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Doctoral Dissertation

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Abstract

Practices, such as outdoor yards for cattle exercise, forested feedlots for cattle raising and slurry application to grass fields, have become more common during the last two decades on cattle farms. At the same time, untilled buffer zones have been established between source fields and water courses for the removal of sediment and nutrients from surface runoff. This thesis sums up studies on phosphorus (P) and nitrogen (N) losses to water from forested feedlots and slurry-amended grass fields. Moreover, different ways of mitigating the losses in a boreal climate are discussed. Studies were conducted in 1996–2008 at Jokioinen, Tohmajärvi, Ruukki and Taivalkoski.

Water samples representing surface runoff were collected from open ditches and analysed e.g. for total solids (sediment) as well as total P (TP), dissolved reactive P (DRP) and total N (TN) to estimate nutrient losses from forested feedlots with different stocking rates (animal units per hectare, AU ha^{-1}) and from slurry-amended grass. Surface runoff samples were similarly analysed to evaluate the efficacy of 10 m wide buffer zones to decrease and retain nutrient losses from pasture and tilled soil. The soil was sampled for plant-available P and mineral nitrogen (SMN) analyses.

Fairly high TP (0.9–1.4 kg ha^{-1} yr^{-1}) and TN (4–16 kg ha^{-1} yr^{-1}) losses occurred in ditch water from forested feedlots where cattle had been reared for 1–3 years. These amounts correspond to the annual losses from cropped fields. The plant-available P (up to 20 mg L^{-1}) in surface soil and the amount of SMN (up to 100–400 kg ha^{-1}) in the 60 cm deep soil layer were highest in places where the cattle gathered, such as bedded and feeding areas (called high-input areas). On coarse-textured soils, common in central and western Finland, there is a risk that NO_3-N is leached from high-input areas into the ground water. Removal of dung from the bedded and feeding areas resulted in lower nutrient amounts in soil as well as lower P and N losses to water.

High losses of TP and DRP (4.4 and 3.6 kg ha^{-1} yr^{-1}, respectively) also occurred in surface runoff from the grass fields where surface application of slurry (40 t ha^{-1}) in autumn was followed by rainfall. Injection of the slurry into the soil decreased TP and DRP losses by 79 and 86%, respectively. Injection may, however, enhance

N leaching into drainage water on coarse-textured soils.

The buffer zones along watercourses were less important in the grazed field than in autumn-tilled soil due to the smaller erosion and nutrient losses from grass than from tilled soil. The surface runoff losses of sediment, TP and TN decreased by more than 50, 30 and 50%, respectively, by buffer zones on tilled soil. In spring, the implementation of buffer zones even increased the losses of DRP, but mowing and removing the residue from the buffer zones effectively decreased the DRP losses in surface runoff.

Nutrient losses on cattle farms can be mitigated by removing dung from the areas of forested feedlots with high stocking rates (> 5 AU ha^{-1} yr^{-1}) using injection of slurry instead of broadcasting, and establishing buffer zones between source areas and watercourses.

Key words:
nitrogen, phosphorus, surface runoff, slurry, outdoor production, domestic cattle, riparian zones, pastures, direct drilling, ploughing, erosion, loading

Ulkokasvatuksen, lannan levityksen sekä suojavyöhykkeiden vaikutus fosfori- ja typpivalumiin suomalaisilla nautakarjatiloilla

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Tiivistelmä

Nautakarjatalous on muuttunut kahtena viime vuosikymmenenä samalla, kun tilakoko ja eläinmäärät tiloilla ovat kasvaneet. Esimerkiksi nautojen ulkoiluttaminen tarhoissa ja ulkokasvatus sekä lietelannan levitys nurmeen ovat yleistyneet. Näistä toimenpiteistä aiheutuva vesistökuormitus tunnetaan pohjoisissa olosuhteissa huonosti. Viime vuosina on myös perustettu suojavyöhykkeitä pellon ja vesistön väliin pidättämään pellolta pintavalunnan mukana kulkeutuvia ravinteita ja maa-ainesta. Tässä tutkimuksessa käsitellään ulkokasvatuksesta ja lietelannan levityksestä nurmeen aiheutuvaa vesistökuormitusta fosforin ja typen osalta sekä kuormituksen vähentämiskeinoja. Kokeet toteutettiin Jokioisissa, Tohmajärvellä, Ruukissa ja Taivalkoskella vuosina 1996–2008.

Tutkimuksessa arvioitiin ravinnekuormituksen suuruutta metsätarhoista eri eläintiheyksillä (eläinyksikköä hehtaarilla vuodessa, ey ha^{-1} v^{-1}) ja lietelannalla lannoitetuilta nurmilta sekä pellon ja vesistön välille perustetun suojavyöhykkeen kykyä vähentää kuormitusta määrittämällä ravinnepitoisuudet valumavesi- ja maanäytteistä. Vesinäytteistä määritettiin muun muassa maa-aineksen, liuenneen fosforin, kokonaisfosforin ja -typen pitoisuudet sekä maanäytteistä viljavuusfosfori ja maan mineraalityppi.

Melko suuria kokonaisfosforin (0,9–1,4 kg ha^{-1} v^{-1}) ja kokonaistypen (4–16 kg ha^{-1} v^{-1}) kulkeumia havaittiin nautojen ulkotarhoista valuvista ojavesistä, kun karjaa oli tarhattu 1–3 vuotta. Määrät vastaavat peltoviljelystä aiheutuvaa kuormitusta. Suurimmat fosforin pitoisuudet (20 mg l^{-1}) pintamaassa sekä mineraalitypen määrät (100–400 kg ha^{-1}) 60 cm:n maakerroksessa mitattiin ruokinta- ja makuupaikoilla, joissa karja kokoontui ja eläintiheys ylitti 5 ey ha^{-1} v^{-1}. Karkeille moreenimaille perustetuissa metsätarhoissa typpeä todennäköisesti huuhtoutui näistä karjan kokoontumispaikoista. Lannan poistaminen ruokinta- ja makuualueilta vähensi tarhoista aiheutuvaa ravinnekuormitusta.

Suuria kokonaisfosforin (4,4 kg ha^{-1} v^{-1}) ja liuenneen fosforin (3,6 kg ha^{-1} v^{-1}) määriä havaittiin myös nurmen pintavalunnasta, kun lietelantaa oli levitetty nurmen pintaan syksyllä ennen sateita. Lietelannan sijoittaminen maahan vähensi 79 % kokonaisfosforin ja 86 % liuenneen fosforin

kuormitusta. Karkeilla mailla niiltä nurmilta, joille lietelanta oli sijoitettu, saattoi huuhtoutua liukoisia ravinteita myös pohjaveteen.

Vesistöjen varsille perustetut suojavyöhykkeet olivat tarpeellisia syysmuokatuilla mailla. Ne poistivat savimaalla yli 50 % pintavalunnan maa-aineksesta, 30 % kokonaisfosforista ja 50 % kokonaistypestä. Laitumella suojavyöhykkeestä saatu hyöty oli pienempi kuin syysmuokatulla maalla, koska eroosio ja ravinnekuormitus olivat nurmelta pienempiä kuin muokatulta maalta.

Nautakarjatilalla ravinnekuormitusta voidaan pienentää poistamalla lantaa ulkotarhoista, sijoittamalla lietelanta nurmeen pintalevityksen sijasta sekä perustamalla kuormittavan alueen ja vesialueen väliin suojavyöhykkeen.

Avainsanat:
typpi, fosfori, pintavalunta, lietelanta, ulkokasvatus, nauta, suojavyöhykkeet, laitumet, suorakylvö, kyntäminen, eroosio, kuormitus

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Humppila, January 2010

Jaana Uusi-Kämppä

List of original publications

This thesis is a summary and discussion of the results of the following articles, which are referred to by their Roman numerals:

I **Uusi-Kämppä, J. 2002.** Nitrogen and phosphorus losses from a feedlot for suckler cows. Agricultural and Food Science in Finland 11:355–369.

II **Uusi-Kämppä, J., Jauhiainen, L. & Huuskonen, A. 2007.** Phosphorus and nitrogen losses to surface waters from a forested feedlot for bulls in Finland. Soil Use and Management 23:82–91.

III **Uusi-Kämppä, J. & Heinonen-Tanski, H. 2008.** Evaluating slurry broadcasting and injection to ley for phosphorus losses and fecal microorganisms in surface runoff. Journal of Environmental Quality 37:2339–2350.

IV **Uusi-Kämppä, J. & Mattila, P. K.** Nitrogen losses after cattle slurry broadcast and shallow injection to grass ley. Submitted to Agricultural and Food Science.

V **Uusi-Kämppä, J. 2005.** Phosphorus purification in buffer zones in cold climates. In: Mander, Ű., Kuusemets, V. & Hayakawa, Y. (Eds.) Special Issue: Riparian Buffer Zones in Agricultural Watersheds. Ecological Engineering 24:491–502.

