts posed by grazing dairy farms on contaminant losses, discusses the role of riparian buffers within these systems in temperate regions and presents options for improved management to reduce their potential environmental impact. The review draws on data primarily from Australia and New Zealand, where the majority of dairy farms are grazed pasture systems, as well as from elsewhere where relevant.

Characteristics of Grazed Dairy Systems

Grazed dairy systems (such as in Australia, New Zealand or Argentina) depend on high-quality permanent pastures to support the majority of the nutritional needs of lactating dairy cows; in contrast to the predominantly confinement systems in Europe and the USA[11,12]. In many European dairy systems grazing has traditionally been in summer[13,14], whereas in the USA grazing is largely associated with extensive livestock systems[15].

Typically, grazing dairy farms are divided into 'paddocks' that are fenced with at least one gateway at one end to allow entry and egress, and which often contain a usually immobile watering point or trough (Fig. 1). Pastures are usually dominated by grasses and may also contain varying proportions of a legume. Pasture productivity can be limited by temperature and water, both of which contribute to the temporal pattern of pasture production for a particular region[13,16].

Greater nutrient supply can significantly boost pasture growth and productivity. In Australia and New Zealand the broad-scale use of phosphorus (P) and potassium (K) fertilizers has been a common practice to overcome naturally occurring nutrient deficiencies[17,18]. While nitrogen (N) was traditionally supplied to pastures through biological fixation by the legume–*Rhizobium* symbiosis, the application of nitrogenous fertilizers is now widely used to increase pasture production. Similarly, in Europe, where P, K and sulfur (S) deficiencies are less common, N fertilizer has been extensively used since the middle of the 20th century[13].

Grazing pastures on a rotation, the length of which is determined by pasture dry matter on offer, increases pasture utilization and thus milk production and profitability[16]. To maximize pasture utilization farmers often 'strip-graze' paddocks, where cows are provided with access to narrow strips of pasture within individual paddocks. The strips are usually not back-fenced, allowing cows to revisit previously grazed strips[10], while ensuring cows have access to immobile water troughs.

Despite the cost advantage of pasture as the major feed source, the grazing industries have increased their use of supplemental feed substantially over the past two decades to meet feed gaps and further increase milk production[19,20]. Feed supplements (such as grain, grain-based pellets with minerals, purchased forages such as hay and silage and increasingly by-products such as palm kernels, citrus pulp and molasses) are used to manage temporal variations in pasture availability, and to balance energy, protein and mineral intakes[13,20]. Thus, more than 90% of Australian dairy farms regularly purchase cereal grain-based supplements of greater than 1.1 $\text{tonne cow}^{-1}\,\text{yr}^{-1}$, and forage inputs ranging from 0 to 1.4 $\text{tonne cow}^{-1}\,\text{yr}^{-1}$ on the average dairy farm[21]. The increased reliance on purchased feed, in addition to increasing fertilizer rates, has generally resulted in greater nutrient inputs and net positive balances for N, P, K and S on grazed dairy farms, leading to soil fertility levels on many paddocks well in excess of that required for pasture growth[22].

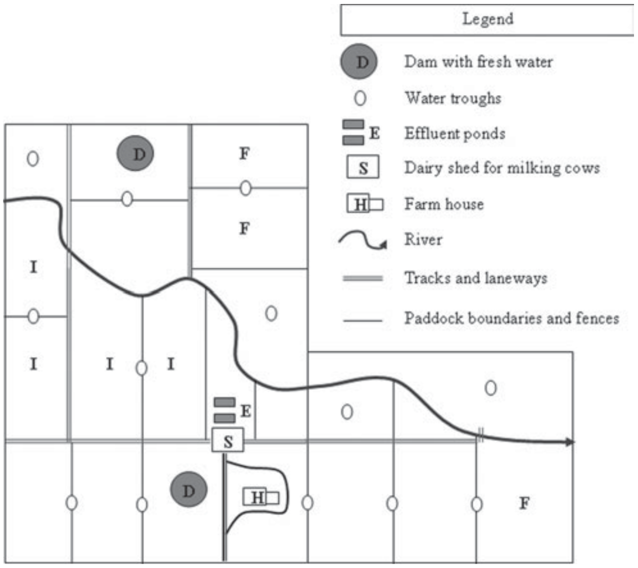


Figure 1. Schematic representation of a grazed dairy farm showing typical management activities. The activities include the dairy shed (S) where the cows are milked at least twice each day; effluent ponds (E) for storage of dairy effluent (cow excreta deposited in the dairy shed during milking combined with the wash down water); farm dams (D) where water is stored for use on the farm. Pastures are subdivided into paddocks that are part of the grazing rotation and are visited by cows throughout the year. Some of the paddocks (F) may be taken out of the grazing rotation during the spring months for forage conservation (hay or silage), for renovation of pastures, or for growing summer fodder crops (e.g., turnips, maize). Some paddocks (I) will be irrigated with effluent from the storage ponds, usually during the dry summer months.

Grazing cows move frequently by means of an interconnecting network of laneways and tracks between paddocks and to the dairy shed where they are usually milked twice daily. In the past, as well as a source of water, waterways were also used for the disposal of dairy shed effluent, and consequently dairy sheds are often located adjacent to or within the riparian zone. To prevent the direct contamination of surface and ground water, farmers are encouraged to collect deposited feces and urine as well as waste milk from concreted areas where cows are held, fed and milked. This effluent, usually stored in earthen-constructed ponds[23], is often used to irrigate pastures (most commonly those close to the dairy shed) during the dry summer period to take advantage of the nutritive value[24]. Application of dairy shed effluent generally increases soil P, K and N, although inconsistencies were observed in the different experiments reviewed by Hawke and Summers[25].

Management of grazed dairy farms often includes the use of 'night paddocks' in which the cows are held between the evening and morning milking, and which are generally located near to the dairy shed. Farms may also have other high animal density areas such as feed pads, yards where cows are held prior to or just after milking, or small paddocks where cows are kept during calving or when in need of special care. Farmers also conserve excess pasture in selected paddocks either as silage (spring) or hay (late spring, early summer). Summer fodder crops such as turnips (*Brassica* spp.), maize (*Zea mays*), and millet (*Echinocholoa utilis*) may also be grown to provide additional forage when pasture growth may be restricted[20,26].