VI **Uusi-Kämppä, J. & Jauhiainen, L. 2010.** Long-term monitoring of buffer zone efficiency under different cultivation techniques in boreal conditions. Agriculture, Ecosystems and Environment. In press. doi:10.10.16/j.agee.2010.01.002

Feedlot studies were planned together with Adjunct Professor M. Manninen at Tohmajärvi and Dr. A. Huuskonen at Ruukkia and Taivalkoski and conducted by J. Uusi-Kämppä. The experiment on slurry application to grass was planned together with the late Professor P. Elonen and conducted by J. Uusi-Kämppä. Adjunct Professor H. Heinonen-Tanski and Dr. P.K. Mattila were responsible for the microbial analyses and the trial of ammonia volatilization from cattle slurry, respectively. The buffer zone experiments were started together with Adjunct Professor T. Yläranta, and J. Uusi-Kämppä conducted the experiments. The papers/manuscripts were prepared by the corresponding author and revised according to the comments and suggestions of the respective co-author and reviewers. Papers III–IV and VI were also revised by Professor E. Turtola and Adjunct Professor H. Heinonen-Tanski. Biometrician L. Jauhiainen, M.Sc., was responsible for methods and analyses in the experiments. The publications were reprinted with the kind permission of the respective copyright owners.

Abbrevations

AU	animal unit
B	broadcast
DRP	dissolved (<0.2 or 0.45 μm) molybdate-reactive phosphorus
GBZ	grass buffer zone
IN	injection
NBZ	no-buffer zone
P_{Ac}	plant-available P extracted with 0.5 M acetic acid-0.5 M ammonium acetate at pH4.65 (soil P)
PP	particulate phosphorus in water
SMN	soil mineral nitrogen
TN	total nitrogen in water, soil, plants and slurry
TP	total phosphorus in water, soil, plants and slurry
TS	total solids in water
VBZ	vegetated buffer zone

Contents

1 Introduction

1.1 Background

The water pollution load is of great concern for the Finnish environment since it causes eutrophication and algae blooming in water bodies. Although only around 7% of the area of Finland is cultivated, agriculture is the largest single source of anthropogenic phosphorus (P) and nitrogen (N) loads to water, causing eutrophication in freshwater lakes and coastal waters of the Baltic Sea (Kauppila and Bäck 2001, Mitikka and Ekholm 2003, Ekholm et al. 2007). Although efforts have been made to mitigate erosion and nutrient losses by different measures presented in EU Agri-Environmental Programmes, no clear reduction in loading or improvement in water quality has been detected (Ekholm et al. 2007). One reason for this may be the specialisation of agriculture into different production fields (e.g. crop, dairy and beef production) and their concentration to certain areas (Huhtanen et al. 2009).

Agricultural nutrient loading mainly originates from diffuse sources for which treatment is not as realistic as it is for point-source waters due to large source areas, huge seasonal water volumes with high variation and generally smaller nutrient concentrations. Phosphorus is often the limiting factor regulating the growth of algae and cyanobacteria in lakes, whereas N tends to be the limiting factor in coastal waters (Tamminen and Andersen 2007). Agricultural P losses are generally divided into DRP and PP fractions, these fractions are operationally defined by filtration and may differ e.g. in sources, pathways and bioavailability. Nitrogen losses include mostly mobile nitrate NO_3^--N (NO-N; hereafter NO_3-N), and ammonium N (NH_4^+-N; hereafter NH_4-N), the latter being generally lower due to efficient adsorption into the soil and nitrification. In addition to this, there are also organic N and P in soil and soil water, originating mostly from plant residues and manure.

1.1.1 Expansion and concentration of farms

While many small dairy farms have shut down milk production, the animal density and percentage of livestock farms have increased in certain regions in Ostrobothnia (Western Finland) and in South and North Savo (central Finland) during recent decades (Valpasvuo-Jaatinen et al. 1997, Information Centre of the Ministry of Agriculture and Forestry 2007). Between 1995 and 2009, the number of dairy farms in Finland fell by 62% (Fig. 1), but the total number of dairy cows declined only by 27%. The number of livestock farms with more than 50 dairy cows exceeded 580 in 2006, while it was approximately 30 in 1995 when Finland became a member of the EU (Information Centre of the Ministry of Agriculture and Forestry 1996, 2007). The largest dairy farms (>100 AU) are generally located in western and central Finland. The recent growth in the size of livestock farms, their concentration in certain regions and high animal density are of concern in terms of contamination of nutrients in runoff.

Cereal production covers 52% and grass cultivation 28% of the utilized agricultural area (2,295,900 ha) in Finland, the rest being other crops (8%) and fallow or in other use (12%) (Information Centre of the Ministry of Agriculture and Forestry 2009). Cereal production is concentrated on clay soils in southern and south-western Finland. The area of grassland decreased by 15% in Finland between 1995 and 2009. The number of cattle per grassland decreased during the last decades when the number of cattle and total area of grassland are taken into account (Fig. 2). The number of pastured animals per forage area averages 1.2 and 1.7 AU ha^{-1} in Finland and in the EU countries, respectively (MTT 2010). In central Finland, the

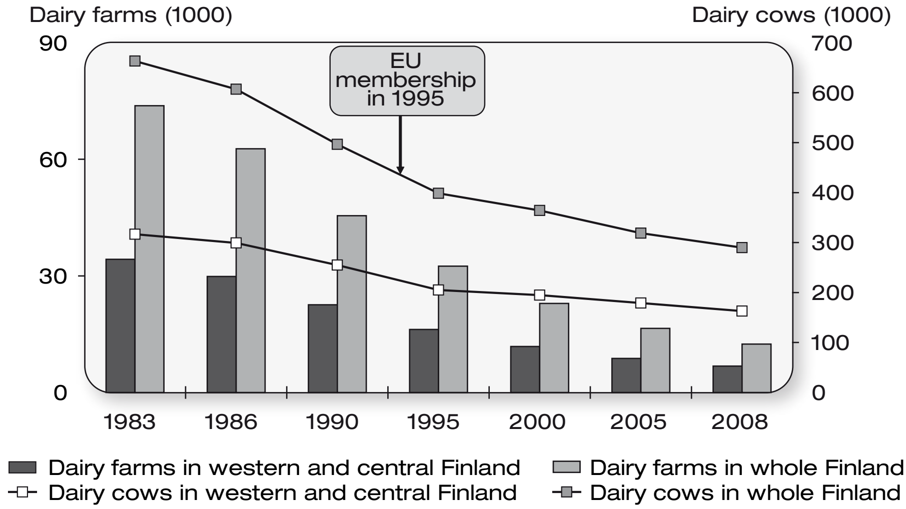

Figure 1. Number of dairy cows and dairy farms in whole Finland, and in western (Ostrobothnia) and central (Savo) Finland between 1983–2008. (National Board of Agriculture 1986, 1987, 1991 and Information Centre of the Ministry of Agriculture and Forestry 1996, 2009).

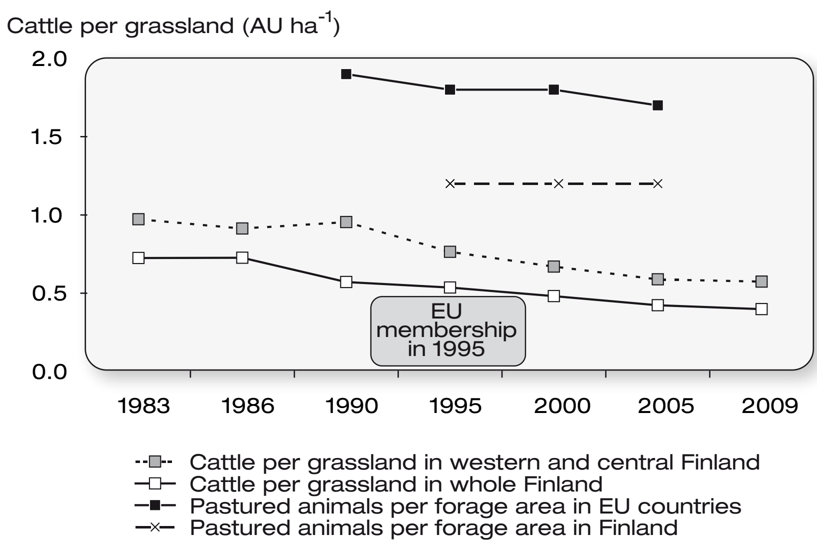

Figure 2. Cattle per grassland in whole Finland, and in western (Ostrobothnia) and central (Savo) Finland between 1983–2009 (National Board of Agriculture 1986, 1987, 1991 and Information Centre of the Ministry of Agriculture and Forestry 1996, 2009) and pastured animals per forage area in EU countries and in Finland (MTT 2010).

soil texture is mostly silt and fine sand, and in the north, peat soils and mineral soils rich in organic matter are common. Dairy farming is most common in central and western Finland where up to 30–60% of the cultivated area can be in grass production. The total pasture area of the whole country is around 80,000 ha (Information Centre of the Ministry of Agriculture and Forestry 2009).

1.1.2 Outdoor production and exercise yards

In boreal areas, cattle have been traditionally kept indoors in winter due to cold weather and snow, whereas in summer, heifers and dairy cows have been on pasture. In the 1980s and 1990s, dairy cows were kept indoors on some farms also during summer, e.g. due to lack of suitable pastures near the shed. However, legislation governing animal welfare provided that since summer 2006 heifers and dairy cows must be allowed to be on pasture or, failing this, another space must be provided to allow the animals to move around. Therefore, outdoor exercise yards were constructed for dairy cows and heifers on cattle farms.

During the last decade, the animal units have increased on dairy farms and new loose-housing barns have been built. Because dairy cows are allowed to walk around inside this new kind of barn, it is not required that the cows in loose-housing barns should still have an opportunity to get out on pasture. On the other hand, on organic farms, cattle are allowed to go out also in the winter months. It has been estimated that there were around 200 exercise yards and outdoor feedlots in Finland at the beginning of the millennium (Puumala et al. 2002). In a study of 100 large Finnish dairy barns, it was presented that 25% of the farms with more than 40 dairy cows had a yard or a small pasture for the exercise of cattle (Kivinen et al. 2007). Thus it can be estimated that around 300 dairy farms had an exercise yard in 2006. The yards were used by approximately 17,000 cows, accounting for more than 10% of the dairy cows in Finland.

Recently, beef animals have been grown outdoors the year round. For example in Taivalkoski, in north-eastern Finland, 25–30 dairy farms have raised young cattle extensively in forest land (0.1 AU ha^{-1}). Suckler cows are also sometimes kept outdoors in forested feedlots in winter months (Manninen 2007). Outdoor production systems for cattle are thus becoming more common in Finland during the winter as well as other seasons (Kauppinen 2000). There is, however, little information available on how to build a good feedlot or exercise yard and on their environmental effects.

1.1.3 Manure management

From the P and N amounts in cattle manure (Ministry of Environment 1989, 2009) and number of cattle (Information Centre of the Ministry of Agriculture and Forestry 2009), the estimated annual slurry P and N amounts are 9000 t and 50,000 t, respectively. The manure P and N amounts are high since up to 70% of the dietary P and N of dairy cows may be excreted in faeces and urine (Huhtanen et al. 2008, Nousiainen et al. 2003, Yrjänen et al. 2003). The manure is mostly applied to the farmer's own fields or to neighbouring farms, and depending on farm-specific practices, a small part of it is dropped on pastures, exercise yards and forested feedlots. At present, many dairy farms prefer continuous grass cultivation instead of crop rotation with grasses and cereals. Slurry is, therefore, spread on fields of silage grass instead of using earlier methods where slurry was applied to cereal fields before autumn ploughing or before tillage in spring. Mineral fertilizer is normally surface applied to grass in spring, whereas cattle slurry is applied for the second harvest due to the wetness and compaction risk for fields in spring. If the growing period is wet, it is not possible to spread slurry with heavy machinery on wet soils in summer. Then the slurry tanks must be emptied in the autumn to provide storage capacity for the winter months.

1.1.4 Buffer zones

Establishing buffer zones (also referred to as vegetative filter strips, grass filter strips, buffer strips, filter strips, riparian buffer zones, etc.) between pollutant source areas and receiving waters is a supplementary way of removing sediment, nutrients and other pollutants from surface and near-surface runoff (Young et al. 1980, Dillaha et al. 1989, Ahola 1990). The buffer zones are under permanent plant cover and they are not tilled, fertilized or treated with pesticides. In Finland, buffer zones have become common since 1995 due to implementation of the Agri-Environmental Support Scheme (EEC 1992), with the current total area of 3 m or 15 m wide buffer zones being around 11,000 ha. This Scheme demands 3 m wide buffer zones along watercourses such as lakes, rivers and brooks as well as around household wells, and 1 m wide edges along main ditches. In addition, the establishment of wider, at least 15 m wide riparian buffer zones, on either side of streams, watercourses or designated groundwater areas, may be eligible for financial support (max 450 euros ha^{-1} yr^{-1}). The riparian buffer zone agreements between a farmer and the state last either 5 or 10 years. Around 0.6 m edges are required by law along all open ditches (Finlex 1997). In Finland, buffer zones are also established in forest lands and in peatlands (Väänänen et al. 2006, 2008).

1.2 Aims of the study

The general objective was to estimate the losses of P and N from manure to surface waters when using different practices and to find measures for minimizing these losses. The more specific aims were:

1. To evaluate P and N losses from outdoor feedlots and exercise yards for cattle and how to mitigate the losses to water (I–II).

2. To estimate the potential of slurry injection to reduce losses of P (III) and N (IV) in surface runoff compared to broadcast slurry.

3. To estimate the potential of buffer zones for mitigation of eroded material and nutrients transported from pasture, and compared to that of tilled clay soil (V–VI).

An experiment on P and N losses to water was started in Tohmajärvi feedlot in autumn 1997 (I). During the following two years, the nutrient losses and environmental damages were so high in the feedlot (stocking rate 25 AU ha^{-1}) that the study was continued in a new feedlot (1 AU ha^{-1}) at Ruukki in autumn 1999 (II). Although the stocking rate was small due to the small number of animals (ten bulls) and there was regular dung removal, the nutrient losses were high and the forest vegetation was mostly destroyed near the shed where the cattle were reared. The third study (2002–2004) was, therefore, executed on five private farms at Taivalkoski where young cattle (0.1 AU ha^{-1}) were kept in forested pasture areas.

The purpose of the slurry application study was to compare two different slurry application methods – surface broadcast and shallow injection – on grass fields (III–IV). Surface application is a profitable and commonly-used practice on most dairy farms. In this study, it was investigated whether slurry injection, generally considered difficult to use, especially on stony soils, could provide a more environmentally friendly method under boreal climate. Losses of

TP, DRP, TN, NH_4-N and NO_3-N to water from the surface-applied slurry were compared with losses from injected slurry on a grass field. Volatilisation of NH_3 from autumn applied slurry and N uptake by grass were measured for N balances. The amounts of soil mineral N (SMN; NH_4-N plus NO_3-N) at different depths were determined to allow an estimation of the risk for NO_3 leaching.

Several studies have looked at the efficiency of buffer zones in removing pollutants from agricultural fields and feedlots (e.g. Dillaha et al. 1989, Vought et al. 1991, Syversen 2002). Most of the studies have been short-term experiments using simulated rainfall after slurry application to field plots. On the contrary, in this study an experimental field with natural rainfall and long-term history of measurements on a clay soil at Jokioinen, south-western Finland was used to estimate the efficiency of buffer zones in mitigating sediment and nutrient losses in surface runoff from grazed fields (2003–2005). The results from pasture were compared with the results from conventionally tilled (1991–2002) and directly drilled plots (2006–2008) obtained at the same site before or after the grazing experiment plots (V–VI).

2 Material and methods

2.1 Experimental sites

The experiments were carried out on forested feedlots situated at Tohmajärvi (eastern Finland, I), Ruukki (near the city of Oulu, western Finland, II) and Taivalkoski (north-eastern Finland) and on two experimental fields, Lintupaju and Kotkanoja, at Jokioinen (south-western Finland, III–VI) (Fig. 3). The forest sites consisted mainly of pine (*Pinus sylvestris*) with birch species (*Betula*) and a few spruces (*Picea abies*).

The soil was coarse-textured at the feedlot sites (I–II) and clay in the experimental fields (III–VI) (Table 1). The pH and the concentrations of plant-available P (P_{Ac}), soil mineral nitrogen (SMN) and TN were highest in the cultivated fields at Lintupaju and Kotkanoja (Table 1) and lowest in the virgin soils near the forested feedlots. There was, however, one exception, at Tohmajärvi, the TN was highest (1.3 and 1.0% in the depth of 0–5 and 5–10 cm, respectively) in the soil with high organic C (37 and 33% at the depth of 0–5 and 5–10 cm, respectively).

The estimated stocking rate (Table 2) on the study sites was calculated according to the formula: SR = nFt / 365A

where:

SR = stocking rate (AU ha^{-1} yr^{-1})

n = number of animals

F = factor of animal unit (AU)

t = annual stocking days (d)

A = size of stocking/source area (ha).

The estimated values of P_{Ac} in soil and surface runoff loss of DRP after 20 years management were calculated using the formulas of Ekholm et al. (2005). The formula is

Table 1. Mean soil pH, plant-available P (P_{Ac}), mineral N (SMN), organic C (org. C) and total N (TN) at the experimental sites at the start of the experiment.

Experimental field	Soil type (FAO, 1998, 2006)	Texture	Depth cm	pH	P_{Ac} mg L^{-1}	SMN mg L^{-1}	Org.C %	TN %
Tohmajärvi (I)	Gleyic Dystric Regosol	loam/sandy loam	0–5	3.7	3.0	4.3	37.1	1.28
			5–10	3.8	1.9	3.0	32.6	0.96
			10–20	4.2	0.9	1.5	17.2	0.47
Ruukki (II)	Haplic Arenosol	sandy	0–5	4.5	5.0	2.7	4.3	0.13
			5–30	5.1	3.8	1.0	1.1	0.04
Taivalkoski	–	fine sandy till	0–5	3.9	1.4	1.8	2.8	0.08
			5–30	4.6	0.5	1.1	1.4	0.05
Kotkanoja (III–IV)	Vertic Cambisol	clay	0–10	6.6	9.6	4.5	2.2	0.14
			10–20	6.6	8.4	6.6	2.0	0.14
Lintupaju (field, V–VI)	Vertic Cambisol	clay	0–20	6.1	8.0	11.5	3.0	0.22
Lintupaju (Buffer zones, V–VI)	Vertic Cambisol	clay	0–20	6.2	6.6	10.4	2.3	n.a.