Many farms have at least one perennial or ephemeral waterway. Farmers may also create shallow drainage lines to assist in removing water (mainly during winter and early spring) from paddocks that are prone to waterlogging. Typically those paddocks are adjacent to waterways. The land alongside waterways on grazed dairy farms has usually been cleared of native vegetation with permanent pastures established, often right up to the stream bank. Farmers may also allow stock direct access to the waterway as a means of supplying the animals with water. Consequently riparian land has generally been managed for the purpose of dairy farm productivity with less emphasis on the detrimental impacts on the broader environment.

Threats to Riparian Ecosystems from Grazing

The riparian zone as defined in this paper is the 'area of land that adjoins, regularly influences or is influenced by the waterway'[27]. This definition does not exclude transient waterways, is based on proximity to surface and/or subsurface water and acknowledges the terrestrial—aquatic interactions in these zones[28,29]. The configuration of riparian landscapes is made up of longitudinal (i.e., corridors), transverse or lateral (terrestrial/aquatic links), vertical (links to groundwater and vegetation canopy) and internal structures. These features, stream size and its location in the drainage network (i.e., headwaters versus floodplain), as well as geomorphology, determine the shape, width and functions of riparian zones[28–30]. Riparian zones are also influenced by vegetation outside of this zone that contributes nutrients, organic matter and shade. On many dairy farms, the areas that farmers are willing to consider for riparian management are usually those most proximal to the stream, and therefore only include a portion of the ecological definition of riparian zones.

In undisturbed landscapes riparian zones support a range of aquatic and terrestrial organisms whose survival is interdependent and who play an important role in the cycling of nutrients in riparian zones[31,32]. Riparian ecosystems therefore also play an important role in maintaining and facilitating dispersal of biodiversity[28,30].

In disturbed environments, the structure, functions and processes in intact riparian zones can attenuate upland anthropomorphic impacts on waterways and the environment. For example, transverse structures physically separate land use impacts from the waterway. Where riparian zones are incorporated into upland land management, ecosystem processes (nutrient transformations, reductions in the velocity of moving water and sediment trapping) specific to undisturbed riparian zones will be modified due to changes in soil physical, chemical and biological properties as well as changes and loss of vegetation[33]. In these instances, a riparian zone may be less able to mitigate environmental impacts due to land-use activities. In fact, riparian structures, such as the vertical links to groundwater, may instead exacerbate environmental degradation. Additionally, loss of vegetation reduces the input of debris to supply nutrients, habitat and the geomorphic structures that moderate flow, decreasing aquatic and terrestrial biodiversity at local and catchment scales.

Poor riparian condition and in-stream water quality, as well as low or no native riparian biodiversity, are features of many grazed dairy farms[34,35]. Farm management activities on grazed dairy farms can be divided into those that have a direct or an indirect impact on riparian zones and waterways (Fig. 2). Activities that directly threaten the riparian zone include stock accessing waterways and riparian areas, and applications of fertilizers and effluent. Indirect impacts generally occur upslope and out of the immediate vicinity of the riparian zone and may be associated with normal farm management practices. Pollution from the directly and indirectly impacting activities can be further categorized into those that originate from point or non-point (diffuse) sources, with point sources of pollution usually most easily contained[7,36,37].

Indirect threats

Hoof impact. Movement of dairy cows on upland pastures can deform the landscape, creating trails, terracettes and enhanced surface roughness by compacting, shearing and moving, and smearing soils. A walking dairy cow could exert vertical pressures of at least 250 kPa[38]—more than double that when stationary[39,40]—and these are intensified during movement upslope, as can occur on steep riverbanks. In upland areas movement impacts can be significant as these soils are often shallower[38]. Decreased infiltration capacity in compacted and pugged (poached) soils results in increased and possibly changed runoff. Mesofauna, such as earthworms, are also disturbed by grazing, leading to decreases in hydraulic

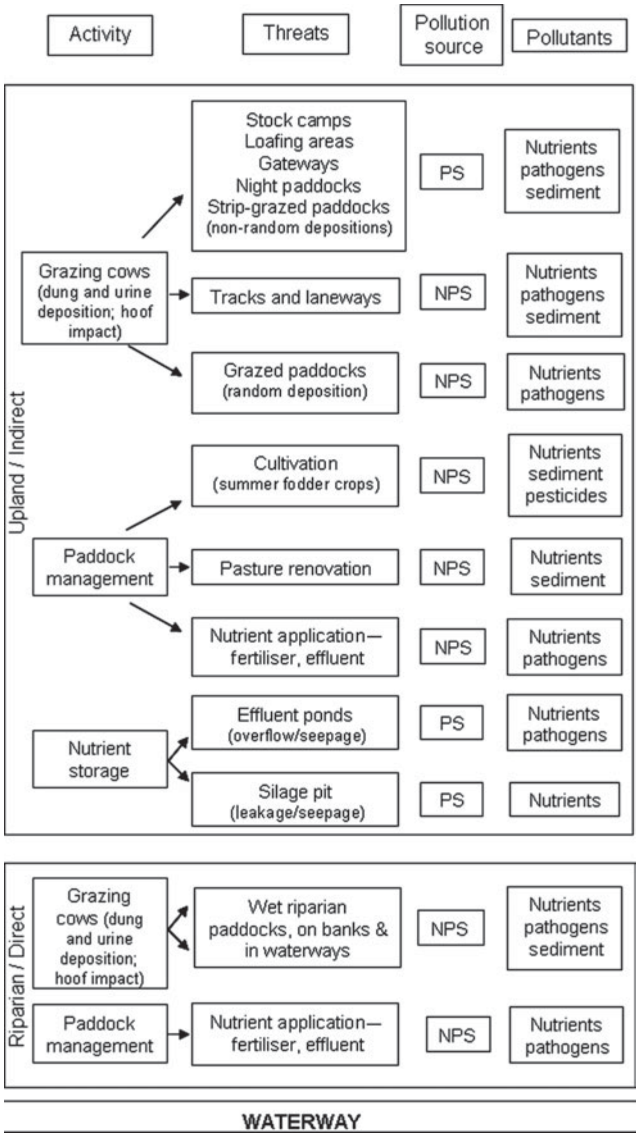


Figure 2. Threats posed by grazing systems on riparian zones and waterways from directly and indirectly impacting management activities, showing the pollution sources (PS, point source, NPS, non-point source) and the contaminants.

conductivity, soil structure and fertility, reducing the potential for recovery of compacted soils[39,40]. Moreover, the impacts of livestock on soil physical properties and pasture are not likely to be distributed evenly across a grazed paddock as cattle spend almost half of their time in less than 10% of the paddock[10,40].

Random excretal deposition. Dairy cows excrete a large percentage of nutrient intake in dung and urine[41]. While research in confinement dairy operations has demonstrated the effect of excess dietary P and N contents in dairy diets on excretions[42,43], limited research has been undertaken in grazing systems. Aarons[44] found in temperate Australian systems that seasonal production and nutrient content of grazed pastures affected nutrient intakes and dung nutrient concentrations (Fig. 3). Nutrient contents in the pasture and dung were highest in spring when pasture growth was greatest, then declined in summer. The feeding of conserved spring silage (with a higher nutrient content than available pasture) in late summer resulted in increased dung P concentrations. While the greater use of supplements in more intensively managed grazed pasture may even out the temporal variation in feed availability observed in purely grass-based systems, an increase in the total amount of P and N excreted by the animals is likely to be associated with the greater feed intake[42,43,45].

When excreta is deposited by grazing cows, P, K and N can be applied to soil at rates (e.g., 240 kg P ha^{-1}, 780 kg K ha^{-1} and 1000 kg N ha^{-1}, respectively) well in excess of typical fertilizer application rates[14,41,46]. Consequently greater soil P, K and N fertility was observed under cattle dung pads[46–49], and urine patches[50].

Seasonal variations in the decomposition rate of deposited dung in the field could affect movement of nutrients from the pad and subsequent nutrient accumulation in soil[51]. In addition to nutrient loss from surface deposits of dung, nutrient movement in surface and subsurface water pathways from high-nutrient-content soils is likely to be a feature of grazing systems, after the dung pad has degraded[36]. Elevated soil P levels were observed for up to 112 days, although the dung pads had completely disappeared in approximately 60 days[52].

Nitrogen leaching losses in grazing systems are primarily determined by urine depositions[53], although greater nitrate leaching also occurs as N fertilizer application rates increase[54–56]. The impact of N fertilizer is two-fold; due in the first instance to the potential for fertilizer N to be mobilized, and secondly through promoting plant biomass and increasing pasture protein content[42]. Thus, while a linear relationship between fecal N and protein intake ($R^2 = 0.53$) was observed, urinary N increased exponentially ($R^2 = 0.95$), such that above an intake of 400 g N day^{-1} greater amounts of N were excreted in urine compared with feces.

High concentrations of microbial pathogens are also deposited in dung and can include fecal streptococci, *Escherichia coli, Salmonella* spp., *Cryptospordium parvum* and *Giardia*, all of which pose a serious threat to human and animal health, and have been shown to be elevated in streams running through grazed pastures[37,57]. *E. coli* counts in dung of up to 10^6 most probable number (MPN) 100 ml^{-1} or 10^9 cells per dung pat and *C. parvum* oocyte concentration of approximately 10^4 g^{-1} feces have been reported, with both transported in runoff[26,58–60]. The numbers of *C. parvum* oocytes in runoff depended on the slope, presence of vegetation and on rainfall intensity. Despite the assertion by McNeill[61] that bacterial pathogen survival diminishes once feces are deposited by the animal, neither McDowell et al.[26] nor Muirhead et al.[60] observed first-order decay kinetics of *E. coli* in pads after deposition. Survival of pathogens in dung deposited for some time on pasture was thought to contribute

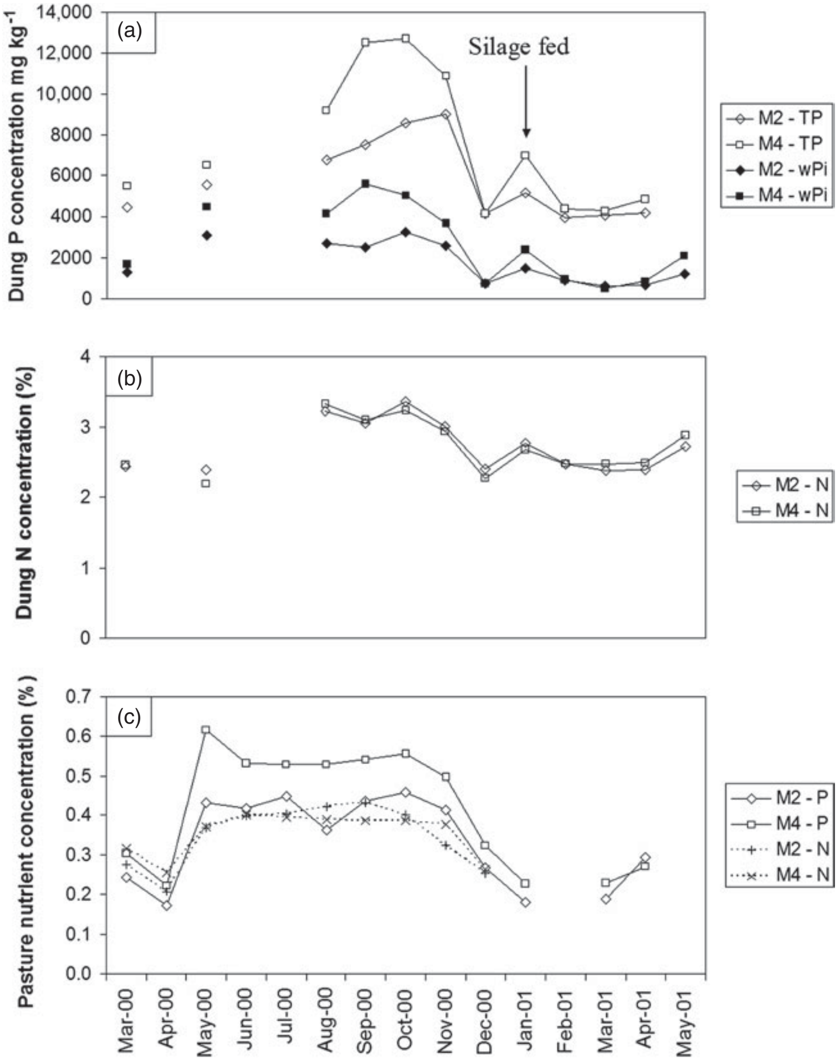


Figure 3. Changes in (a) dung P (Total P [TP], mg kg^{-1}; water extractable inorganic P [wPi], mg l^{-1}), (b) dung N (%) and (c) pasture P and N concentrations (%) over the 2000/2001 lactation, from cows grazing pastures that had been stocked at 3 cows ha^{-1} and received P fertilizer at 35 kg (M2) and 140 kg (M4) ha^{-1} yr^{-1} for 6 years (Aarons[44]). No nitrogen fertilizers were applied over the 6 years of the study. Dung samples were randomly collected from 3 cows on each of 5 mornings once each month. Pasture samples were collected from paddocks that cows had grazed, except in February 2001 (summer) when there was insufficient pasture.

approximately 16% of the catchment *E. coli* load via overland flow[62].