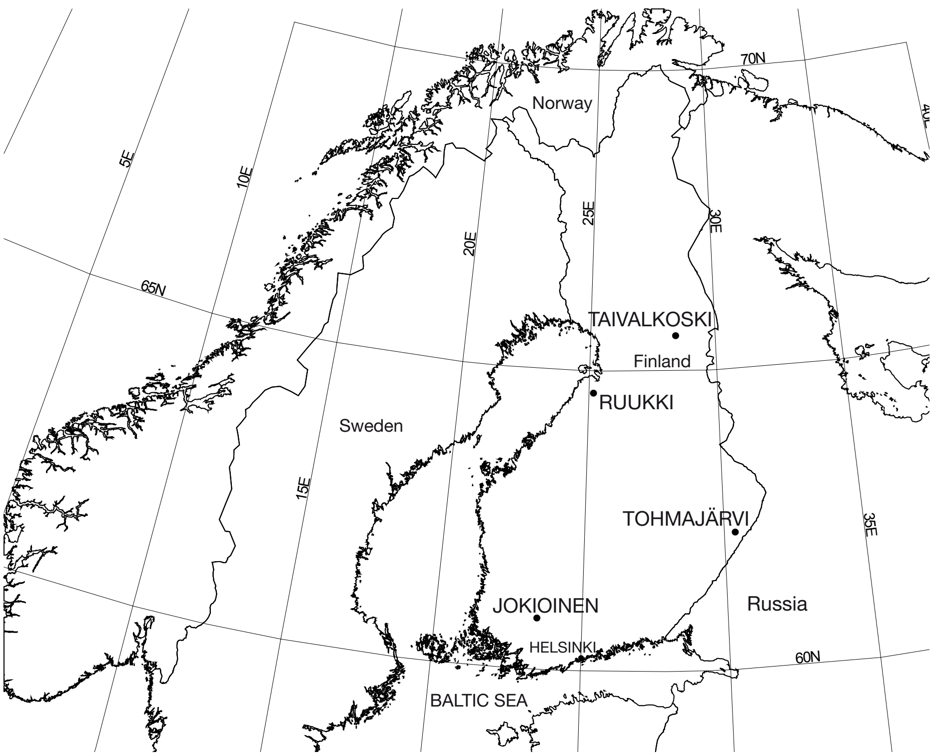

Figure 3. Location of the experimental sites (Figure by Harri Lilja, MTT).

based on phosphorus fertilizer experiments on field plots.

2.2 Forested feedlots

2.2.1 Tohmajärvi

Nutrients losses from forested feedlots for suckler cows were studied at the Suckler Cow Research Station of MTT at Tohmajärvi in October 1997–May 2000 (I). The pens had been in use for 1 or 2 winters before the experiment was started. The acidic soil had a high concentration of organic C (Table 1). In the front part of the pens, the accumulated dung and part of the surface soil was removed.

One suckler cow was considered to equal half a dairy cow unit (= 0.5 AU), since its annual P load in dung is 10 kg ha^{-1} compared with 19 kg ha^{-1} for a dairy cow (Ministry of the Environment 2009). Suckler cows (ca. 32 heads) were reared in four pens (975–1300 m^2) for 7.5 months in winter. In summer, the cows with their calves grazed on nearby pastures. Thus, the annual stocking rate in the pens was estimated to be 25 AU ha^{-1} yr^{-1} (Table 2). In reality, in terms of dung P losses the stocking rate was less than the estimate of 25 AU ha^{-1} yr^{-1}, since part of the dung was removed from the front part of the feedlot. A bedded area, a shelter or a three-walled shed, a feeding fence and a drinking bowl were provided in the front part of each pen (I). The cattle also spent most of their time in the front part (Adjunct Professor Merja Manninen, personal communication, MTT, Jokioinen, May 14, 2009).

2.2.2 Ruukki

A feedlot of 1 ha^{-1} (100 x 100 m) for 10 growing bulls was constructed in a forest at the North Ostrobothnia Research Station of MTT situated at Ruukki in autumn 1999 (II). There was a three-walled shed with feeding and drinking facilities in the upper part of the feedlot. The shed and the lot area were divided into two pens and

Table 2. Experimental sites and years, number of animals, size of source area, factor of animal unit, stocking days and stocking rates.

Site (Years)	Number of animals	Size of source area, ha	Factor of animal unit, AU[2]	Stocking days, d	Stocking rate, AU ha^{-1} yr^{-1}
Tohmajärvi (1997–2000)	ca. 32 suckler cows	0.44	0.5	247	25
Ruukki[1] (1999–2001)	10 bulls	1	0.5	365	1
Taivalkoski (2002–2003)	12 (9–16) heifers or bulls	35 (13–67)	0.5	208	0.1
High input	12	0.5	0.5	157	5
Kotkanoja (1996–2001)	slurry	0.2	–	–	3.6–3.9
(2002–2004)	3 heifers	0.3	0.5	10–40	0.1–0.5
Lintupaju (2003–2005)	2–4 heifers or cows	0.7	0.5–1.0	24–48	0.2–0.6
2006, 2008	slurry	0.7	–	–	0.3, 1.1

[1] 80% of the dung was removed, thus 20% of dung P was left in the feedlot area (II).
[2] A dairy cow is the standard measure of an animal unit.

both of them held 5 bulls. The first herd of bulls was reared in November 1999–October 2000 and the second herd in November 2000–December 2001. A growing bull was considered as 0.5 AU based on its estimated P load (II). Since about 80% of the dung (as well as N and P) was removed from the feedlot area, the average stocking rate was evaluated to be only 1 AU ha^{-1} yr^{-1} (Table 2). The bulls spent 43% of their time in a three-wall shed or in the vicinity of the shed in the upper part of the lot and 57% in the forested area (Tuomisto et al. 2008).

2.2.3 Taivalkoski

The effects of outdoor production on the P and N contents in the soil of forest feedlots with a low stocking rate (mean 0.1 AU ha^{-1}) were studied on five private farms at Taivalkoski between October 2002 and June 2004 (Uusi-Kämppä et al. 2006). Growing heifers and bulls were fed outdoors the year round. The bedded areas had been in the same places since the start of rearing (4–6 years), whereas the feeding places were moved annually or every second year. The same conversion factor of 0.5 AU was used also at Taivalkoski. In high-input areas (feeding and bedded areas of ~0.5 ha), the stocking rate was estimated to be up to 5 AU ha^{-1} yr^{-1} (Table 2).

2.3 Field experiments

2.3.1 Slurry application to grass (Kotkanoja)

An eight-plot field study was conducted to monitor losses of P (III) and N in surface runoff and ammonia losses through volatilization (IV) from perennial ley, which received cattle slurry applications. The experimental plots (6 m x 70 m) had a fairly even slope (<0.9%), with a short steeper slope (0.9–1.7%) at the lower end. Slurry was either surface broadcast or shallow injected into the soil after cutting of the grass. At first, cattle slurry was applied annually in summer 1996–1997 (Phase I) and then biannually in summer and autumn 1998–2000 (Phase II) to the same plots. The annual slurry amounts (30–60 t ha^{-1}) were moderate in Phase I, while high amounts (80–90 t ha^{-1}) were spread during Phase II (III–IV). The applied P amounts of 64 and 69 kg P ha^{-1} yr^{-1} in slurry via broadcast and injection, respectively, corresponded to 3.6 and 3.9 AU in Phase II (Table 2). In this thesis, the P losses in surface runoff were calculated for the slurry application area (3 m x 50 m and 5 m x 50 m in Phase I and II, respectively) just as N losses were presented in Paper IV, because of the better evaluation of the real nutrient losses from the slurry application than in the method described in Paper III. In Paper III, the P losses were diluted by runoff from border areas.

The grass field was ploughed in October 2000. Residual effects of slurry applications on barley were studied in 2001 (Phase III). After that, the field area and four 10 m wide buffer zones were pastured and the P and N losses in surface runoff were studied in 2002–2004.

2.3.2 Buffer zones for retention of loading (Lintupaju)

The effects of 10 m wide grass buffer zones (GBZ) and buffer zones under herbs and scrubs (VBZ) on the surface runoff losses of total solids, phosphorus and nitrogen were studied in six plots (18 m x 70 m) on clay soil at Jokioinen altogether for 18 years (V–VI). The field area above the buffer zones was fairly even, whereas the buffer zones were on a steep slope (12–18%). Both the source field and buffer zones had been under intensive crop production before the experimental field was established in autumn 1989. To analyze the inherent differences between the plots, all the plots were similarly cultivated (the source field area was sown with barley in May and the steep slope was in set-aside) and surface runoff was measured from autumn 1990 to spring 1991 (Uusi-Kämppä and Yläranta 1996). The GBZ and VBZ were established in May 1991. The grass was cut annually and the residue removed on the GBZs at the end of July or beginning of August, whereas scrubs and herbs were not cut on the VBZs. The nutrient losses in surface runoff and the concentration of plant-available P in surface soil on the GBZ and VBZ plots were compared with corresponding results for plots without a buffer zone (NBZ) (V–VI).

The source field and the slope area on the NBZs were under pasture from May 2003 to April 2006. The area was grazed by cattle (72, 234 and 128 cow grazing days ha^{-1} yr^{-1} in summers 2003, 2004 and 2005, respectively), thus the annual stocking rate was 0.2–0.6 AU ha^{-1} (Table 2). The results from the pasture were compared with the results from the conventional tillage (autumn ploughing, 1991–2002; V) and direct drilling (May 2006–December 2008; VI). The annually used fertilizer amounts on the cereal field (around 18 kg P ha^{-1} and 90 kg N ha^{-1}) were typical for Finnish farms (VI). The grass on the pasture was killed off with Roundup (3 L ha^{-1}) in August 2005, and barley was direct drilled into the grass stubble in May 2006. The barley was harvested in August. On the following day, slurry (20 t ha^{-1}) was broadcast and winter wheat direct drilled. The wheat was harvested in August 2007. In May 2008, spring wheat was direct drilled after slurry broadcast. The broadcast slurry included phosphorus 6 and 19 kg ha^{-1}in 2006 and 2008, respectively, thus the stocking rate was estimated to be 0.3 and 1.1 AU ha^{-1} yr^{-1} in direct drilling (Table 2).

2.4 Soil sampling and analyses

2.4.1 Sampling

Soil was sampled to estimate nutrient losses to water from the experimental sites. Feedlot soil samples were collected from the surroundings of the bedded area, from the feeding area and the area where the cattle spent less time. Control samples were taken from the forested soil outside each feedlot. At the Tohmajärvi feedlot, surface soil samples were mostly taken from depths of 0–5 or 0–10 cm, other sampling depths being 5–10, 10–20, 20–40, 40–60 and 60–100 cm (I). In 1999, the surface soil was sampled from a depth of 0–20 cm due to a muddy area in the front part of the lot. At the Ruukki and Taivalkoski feedlots, the sampling depths were always 0–5, 5–30 and 30–60 cm (II).

At Taivalkoski, samplings were carried out on five feedlots in October 2002 and June 2003. The following autumn and spring samples were taken from one of the five lots to estimate the size of the high input areas (bedded and feeding areas) in the feedlot. Seven samples were taken from the bedded area (0.12 ha) and seven samples from the feeding area (0.16 ha). One sample was taken from the middle of the high-input area and two samples from the edges of the high-input area. The rest of the samples were taken 15 and 30 m from the edge of the high input area.

On the Kotkanoja and Lintupaju fields, soil was sampled to depths of 0–10, 10–20, 20–40 and 40–60 cm (and a few times 60–100 cm) with a drill. Because plant-available P is concentrated in the surface soil, soil was sampled from depths of 0–2, 2–5 and 5–10 cm for P analyses (III, V–VI).

2.4.2 Soil analyses

Soil samples were frozen immediately after sampling for soil mineral nitrogen (SMN) determinations. Samples were thawed overnight (+4°C) before NH_4-N and NO_3-N analyses, and 40 ml of moist soil was subsequently extracted with 100 ml of 2 M KCl for 16 hours (Sippola and Yläranta 1985). After filtration, the NH_4-N and NO_3-N concentrations in the extracts were measured with a Scalar autoanalyser. The plant-available P (P_{Ac}) in the soil was determined by extracting dried, ground and sieved soil samples using the Finnish method of acid ammonium acetate at pH 4.65 (Vuorinen and Mäkitie 1955).

2.5 Water sampling and analyses

2.5.1 Ditch water

Ditch water was sampled for N and P analyses from the lower part of Tohmajärvi and Ruukki feedlots (I–II). At Tohmajärvi, water was collected into a pond from where it was pumped out 19 times from the end of April 1998 to the end of August 1998. Water samples were taken and the amount of water measured when emptying the pond (I). At Ruukki, a V-notch weir was used to measure the water volume from April 2000 to June 2002 (II). The water level was measured at the time of sampling. Water was sampled manually three times a day during the peak runoff period in spring. During other periods, samples were taken once a day and subsamples bulked for the week. Water samples could not be taken from the Taivalkoski feedlots.

2.5.2 Percolation water

Percolation water was collected with gravity lysimeters buried in the soil at a depth 30–40 cm in the Tohmajärvi feedlot from October 1997 to July 2000 (I). The lysimeters were situated in the front part, rear and outside the feedlot. Each lysimeter consisted of a 2 L polyethylene bottle and a plastic funnel (diameter 0.2 m) filled with quartz sand (see Derome et al. 1991). The bottles were emptied eight times by a vacuum pump, the water volume was measured and samples were taken for the analyses.

2.5.3 Surface runoff

Surface and near-surface runoff (referred to in the following as surface runoff) to a depth of 30 cm was collected in a modified collector trench planned by Puustinen (1994) at the lower end of each experimental plot on the Kotkanoja and Lintupaju fields (III–VI). Water flowing in plough layer situated on the dense clay layer is typical in Finnish clay soils since the saturated water conductivity decreases rapidly at the depth of 20 cm (Turtola and Paajanen 1995, Turtola et al. 2007). The surface runoff was filtered through a gravel layer into a collector trench. At Kotkanoja, the surface runoff water was fed by pipes into plastic tanks (2.0 m^3) buried in the soil (III–IV). The water volume was measured by flow meters (Oy Tekno-Monta Ab; JOT company, 1992) when emptying the tanks, and flow-weighted subsamples were taken through self-made samplers for laboratory analyses (III–IV).

On the Lintupaju field, the water was conducted through plastic pipes to an observation building where the total volume of runoff was measured volumetrically with a tipping bucket gauge and the number of tippings was continuously recorded on a clock-driven chart (V–VI). Representative flow-weighted subsamples were taken for chemical analyses. The drainage water could not be measured from these two experimental fields, since the old drainage system was not rebuilt when the sites were established for surface runoff studies. In addition to this, the surface runoff losses were more interesting than the subdrainage losses from the buffer zone field.

2.5.4 Storage and water analyses

The water samples (III–VI) were stored in the dark at +4° C for days or weeks before analysis. Since spring 1995, the DRP, NH_4-N and NO_3-N were typically analysed on the day of sampling. Storage for two weeks probably did not have much effect on the concentrations of TP, TN and NO_3-N, but the concentrations of NH_4-N may have decreased during the prolonged storage (Turtola 1989). Water samples taken in the Tohmajärvi and Ruukki feedlots were frozen and stored at -20°C for several weeks before analysis (I–II). Freezing and thawing cycles are common in these places in spring and, according to Monaghan et al. (2002), analysing water samples for DRP within 1–2 h of thawing gives the same results as fresh samples.

The concentration of total solids was determined as evaporation residue after drying at 105°C. For the analysis of DRP, NH_4-N and NO_3-N, the samples were filtered using a pore size of 0.45 µm (Sartorius 11306-50-PFN) before 1995 and after that 0.2 µm (Nuclepore® Polycarbonate). The concentration of DRP was determined by the molybdate blue method, using ascorbic acid as the reducing agent (Murphy and Riley 1962, SFS 3025). The TP was analysed by the same method after peroxodisulphate digestion (SFS 3026). Particulate P was calculated as the difference between TP and DRP. The concentration of TN was determined from unfiltered water samples by oxidation of N compounds to NO_3 in alkaline solution (SFS 3031). The NO_3-N and NH_4-N were analysed according to the Finnish standard methods SFS 3030 (1990) and SFS 3032 (1976), respectively.

2.6 Statistical analyses

The statistical analyses were performed using the ANOVA model which takes into account the experimental design used (I–VI). Models were fitted using the SAS/MIXED procedure. At the Ruukki feedlot, the response variable was the measured change in the soil status from the initial sampling values before the bulls were introduced (II). The three soil depths were analysed separately using a SAS/MIXED procedure using the REML estimation method. Log transformation was used for the values of NH_4-N.

For the Kotkanoja field (III–IV), the data were analysed using a mixed model. In the water analyses, study phase, treatment and their interactions were used as fixed effects, whereas block, block × treatment and block × study phase were used as random effects. Each block included two or three adjacent plots with different treatments. In the P_{Ac} analyses, study phase was replaced by depth in the model. The amounts of the grass yield and the biomass N as well as the amounts of NO_3-N, NH_4-N and SMN in the soil were analysed with study phase being replaced by sampling date. The soil data were log-transformed before analysis because of skewed distributions.

For the Lintupaju buffer zone field, the statistical analyses were based on the experimental design used, which was a randomized complete block design (VI). Three adjacent plots were included in one block. Measurements were repeated at several time points (e.g. spring and autumn) during the study. The results from pasture and direct drilling were analysed together, whereas the results from conventional tillage were analysed alone. The distributions of all the concentrations were skewed. Logarithmic transformations were made before the statistical analyses to normalize the distributions. All the estimates were transformed back to the original scale. The proportions of P_{Ac} in the 0–2 and 2–5 cm layers were analysed statistically so that the response variable was the difference between the two depths, i.e. $\log P_{Ac(0–2)} – \log P_{Ac(2–5)}$. This means that the results can be interpreted as the ratio of P_{Ac} at 0–2 cm to P_{Ac} at 2–5 cm.

3 Results and discussion

3.1 Nutrient losses to water from forested feedlots

3.1.1 Phosphorus in feedlot soil

High P_{Ac} values, predicting surface runoff DRP losses (Sharpley et al. 1986), were measured from the feedlot soil floors (0–5 cm) in the areas where the cattle gathered (Fig. 4). At Ruukki, the P_{Ac} decreased when the distance from the high-input areas such as bedded and feeding areas or from the fence dividing the lot into two pens increased (II). In sow paddocks in the UK, pigs were found to defecate and urinate in areas adjacent to boundaries (Watson et al. 2003). In equine paddocks, high P_{Ac} values were also measured in feeding and defecating areas (Närvänen et al. 2008).