Non-random excretal deposition. Animal behavior, driven by the availability and location of water and shade, landscape topographical features (e.g., hillslopes), and pasture growth and season, contributes to the concentration of animal excreta within the landscape and large-scale spatial heterogeneity in soil nutrient status[10,15,63]. Additionally, soil compaction and the resulting influence on soil hydrology will exacerbate the effect of stock camping behavior on movement of nutrients via overland flow[38]. Nutrient accumulation zones identified in the stand-off area near to the dairy shed appeared to cause elevated soil P levels down-slope and close to the waterway. Groundwater nutrient concentrations were affected in the areas with elevated soil nutrient levels[64].

Herd management (i.e., frequency of visits, duration and cow density) also influences spatial deposition of dung and urine and nutrient accumulation[22,44,64]. The use of night/day paddocks appear to lead to nutrient accumulation while uneven nutrient distribution was reported in strip-grazed paddocks where back fencing was not used.

Paddock management and nutrient storage. A number of studies have demonstrated the impact of fertilizer, dairy shed effluent and cultivation on nutrient, pathogens and sediment contamination of waterways when hydrological conditions are appropriate. For example, P and N runoff losses were related to time since grazing and fertilizer application, reflecting the diverse forms and sources of these nutrients in soil, plant, and faeces and how management activities can influence their availability[26,65–67]. McDowell et al.[26] reported losses of P, N and *E.coli* from soil in which forage crops (*Brassica* spp.) had been grown and then subsequently grazed. They subsequently estimated P losses from fertilizer application of approximately 12% of the estimated total P lost, while dung P comprised between 25 and 36%. Monaghan et al.[62] found that dairy shed effluent was an important source of nutrients and fecal bacteria in a study modeling land-use impact on catchment water quality in New Zealand. Additionally, nutrients and pathogens concentrated in silage pits and effluent ponds may pollute the environment if these storage facilities leak or overflow and concentrated material reaches water transport pathways[37].

Direct threats

Hoof impact. In summer stock may preferentially graze riparian pastures in response to better forage quality (compared to more upland areas) and the access to water[15,38]. In winter and early spring paddocks adjacent to waterways are often very wet due to the vertical links in riparian zones. Soil structure is likely to be severely degraded affecting plant growth directly (low water infiltration, low oxygenation, stunted root growth) and indirectly as the ability of the meso and microflora to cycle nutrients required for adequate plant growth is reduced. Grazed pasture soils were reported to have considerably lower hydraulic conductivity and negligible macropore flow compared with native riparian pastures and ungrazed forests, suggesting a greater tendency to runoff losses[33,38].

Vegetation loss. Grazing stock trample and consume native riparian vegetation, with the resultant loss of understorey species increasing the likelihood of soil erosion, sedimentation of waterways, reduced aquatic life as well as declining native biodiversity such as woodland bird populations[68,69]. In contrast, Trimble and Mendel[38] reported that the greater grass growth observed when understorey vegetation was removed by grazing cows might decrease erosive losses.

An additional impact in Australian systems is the increased salinity observed in response to the replacement of native trees with annual and temperate pasture grasses[70], a likely outcome in grazed dairy pastures. The converse is also true, i.e., afforestation of a riparian zone can lower the water table and lead to lower stream flow, although the percentage decline (55–84%) varies in specific instances[71].

Excretal deposition. Deposition of feces and urine in waterways may directly introduce substantial amounts of nutrients and pathogenic organisms[58,72]. Presuming cows deposit dung an average of 12 times each day[41], each animal spends approximately 15 min standing in the stream, and that the riparian paddock is visited 17 times, a herd of 300 cows is estimated to deposit 0.8 and 3.4 kg P and N and 6.4×10^{11} *E. coli* cells, respectively, over a lactation (Table 1). The contribution from this herd needs to be considered in the context of dairy catchments where many farmers may have unfenced riparian zones. Direct deposition of feces accounted for 8×10^{8} colony forming units $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ in the Bog Burn catchment, although cows were excluded from 84% of waterways[62].

Cows are also more likely to frequent unfenced waterways in more intensively managed grazing systems as the larger feed intake by these animals will result in greater body heat levels and an increased requirement for water[15]. Davies-Colley et al.[58] observed a tendency for cows to defecate 50–60 times more frequently in the stream than on the adjacent laneway. In contrast, James et al.[72] observed that cows defecated more frequently in the 10 m of the riparian zone immediately adjacent to the waterway than in the river. These differences notwithstanding, excreta deposited in riparian zones can also influence the waterway through transverse or vertical flow of water.

With higher leaching losses of NO_3-N reported under legume pastures in summer when the legume component decomposes, and the application of up to 1200 $\mathrm{kg\,N\,ha}^{-1}$ in a urine patch, the connectivity to groundwater in grazed riparian pastures may contribute to increased movement of N to waterways[41,53,73]. Leaching losses from urine patches, due to large increases in soil solution NH_4^+, which are then rapidly nitrified[50], are influenced by soil drainage characteristics[73] and seasonal conditions[53]. Phosphorus leaching can also be enhanced in soils that are seasonally anaerobic, as would be the case for most riparian soils[74], explaining increases in groundwater P concentrations observed in grazed riparian soils.

Paddock management. Inaccurate application of nutrients and chemicals to grazed riparian pastures can lead to contamination of waterways with fertilizers, dairy shed and dairy factory effluent, and pesticides[37,75], while inadequate management of storage ponds (poor design, infrequent emptying) can result in loss of effluent to the waterway. Applying effluent to pastures, especially to riparian paddocks, can degrade water quality. Intensification of the industry resulting in increases both in the volume of dairy shed effluent, and in the concentration of nutrients in the effluent[75] is likely to increase this impact.