At Tohmajärvi with a stocking rate of 25 AU ha^{-1}, the P_{Ac} was 7.3–28 mg L^{-1} at 0–5 cm in the front part after the penning of 7 or 15 months. When the pens had been in use for four winters (ca. 78 months), the P_{Ac} was 41 mg L^{-1} (0–20 cm) in the muddy area of the front part, decreasing rapidly in the deeper layers. In the rear part, where the cows with their calves gathered only in spring, the P_{Ac} was much lower, being 3.4–10.3 (0–20 cm). There was no clear relationship between soil P_{Ac} and DRP concentration in surface runoff due to high P_{Ac} values in acidic forest soil (Fig. 5). Water extraction would probably have given smaller values for soil P, and the DRP concentration would have agreed better with it.

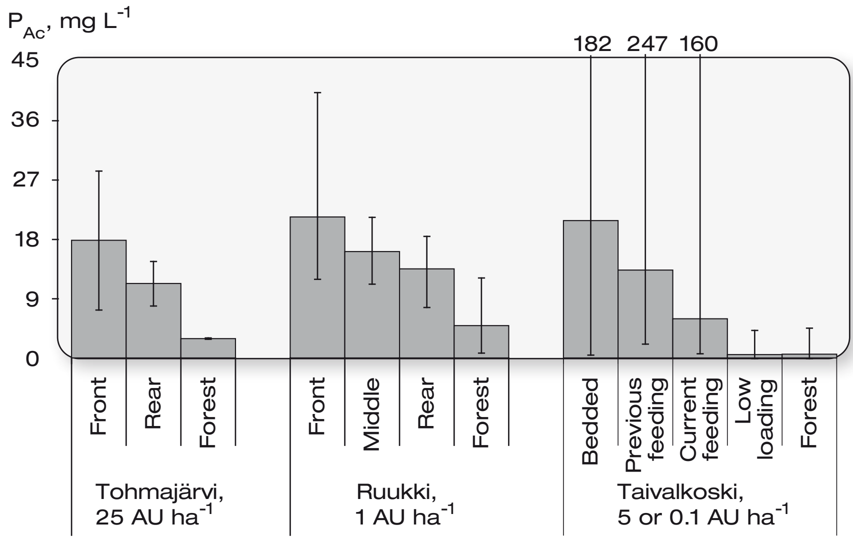

Figure 4. Plant-available P (P_{Ac} , mg L^{-1}) in surface soil (0–5 cm) in the different parts of feedlots and with different stocking rates (AU ha^{-1}) (I–II). Averages of Tohmajärvi and Ruukki and medians of Taivalkoski samples (Uusi-Kämppä et al. 2003, 2006). Bars indicate P_{Ac} ranges.

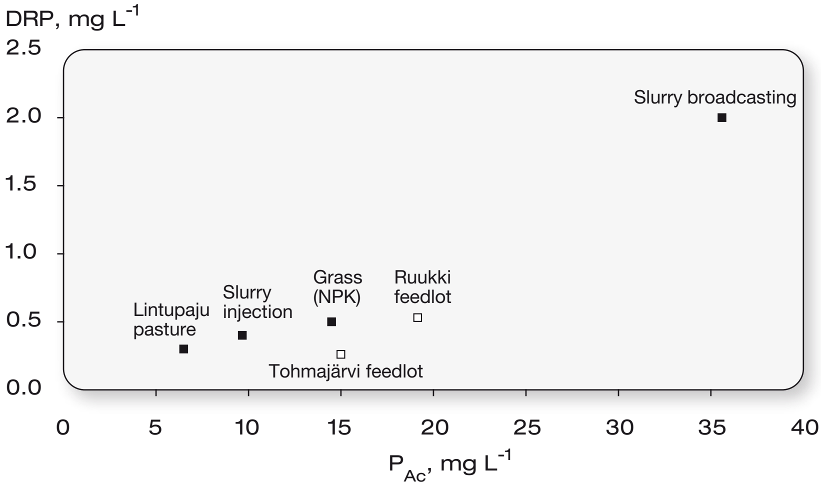

Fig. 5. Relationship between plant-available P (P_{Ac}) in surface soil (0–2 or 0–5 cm) and dissolved reactive P (DRP) in surface runoff for four agricultural soil samples at Jokioinen (■) and two feedlot soil samples at Tohmajärvi and Ruukki (□).

Also at Taivalkoski the highest P_{Ac} values were observed in the bedded (median 20.7 mg L^{-1}), previous feeding (13.3 mg L^{-1}) and current feeding (6.00 mg L^{-1}) areas, but there was great variation in P_{Ac} values (Fig. 4). P_{Ac} values as high as 160, 182 and 247 mg L^{-1} were measured in one current feeding area, bedded area and old feeding area, respectively (Fig. 4). In the large forest areas with low stocking rate (around 0.1 AU ha^{-1}), the P_{Ac} values were as low as in the surrounding forests. These feedlots had been in use for 4–6 years and the bedding areas had been in the same place since the start, but the feeding places were changed annually in most cases due to accumulated faeces, scraps of feed and mud, which may explain some high P_{Ac} values (cast-off feeding place) in low-input areas. Because the cattle gathered in the bedding and feeding places, the actual stocking rate on these sites may have been even 5 AU ha^{-1} rather than the 0.1 AU ha^{-1} which was obtained by dividing the number of animals by the total area of the feedlot. The dung was not removed from the high input areas of the feedlots

The size of the high-input areas (bedding and feeding areas) and the P_{Ac} in the high input areas were measured in one feedlot at Taivalkoski. According to the Finnish classification for soil fertility (Viljavuuspalvelu 2008), the P_{Ac} was from fair to high, 4.2–33 mg L^{-1}, (Fig. 6) in the middle of the bedding area (0.12 ha) and in the middle of the feeding area (0.16 ha). The P_{Ac} was poor or rather poor, 0.3–5.7 mg L^{-1}, about 20 m from the centre of the high input areas and poor over 30 m from the centre of these high-input areas. Thus, the proportion of high-input areas was small in the large feedlot areas. In sow paddocks in the UK (Watson et al. 2003) and in indoor pig fattening areas in Sweden (Salomon et al. 2007), the distribution of excreta was found to vary temporally and spatially and was highest in autumn and near plot boundaries and places for resting, feeding and drinking. At Taivalkoski, the P_{Ac} values increased up to 4.5 mg L^{-1} in the deeper soil layer (30–60 cm) of the high input areas, which might be a result of mixing of soil layers by cattle hoofs as presented by Olson et al. (2005).

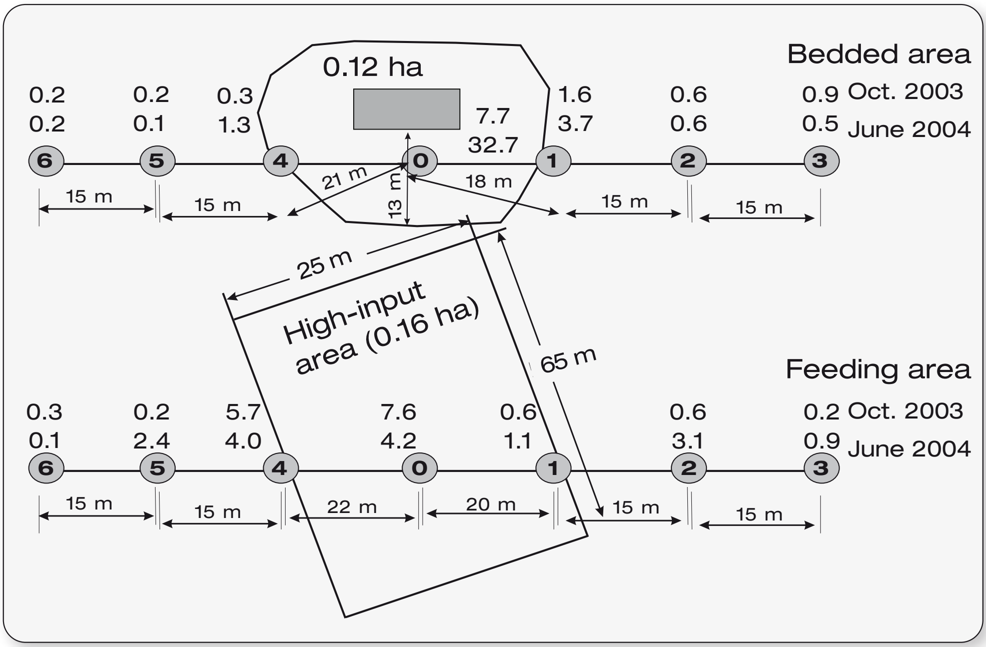

Figure 6. Plant-available P (P_{Ac}, mg L^{-1}) on soil surface (0–5 cm) in the Taivalkoski feedlot (Uusi-Kämppä et al. 2006). High-input areas include the bedded area (0.12 ha, above) and the feeding area (0.16 ha, below). The upper and lower values were measured in October 2003 and in June 2004, respectively. (Figure by Sami Huttu and Kaarina Grék, MTT).

According to the formula of Ekholm et al. (2005), the P_{Ac} would have been 15.5 mg L^{-1} and 0.9 mg L^{-1}, respectively, in the Tohmajärvi feedlot. These estimated values agreed well with the ones measured at Tohmajärvi. At Ruukki, however, the estimated P_{Ac} was double the measured P_{Ac} after two years of penning (Table 3). In the virgin forest, outside the feedlot, the P_{Ac} was only 2.9–3.1 mg L^{-1}. After rearing for 20 years at Tohmajärvi, the estimates of P_{Ac} in soil (0–20 cm) and DRP in surface runoff calculated according to Ekholm et al. (2005) would have been as high as 2700 mg L^{-1} and 170 mg L^{-1}, respectively, if the dung was not removed (Table 3). However, these high values are not within the range of the model. At Ruukki, the P_{Ac} would have been 21 mg L^{-1} (0–20 cm) and DRP in surface runoff 1.3 mg L^{-1} after 20 years of rearing bulls without dung removal (Table 3).

3.1.2 Nitrogen in feedlot soil

The SMN amount, like the soil P_{Ac}, was greatest in the high-input areas of feedlots (I–II). The SMN was below 10 kg ha^{-1} in virgin forested soils. Most of the SMN was in the form of NH_4-N, but high NO_3-N amounts were sometimes found, predicting N leaching (Fig. 7). Only a small part of NH_4-N was nitrified into NO_3-N, probably due to low pH in forest soil or a lack of molecular oxygen, which was probably exhausted in the upper feedlot soil layers. Some NO_3-N may also have been leached before soil sampling. At Tohmajärvi, average N amounts as high as 440 kg ha^{-1} NH_4-N and 30 kg ha^{-1} NO_3-N were detected in the soil (0–60 cm) of high-input areas (I). At Ruukki, the increases of NH_4-N and NO_3-N were up to 50–100-fold during rearing. There were great differences in NH_4-N amounts in different parts and at different depths and times. At Taivalkoski, high NO_3-N amounts were measured in the bedded and previous feeding areas (Fig. 7).

The concentrations of NH_4-N and NO_3-N in the soil were 50–130 mg L^{-1} and 0.1–13.8 mg L^{-1} (0–40 cm), respectively, in the front part of the feedlot at Tohmajärvi (I). In a feedlot (300–600 head ha^{-1}) in Kansas, USA, the corresponding numbers were much higher, being 376–8000 mg kg^{-1} NH_4-N and up to 75 mg kg^{-1} NO_3-N in the 0–25 cm soil layer (Vaillant et al. 2009). The NO_3-N concentrations were usually low in deep feedlot soil layers in Kansas, USA, and in Alberta, Canada, when the surface soils were covered with manure (Mielke et al. 1974, Kennedy et al. 1999, Vaillant et al. 2009).

At Tohmajärvi, the highest NO_3-N amounts (up to 20–40 kg ha^{-1}) were observed in the top layers of 0–40 cm, with exceptional high NO_3-N amounts (16 kg ha^{-1}) also in deeper layers after the rainy summer in 1998 (I). At Ruukki, 15 and 11 kg ha^{-1} NO_3-N was found in the front part at 5–30 cm and 30–60 cm, respectively, after 18 months of rearing (II). At Taivalkoski, up to 50 kg NO_3-N was detected in the soil at 30–60 cm in old feeding places (Uusi-Kämppä et al. 2003). Thus, NH_4-N was nitrified into NO_3-N which may leach into deeper soil layers. Vaillant et al. (2009) pointed out that if a feedlot area is no longer used as a feedlot, the NO_3-N may increase via mineralization or nitrification and leach into the groundwater. Therefore, when a feedlot is closed, the removal of surface soil layer of 25 cm is recommended from the lots in the USA (Vaillant et al. 2009).

Table 3. Experimental sites, duration of P input, annual P balances, and initial, measured and estimated (according to Ekholm et al. 2005) concentrations of plant available P (P_{Ac}) in soil (0–20 cm) and dissolved reactive P (DRP) in surface runoff water.

Site	Duration	P balance	P_{Ac} (initial)	P_{Ac} (measured)	P_{Ac} (estimated)	DRP (measured)	DRP (estimated)
	yr	kg ha^{-1} yr^{-1}	mg L^{-1}				
Tohmajärvi (I)	4	400	1.7[1]	18	15	0.3	0.88
	20	450	1.7[1]		2700		170
Ruukki (II)	2	18	3.4	6.6	3.5	0.5	0.18
	20	18	3.4		4.3		0.22
	20	90	3.4		21		1.3
Taivalkoski	4	37	1.7[1]	4–30	1.9	n.a.[2]	0.076
	20	37	1.7[1]		4.5		0.24
Kotkanoja (III)	5	32	9	8.4	10	0.4–2.0	0.59
	20	50	9		18		1.1
Lintupaju (VI)	3	-3	5.4	4.6	5.1	0.3	0.28
	20	-3	5.4		4.1		0.21

[1] measured from the adjacent forest
[2] not analysed

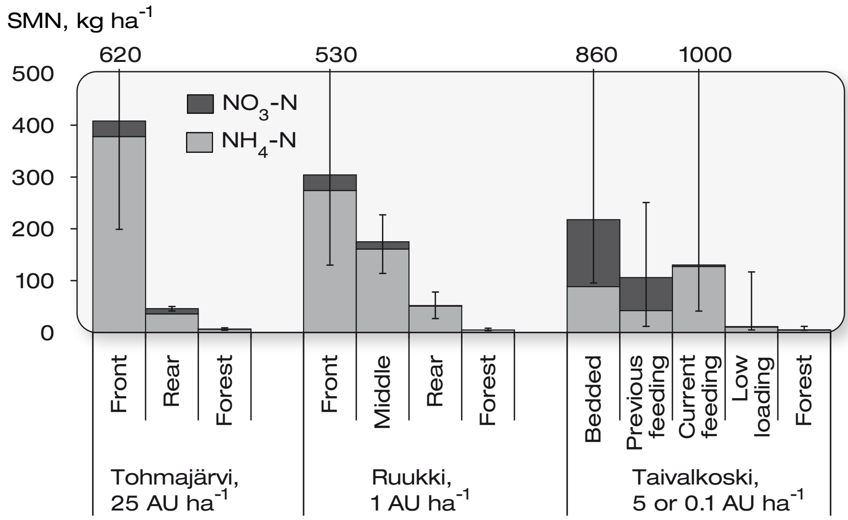

Figure 7. Soil mineral nitrogen (SMN, NH_4-N + NO_3-N, kg ha^{-1}) in the soil layer 0–60 cm in different parts of feedlots and with different animal densities (AU ha^{-1}, I–II). Averages for Tohmajärvi and Ruukki and medians for Taivalkoski (Uusi-Kämppä et al. 2003, 2006). Bars indicate SMN ranges.

3.1.3 Nutrient losses in ditch water

The highest runoff volumes and nutrient losses from the forested feedlots (e.g. I and II) were observed during snowmelt, as was also found for agricultural fields by Øygarden (2000), Syversen (2002) and Puustinen et al. (2007). In some Canadian feedlots, a mixture of manure and snow was removed prior to thawing in spring (Kennedy et al. 1999). This management dries the pens rapidly and mitigates snowmelt runoff. In the feedlots studied here, some runoff was measured in autumn, but the runoff was negligible in summer. In winter, there was no runoff due to continuous snow and frost. Nutrient losses were also highest during high runoff situations in spring. The spring runoff could have been mitigated by removing snow from the lots and preventing runoff entering the lots from the surrounding areas (Puumala et al. 2002).

The losses of DRP, TP and TN to the water of a nearby ditch from the Tohmajärvi feedlot were estimated to be 0.07, 1.4 and 16 kg ha^{-1}, respectively, in the period from the end of April to the end of August 1998 (Table 4). This probably represents the main loading from the lot in that year, although the runoff was only 27 mm (Table 4). Some runoff and nutrient losses were missed during the autumn runoff, since the water volume was not being measured anymore. In autumn, the nutrient concentrations were, however, as high as in spring. At Ruukki, the annual DRP, TP and TN losses to a nearby ditch were 0.6, 0.9 and 3.5 kg ha^{-1}, respectively (II). The annual TP and TN loads from soil-floor feedlots were as high as in the surface runoff from cultivated fields (III–IV). The annual losses of TP and TN at Tohmajärvi were only slightly higher than at Ruukki (Table 4), although stocking density was higher at Tohmajärvi than at Ruukki. The pens had also been used for a longer time at Tohmajärvi (16–24 months) than at Ruukki (0–24 months). In addition, at Tohmajärvi, the ditch water was collected near the front part of the lot (high input area) whereas at Ruukki, water was collected near the rear part of the lot (low-input area). The water collection may have failed at Tohmajärvi or the dung removal in the front part of pens was effective enough to decrease nutrient losses. Instead, the annual TN and NH_4-N losses in percolation water were remarkably great at the Tohmajärvi feedlot (Table 4).