Shallow subsurface drains, installed to remove water from frequently flooded or wet riparian pastures, can provide a route for applied effluent to waterways. For example, Monaghan et al.[62] found that surface drains contributed 6% of the annual *E. coli* load, while mole-pipe drainage of effluent-irrigated pastures contributed 18% of the catchment P load[76].

Approaches to Improve Riparian Management

Traditionally, decreasing the degrading impacts of grazing systems on waterways has been based on the creation of a fenced vegetated buffer immediately adjacent to the

Table 1. Nutrient (N, P) and *E. coli* deposition rate calculated for areas of a grazed dairy farm receiving random or non-random dung deposits. Calculations are based on published and experimental data.

					Deposition rate (contaminant deposited in dung cow^{-1}*HDP)		
Deposition type	**Location**	**Area (ha)**	**Annual herd deposits (potential, HDP) (cow visit ha^{-1} yr^{-1})**		**Dung-P**[6]	**Dung-N**	**Dung-*E. coli***
– random	Paddock[1]	3.6[2]	HDP = (ρ[3] × Dn[4] × F[5]) HDP = ((300/3.636) × (128/24) × 17)	**7481**	**111.3** kgP ha^{-1} yr^{-1}	**482.9** kgN ha^{-1} yr^{-1}	**8.98×10^{13}** cells ha^{-1} yr^{-1}
– non-random[7] (influenced by animal behaviour)	Waterway		300 cows visit creek Dn = 15 min in creek *F* = 17 visits to this riparian paddock during the lactation HDP = (300 × (0.25/24) × 17)	**53**	**0.79** kgP yr^{-1}	**3.4** kgN yr^{-1}	**6.38×10^{11}** cells yr^{-1}
– non-random[8] (influenced by grazing management)	Night paddocks	3.6	*P* = 300 cows Dn = 12 h; 6 pm–6 am *F* = 304 visits i.e., every night for lactation HDP = ((300/3.636) × (12/24) × 304)	**12,541**	**186.6** kgP ha^{-1} yr^{-1}	**809.6** kgN ha^{-1} yr^{-1}	**1.50×10^{14}** cells ha^{-1} yr^{-1}
	Dairy shed[9]		300 cows Dn = 2 h *F* = 608 visits i.e., twice daily for lactation HDP = (300 × (2/24) × 608)	**15,200**	**226.2** kgP yr^{-1}	**981.3** kgN yr^{-1}	**1.82×10^{14}** cells yr^{-1}

Farm data

Herd size: 300 cows.

Grazing area: 200 ha.

Lactation length: 304 days (Aug. through to May).

Milking times: 6–8 am; 4–6 pm.

Rotation lengths: Spring—15 days; summer 30 days; autumn 21 days; winter 30 days.

- Spring—cows graze during the day and overnight—then return in 15 days, from Sept. 1 to Nov. 30.
- Summer—cows graze for 2 days and nights—then return in 30 days from Dec. 1 to Mar. 31.
- Autumn—cows graze for 2 days and 1 night—then return in 21 days from Apr. 1 to May 31.
- Winter—cows graze for 2 days and nights—then return in 30 days from Jun. 1 to Aug. 31.

Number of paddocks: 55 paddocks.

[1] Refers to where cows graze as part of their lactation. Note: not including night paddocks.

[2] Average area = 200 ha over 55 paddocks.

[3] ρ = Number of cows ha^{-1}; based on the size of the location.

[4] Dn = Number of hours for each visit on a per day basis; Dn_{sp} = 8 (day) + 12 (night) = 20; Dn_{su} = 16 (day) + 24 (night) = 40; Dn_a = 16 (day) +12 (night) = 28; Dn_w = 16 (day) + 24 (night) = 40.

[5] *F* = Number of visits for lactation.

F_{sp} = 7 visits; F_{su} = 4 visits; F_a = 3 visits; F_w = 3 visits.

Assumptions

Dung deposition cow^{-1} day^{-1}: 12 pads (James et al.)[72].

Average dung dry wt: 0.2 kg pad^{-1} (Haynes and Williams[41], Aarons[44]).

Average dung P, N concentration: 0.62, 2.69% respectively (Aarons[44]; see Fig. 3).

Average *E. coli* concentration: 10^9 cells dung pat^{-1}.

[6] *Calculations of contaminant deposition per cow*

Total P dung deposit^{-1} = 0.2 × 0.62% = 0.00124 kg.

Total P deposited cow^{-1} day^{-1} = 0.2 × 12 × 0.62% = 0.01488 kg.

Total N dung deposit^{-1} = 0.2 × 2.69% = 0.00538 kg.

Total N deposited cow^{-1} day^{-1} = 0.2 × 12 × 2.69% = 0.06456 kg.

Total *E. coli* cells deposit^{-1} = 10^9 cells.

Total *E. coli* deposited cow^{-1} day^{-1} = $10^9 \times 12 = 1.2 \times 10^{10}$.

[7] Non-random deposits influenced by animal behavior also occur in camp areas (e.g., water points, shade/shelter, topographical features in the landscape), laneways and feedpads. Contaminant deposition in these areas has not been calculated.

[8] Non-random deposits influenced by grazing management also include strip-grazing and conservation paddocks. Contaminant deposition in these areas has not been calculated.

[9] If the area is known of the part of the dairy shed where excreta is deposited and collected, then loading rates on an area basis can be calculated.

waterway. However, changed management both of the riparian zone and upland areas is recommended, with changes to typical day-to-day farm activities required to augment the effectiveness of established buffer strips in attenuating losses from fields[37,77,78]. The effectiveness of changed management depends on the extent of direct and indirect land-use impacts, how effectively these impacts can be moderated and how much of the riparian zone is appropriately managed.

Upland management

Diminishing losses from non-random excretal deposition may require infrastructure to contain and improve the collection and storage of excreta from feed pads and stand-off areas[79], changing paddock grazing management to restrict the time cows graze cropland or pasture in winter, and providing alternate water sources and managing forages to control where cows camp[15,18,62]. Targeted applications of fertilizer or effluent at times when runoff is less likely to occur, based on soil testing[80,81] and considering the solubility of the fertilizers used[18,62], will minimize non-point sources of nutrients. Likewise, conservation tillage practices can reduce sediment and particulate nutrient losses[82]. However, the impacts from random deposition of dung on grazed paddocks are less easily managed through improved farm practice.

Riparian management

Within riparian areas practices similar to those for upland areas apply[79–81]. However, there are little data in the literature supporting the on-site and catchment benefits to be accrued from implementing grazing best management practices. In one such study McDowell et al.[26] suggest that total P losses could decrease by one-third when animals are moved away from riparian areas, based on dung P comprising between 25 and 36% of estimated total P losses. However, Agouridis et al.[15] recommend critical investigation of grazing best management practices that are expected to deliver enhanced water quality.

Buffers. Riparian buffers (or variously named, riparian forest buffers, vegetated buffer strips, grass filter strips, vegetated filter strips, etc.) offer opportunities to reduce nutrient and pathogen losses to waterways while improving biodiversity values. However, fencing, buffer widths, species selection and the configuration and management of these strips are design issues that can greatly influence how effectively riparian buffers mitigate the impacts of grazed dairy systems[77,83,84].

Fencing. In addition to improvements in water quality[62,79,85], fenced revegetated riparian zones had significantly greater native small mammals, birds and vegetation compared with unfenced grazed sites[34]. However, the lost production associated with fencing riparian buffer areas[15] as well as fencing costs are often considered a substantial disincentive for many farmers[86]. In the associated study riparian pasture production was, on average, 25% greater than that on more elevated parts of three dairy farms and was considered a valuable feed source by farmers[86]. However, the fenced pasture represented only 0.2–1.7% of that available for milk production. These farmers indicated that fencing riparian areas improved herd management; specifically less time spent locating stock. Improvements in animal health and production from minimizing access to contaminated water are also likely. Despite the production and management benefits, how readily farmers fence and revegetate riparian zones often depends on the width of the zone to be managed.

Widths. The width of the fenced zone will greatly influence the effectiveness of the riparian buffer; however, there is little consensus in the literature as to the optimum width. Widths of as little as a meter were suggested to be of some benefit to the environment, trapping sediment as well as soluble nutrients if infiltration is increased[77]. However, Collins et al.[87] recommended buffer widths of greater than 5 metres to increase the entrapment of *E. coli* and *Campylobacter* under high flow rates. In contrast, McNeill[61] suggested that although buffers up to 30 m decreased bacterial concentrations in runoff, they were not adequate to meet water quality guidelines.

Grass buffers were reported to retain most sediment in the first 5 m, while over 15 m was required to decrease bioavailable P by more than 60%[78]. These authors recommend basing riparian grass buffer widths on the ratio of the buffer strip area to the source area, especially where topography concentrates water flow toward the buffer zone. While results in the literature are variable, they generally indicate that high ratios are better suited to attenuating nutrient loss from arable (i.e., cultivated) land especially in high-flow events. However, concentration of water flow through buffers can mean that the effective buffer area is considerably smaller than the gross buffer area, substantially reducing the sediment trapping capacity of the buffer[88]. In addition, this effectiveness is further reduced by soil compaction[78].

Narrow-fenced buffers are also less suitable from an ecological point of view as fencing recommendations for the creation of wildlife corridors are invariably much greater[89]. Recommended widths for most birds (including large birds of prey) and animals are 50–100 m[90,91]. Price et al.[91], recognizing the impracticality of these widths, suggest islands of 50–80 m with 20 m corridors in the intervening space.

Vegetation. Forested riparian buffers potentially create the most variable and hence ecologically favorable habitats. Consequently, restoration of riparian forests is frequently preferred from a biodiversity point of view[92], although Osbourne and Kovacic[84] suggest that grass riparian buffers also fulfill this function in the mid-Western United States. Forested riparian buffer zones generally increase water infiltration, reduce sediment loss from the surrounding land and promote sediment deposition and nutrient retention[84,93–98]. For example, average sediment loss declined by an order of magnitude after establishment of a forested riparian buffer. Phosphorus and N loss in runoff from agricultural land can also be significantly reduced; N more so than P. Groundwater nitrate is removed either through plant uptake via tree roots or denitrification processes in the soil although this was dependent on the depth to the water table[84,94,99]. In addition, the forested vegetation contributes terrestrial and aquatic (woody debris and snags) habitat, patch connectivity and reduces dieback of remnant vegetation[15,28,100].

Despite the benefits mentioned above, the presence of a riparian forest buffer is not always beneficial to water quality. Total P export remained the same after fencing and establishment of a *Eucalyptus* forest buffer but the proportion of reactive P increased[96]. Osbourne and Kovacic[84] reported increased total and dissolved P concentrations in shallow lysimeters below riparian forests compared with crop land where these were located immediately adjacent to a waterway. Forested riparian buffers can also result in reduced ground and lower storey vegetation as the tree canopy closes[38,101] leading to greater surface water movement through the riparian zone[71,102]. However, the improved hydraulic conductivity of forested riparian soils may compensate for the greater overland flow[33]. Reduced water yield, due to increased transpiration by trees may also decrease the extent of wetlands as well as in-stream vegetation contributing to higher stream baseflow nitrate concentrations[71], although groundwater nitrate declined under trees[84].

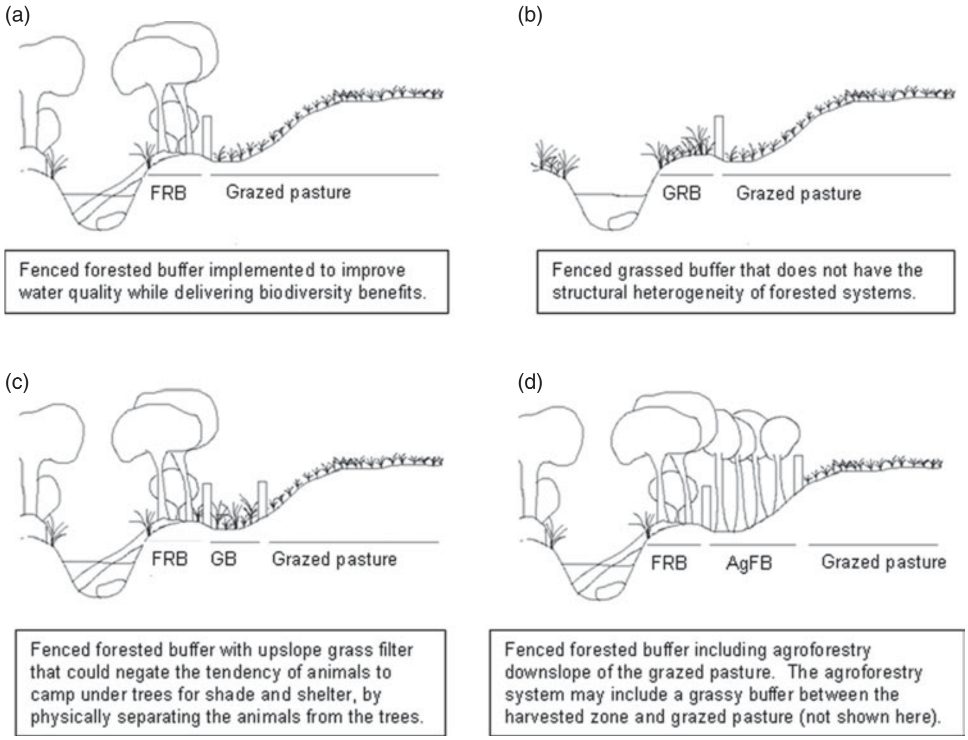
The tendency of cows to seek shade and shelter and to graze near to waterways may further decrease the effectiveness of forested riparian buffers. Contaminant transport could readily occur in conditions of infiltration-excess or saturation-excess overland flow[103], while shallow groundwater would provide a translocation pathway for nitrate-N from urine and dung. Areas of bare ground such as gateways, water troughs and feeding areas may position high contaminant areas within a few meters of a forested buffer which may be incapable of attenuating the pollutant threat to the waterway. Monaghan et al.[104] observed that although areas used for dairy wintering occupied only 10% of the catchment area, they contributed up to 60% of modeled N losses. Greater concentrations and loads of *Cryptosporidium* oocytes were recovered in runoff from fecal pads created on bare soil blocks compared with blocks with more than 90% vegetated cover[59], particularly during low-intensity rainfall events of long duration. The distance the oocytes moved depended on topography and vegetative cover. While bacterial loads declined by 95% when fecal deposits were located a minimum of 2.5 m from the waterway, this could still result in 5×10^4 MPN 100 ml^{-1} reaching the waterway in runoff from each fecal deposit[15,60].

An alternative to riparian forest buffers is grass buffer strips, which have been shown to significantly reduce nutrient and sediment losses[105,106] through increased infiltration, sediment deposition and filtration processes[83,107]. For example, the continual cover and growth afforded by perennial grasses reduced runoff volume and velocity through absorption of up to 90% of the shear stress[78]. The grass cover also decreases raindrop impact with a minimum of 70% cover recommended to control hillslope erosion and dense ground cover required to prevent gully erosion, especially at degraded sites. Adsorption of colloidal particles to grass is likely to contribute to very minor nutrient trapping while hillslope and gully erosion control reduces loss of organically bound N and P as well as particulate P[83].

As with forest buffers, denitrification and/or plant uptake can slow nutrient loss in grass buffer strips. These processes require long retention times within the grassy buffer. However, it is important to note that the effectiveness of a grass buffer depends on its vegetative structure, width, soil type, position in the landscape and management, and will vary from time to time[78,89]. For instance, N leaching is increased under pastures with a clover component[14,15], while P retention in a grass buffer can vary seasonally and may decline over the longer term. Additionally, resistance to flow decreases if vegetation is submerged or if grass height is too great leading to lodging and increased water movement via preferential routes[78].

The historical debate regarding the most appropriate vegetation for riparian zones[99,108] continues. Dosskey et al.[109] compared the effectiveness of grass and forest (half-trees and shrubs, half-grass) buffers and observed no difference between the two types in the first ten growing seasons, due primarily to the similarity in ground cover. The greatest improvement occurred in the infiltration capacity of the filters, while some improvement in sediment deposition and little or no difference in dilution processes were observed. Alternatively, grass buffers were more effective than *Eucalyptus* buffers at reducing nutrient and sediment movement from sheep-grazed pasture. No runoff was recorded in the grass buffer in summer, while the forested buffer functioned as a sediment source throughout the year[102,103]. Soils under the eucalypt buffers appeared to have developed a surface crust, due to ploughing and subsequent compaction, which lowered infiltration. In contrast, Cooper et al.[33] found that the saturated hydraulic conductivity of native forest and set-aside riparian areas was at least 6 times greater than that of grazed riparian land, most likely due to the natural recovery of soil physical properties when grazing animals are excluded[39].

The set-aside soils had larger pools of bioavailable P, although they had not received P fertilizer for 12 years. In a review of a number of studies, median total P declined by 15% under riparian forest buffers compared with decreases of 50% for grass filter strips, while median dissolved P losses were greater under forest filters (60%) than grass filter strips (30%)[80]. Osbourne and Kovacic[84]



Fenced forested buffer implemented to improve water quality while delivering biodiversity benefits.

Fenced grassed buffer that does not have the structural heterogeneity of forested systems.

Fenced forested buffer with upslope grass filter that could negate the tendency of animals to camp under trees for shade and shelter, by physically separating the animals from the trees.

Fenced forested buffer including agroforestry downslope of the grazed pasture. The agroforestry system may include a grassy buffer between the harvested zone and grazed pasture (not shown here).

Figure 4. Different configurations of riparian buffer strips that can be used on grazed dairy farms to mitigate contamination of waterways. FRB, forested (native vegetation) riparian buffer; GRB, grassed riparian buffer; GB, grassed buffer (may be strategically grazed or mechanically harvested; AgFB, agroforestry (native or exotic) buffer.

reported that grass buffers more effectively reduced total and dissolved P losses, although the trees assimilated more nitrate-N.

Alternative riparian management and configuration

A well-managed pasture that is not overgrazed could constitute a grass filter strip. Strategic grazing of grass buffer zones[110] at lower stock intensities during the drier months of the year would contribute carbon inputs in feces that may sustain long-term denitrification requirements of these areas[39,40,99], although stock access should be restricted during the wetter months. Lower fertilizer use in the grassy buffer strips and incorporation of native grasses can contribute to increased biodiversity values, although native grasses do benefit from small additions of fertilizer (M. Mitchell, pers. comm.). An alternative to strategic grazing is to use the grass buffer strips for fodder conservation and withhold grazing from these areas, particularly as mechanical harvesting contributes less soil physical damage than grazing[39]. Buffers such as these can be placed downslope of summer fodder crops or reseeded pastures[77].

An alternative riparian configuration is the combination of a grassed buffer strip managed alongside and upslope of a forested riparian buffer (Fig. 4). A three-zone riparian forest buffer system incorporating an agroforestry zone is the recommended approach for establishing riparian buffers in the USA[77,111]. The forests are managed as a source of additional on-farm income with the advantage of increasing the area revegetated alongside rivers and streams. Water quality was not compromised by harvesting timbers within this 45–55 m zone (zone 2) located between an 8 m grass filter strip upslope (zone 3) and a 10 m permanently forested zone downslope (zone 1) and adjacent to the river. Grass buffers in conjunction with forest filter strips should eliminate virtually all sediment and associated nutrient loss, as these strips can each trap in excess of 90% of sediment loss from agricultural sources[107].

Naiman and Décamps[30], as well as researchers at Iowa State University and the University of Missouri Center for Agroforestry[112], also describe 'multi-species' riparian buffers consisting of three zones (albeit of different widths) where the function of the two zones closest to the river is to maximize contaminant removal, while the third zone slows water movement, thereby contributing to coarse sediment deposition. Infrequent harvest of the second zone improves the functions of zone 1, suggesting that appropriately managed agroforestry would improve environmental outcomes.

Despite the potential economic benefit and subsequent incentive for farmers to implement a zoned approach to improving riparian management, current agroforestry codes of practice discourage the harvesting of riparian forest buffers in Brazil and many states in Australia. The converse is true for Germany and the USA where many farmers adopt riparian forest buffers for both environmental and economic benefit[113,114]. Water quality concerns associated with harvesting (i.e., logging) appear to influence theses codes of practice for riparian forestry. Dominant sediment sources, the general harvesting area and buffer widths are important management factors for protecting waterways from logging operations[115,116]. However, a number of planning tools for determining optimum widths and placement of riparian buffers have been developed[117–119].

An additional riparian buffer configuration is the installation of wetlands to manage nutrient losses in cases where subsurface flow dominates transport processes, as recommend by Osbourne and Kovacic[84]. Wetlands should be designed to maximize retention times based on the contaminant of concern and can be very effective in reducing nutrient losses to waterways[93,120]. This approach was adopted downslope of cropping in the riparian management system, but apparently not considered for grazed pastures[112], despite nutrient losses in drainage from grazed pastures[18,62,76].

Future Research Needs

Decreasing the environmental impact of intensive grazed dairy systems requires quantification of the nutrient inputs, flows and inefficiencies in these systems, and integration of these with hillslope–riparian–stream source transport models for N and P to better manage upland nutrient sources[18,22,26,62,66]. Improving the efficiency of nutrient use by dairy cows is an important first step[121], particularly the relationship between nutrient intake and excretion in grazing systems, where pasture intake can be less accurately defined. Dietary intake may then be manipulated to reduce nutrient loading rates. When linked to the distribution of animals throughout the landscape, the extent of nutrient loss to the environment from diffuse or point sources can be more accurately quantified and better managed.

While fencing waterways to exclude stock is important the width, vegetation types and configuration of fenced zones in grazed systems need to be examined to ensure improved catchment outcomes. The suitability of the buffer area/source zone ratio should be tested as one means of determining appropriate widths for grazing systems[78]. Ideally the effectiveness of these ratios should be measured downslope of grazed pastures, grazed forage cropland, and nutrient accumulation areas such as waterpoints or gateways. Vegetation types for fenced riparian zones to meet ecological and water quality requirements, and the suitability of multi-zone riparian buffer systems that incorporate a grassy filter strip with a forested buffer need to be evaluated. A configuration to be tested in grazing systems could also include the three-zone system recommended by the NRC for cropping systems[77,112] and incorporate wetlands to manage subsurface flow in drains[121].

Whichever configuration is identified as most suitable, both the short- and long-term effectiveness of the selected riparian buffer will need to be assessed, particularly using widths typical of those used by farmers[89]. These assessments will give farmers and natural resource managers confidence that recommendations will not contribute to environmental degradation in the future. One approach is to compare sites that are grazed, have been fenced or are undisturbed to measure differences due to changed management over time[33,34]. An alternative is to establish grass and forested buffers and measure their effectiveness at attenuating sediment and nutrient loss over time compared with established grass or cropland[109]. The latter approach has the disadvantage of requiring a longer study period for the experimental design. In addition, year-to-year variation may confound results. For example, Dosskey et al.[109] could not explain the unexpected nitrate and nitrite–N enrichment observed in the first season of a study investigating the effectiveness of filter strips in mitigating surface runoff losses. In contrast, taking measurements at different sites that have previously had fencing/vegetation treatments imposed has the benefit of more rapid assessment, although confounding location differences will have to be carefully managed. Rainfall simulators are often used to facilitate runoff measurement. However, the higher rainfall intensities used often result in infiltration-excess overland flow, rather than saturation-excess overland flow, influencing runoff sediment and nutrient concentrations and the conclusions that can be drawn for pasture systems[66,102,103].

Monitoring riparian soil P status, including the P sorption characteristics of different soil horizons is recommended as a means of determining when fenced riparian strips are approaching P saturation, and therefore the possibility of releasing P to the environment[74,122]. This method should be tested on a range of soils in fenced riparian zones to determine the potential for P saturation of these areas. The effectiveness of grazing or harvesting to mine soil P, or mixing topsoils with subsoils needs to be evaluated, especially those using dairy cows for P removal.

Conclusions

Grazing systems are largely defined by cow movement in the landscape. The density of animals, frequency and duration of visits are a function of animal behavior and grazing management practices, which influence random and non-random deposition of excreta around the farm. Consequently, grazed dairy systems are likely to contribute to waterway and catchment degradation differently to confined dairy operations.

The preference of cows to camp near forested areas and the deposition of feces and urine with high nutrient and bacterial loads cast doubt on water quality improvements expected for current recommendations for fencing and revegetating riparian zones in grazed dairy systems. While forested and grassy buffers can potentially improve water quality, a combination configuration is recommended to meet ecological and biodiversity requirements while minimizing contaminant loss from grazed dairy farms and contributing to farm productivity. However, appropriately designed experiments are required to elucidate their effectiveness in the long term and in comparison with current recommendations. To have widespread applicability, these experiments need to take into consideration different topographies, runoff intensities and source areas (camp areas versus grazed pasture) and investigate sediment, nutrient and pathogen retention.

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