The mean annual DRP concentrations in feedlot ditch water were 0.3 and 0.5 mg L^{-1} at Tohmajärvi and Ruukki, respectively (Table 5). In the Ruukki feedlot, the nutrient concentrations increased year after year, the highest daily mean DRP concentration being 2.5 mg L^{-1} in spring runoff after two stocking winters (II). High DRP concentrations in the Ruukki feedlot were observed especially in afternoons (II). This was due to melting of the surface of the feedlot after the overnight frost. Melting started slowly in the morning and accelerated in the afternoon. A similar diurnal variation in runoff TP concentrations was reported by Pekkarinen (1979) from fields in southern Finland.

In Finnish unmanaged forest basins, the mean concentrations of DRP, TP and TN were <0.017–0.045, 0.022–0.060 and 0.560–1.700 mg L^{-1}, respectively, in 1981–2001 (Rekolainen 1989, Pietiläinen and Rekolainen 1991, Joensuu et al. 2001). The nutrient concentrations in the ditches adjacent to the Tohmajärvi and Ruukki feedlots were 10–200-fold compared to the background concentrations from unmanaged forests.

In the soil floor of exercise yards and forested feedlots, part of the nutrients are stored in the soil decreasing the nutrient losses in runoff water, whereas in yards and feedlots with a concrete or asphalt floor, the median concentrations of DRP, TP, NH_4-N and

Table 4. Mean annual losses of dissolved reactive P (DRP), total P (TP), total N (TN), NH_4-N and NO_3-N in ditch, percolation or surface runoff water at different experimental sites and practices 0–5 years after the start of the management.

Site	Practice	Water	Year	Runoff	DRP	TP	TN	NH_4-N	NO_3-N
				mm yr^{-1}	kg ha^{-1} yr^{-1}				
Tohmajärvi 1998 (I)	Feedlot	Ditch	3rd or 4th	27	0.07	1.4	16	11	0.2
	Front part	Percolation	3rd or 4th	180	0.07	5.4	670	560	0.1
	Rear part	Percolation	3rd or 4th	200	0.8	1.6	88	48	19
Ruukki 2001 (II)	Feedlot	Ditch	1st–2nd	145	0.55	0.9	3.5	1.4	0.2
Kotkanoja 1998–2000 (III–IV)	Slurry broadcasting	Surface runoff	3th–5th	110	1.72	2.4	6.2	1.8	0.3
	Slurry injection	Surface runoff	3th–5th	110	0.48	0.9	3.6	0.3	0.5
	NPK fertilization	Surface runoff	3th–5th	90	0.51	0.7	2.4	0.2	0.2
Kotkanoja 2002–2004	Pasture	Surface runoff	1st–3th	53	0.43	0.6	1.2	0.4	0.3
Lintupaju 2003–2005 (VI)	Pasture (NBZ)	Surface runoff	1st–3th	120	0.44	0.7	1.8	0.2	0.2

Table 5. Mean annual concentrations of dissolved reactive P (DRP), total P (TP), total N (TN), NH_4-N and NO_3-N in ditch, percolation or surface runoff water at different experimental sites and practices 0–5 years after the start of the management.

Site	Practice	Water	Year	DRP	TP	TN	NH_4-N	NO_3-N
				mg L^{-1}				
Tohmajärvi 1998 (I)	Feedlot	Ditch	3rd or 4th	0.3	5.2	60	39	0.6
	Front part	Percolation	3rd or 4th	0.04	3.0	370	310	0.06
	Rear part	Percolation	3rd or 4th	0.4	0.8	44	24	9.4
Ruukki 2001 (II)	Feedlot	Ditch	2nd	0.5	0.9	3.1	1.3	0.2
Kotkanoja 1998–2000 (III–IV)	Slurry broadcasting	Surface runoff	3th–5th	2.0	2.7	6.9	2.4	0.4
	Slurry injection	Surface runoff	3th–5th	0.4	0.6	2.9	0.4	0.5
	NPK fertilization	Surface runoff	3th–5th	0.5	0.7	2.1	0.3	0.3
Kotkanoja 2002–2004	Pasture	Surface runoff	1st–3th	0.8	1.1	2.3	0.7	0.5
Lintupaju 2003–2005 (VI)	Pasture (NBZ)	Surface runoff	1st–3th	0.3	0.7	1.6		

TN in runoff water may be as high as 22–53, 40–74, 56–130 and 150–250 mg L^{-1}, respectively (Uusi-Kämppä et al. 2008). At a feedlot in Alberta, Canada, high concentrations of TP (43–73 mg L^{-1}) and TN (210–305 mg L^{-1}) were also found in runoff from old soil-floor pens with stocking rates of 280–580 AU ha^{-1} due to their reduced capacity to fix, store or adsorb these elements (Kennedy et al. 1999).

3.1.4 Nutrient losses in percolation water

At the Tohmajärvi feedlot, the percolation water was collected at a depth of 30–40 cm (I). The mean concentrations were high in the front part of the pens: 3.0 mg L^{-1} TP, 310 mg L^{-1} NH_4-N and 370 mg L^{-1} TN (Table 5). In the rear of the pens, the corresponding concentrations were less than 10% of those in the front part. However, the NO_3-N concentration was high (9.4 mg L^{-1}) in the rear, whilst in the front part it was negligible. In the bedded area, the nutrient concentrations were as high as in the front part, but the water volume was substantially smaller than in the open areas. Outside the feedlot, the nutrient concentrations were negligible, only the TN concentrations were sometimes elevated, exceeding 10 mg L^{-1} TN. Based on the high SMN and high nutrient concentrations in the percolation water, nutrient leaching may be high from the high-input areas of the feedlots and in coarse-textured soils it may cause groundwater pollution.

3.1.5 Mitigation of feedlot runoff losses

Nutrient losses into water can be decreased by replacing surface soil and by draining the yard soil (Puumala et al. 2002). Regular removal of dung from cattle feedlots as well as from equine paddocks has been found to mitigate nutrient losses to surface runoff water (Airaksinen et al. 2007, Uusi-

Kämppä et al. 2008). In some aspects, the regulations issued for exercise yards would also be applicable to forested feedlots. For example, it has been recommended that exercise yards should be located 30–100 m away from watercourses and household wells and 10 m from open ditches (Ministry of the Environment 2009). According to the same guidelines, in outdoor feedlots the area around feeding facilities should have a dense surface (i.e. concrete), from which the dung can be easily removed. The feedlot runoff must be observed and purified to mitigate nutrient losses to water when needed (Ministry of the Environment 2009). According to the results of Papers I and II, a dense surface could also be recommended for bedded areas in feedlots. The feedlots should not be established in groundwater areas due to the risk of nitrogen leaching into deeper soil layers.

Collecting water in sedimentation ponds or slurry tanks is suggested, if the feedlot runoff is rich in nutrients or faecal microorganisms (Puumala et al. 2002). During spring runoff, it may, however, be difficult to collect runoff due to freezing of ponds and the high instantaneous water volumes. Surface runoff water from equine source areas has been successfully purified in a sedimention pond by adding ferric sulphate to the water (Närvänen et al. 2008). Sulphate application may also be suitable for the purification of cattle feedlot runoff. In the USA, buffer zones and vegetative treatment systems have been used to retain pollutants from feedlot runoff (Young et al. 1980, Dillaha et al. 1986, Koelsch et al. 2006).

3.2 Nutrient losses from slurry-amended grass field

3.2.1 Nutrients in soil

During the first two years of slurry application, there was no significant change in P_{Ac} values in the surface soil (0–10 cm) of the Kotkanoja field compared to the values measured before applications (III). According to calculation using the formula of Ekholm et al. (2005) it would have taken 20 years to double the initial P_{Ac} value of 9.0 mg L_{-1} with the field P balance of 50 kg ha^{-1} yr^{-1} (Table 3). However, when thin soil layers (0–2 cm) were sampled from the soil surface, high P_{Ac} values (up to 25 and 65 mg L^{-1}) were observed after biannual slurry broadcast (III). Turtola and Yli-Halla (1999) also found high P_{Ac} concentrations in surface soil (0–5 cm) after slurry broadcast. In the slurry injection plots, P_{Ac} increased most at soil depths of 2–5, 5–10 and 10–20 cm (III).

The SMN amounts were measured in the 0–60 cm soil column to estimate N leaching into drainage and ground water (IV). The amounts of SMN were 8–35 and 9–46 kg ha^{-1} from broadcast and injected plots, respectively. Most of the N was in the form of NH_4-N. During biannual slurry application, the SMN amounts in spring were only slightly higher (0–30 kg ha^{-1}) or even lower (4–6 kg ha^{-1}) than in the previous autumn, although 105–155 kg ha^{-1} TN in slurry was added to the grass field after autumn sampling. In the injection plots, the SMN amounts in spring were significantly higher (p=0.03) than in the plots where slurry was broadcast, probably due to lower NH_3 volatilisation and slightly higher N inputs in injection (IV).

For NO_3-N, the amounts in the injection plots were about 7 kg ha^{-1} higher than in the broadcast plots in the year 1999 (p<0.001). The highest mean amount of NO_3-N (25 kg ha^{-1}) was observed in the injection slits (0–20 cm depth) in October 1999 after a dry growing season. Thus, although injection decreased N losses to the air via NH_3 volatilisation and into surface runoff, it may have enhanced N leaching into drainage water. Cameron et al. (1996) observed the amount of leached NO_3-N to be consistently higher after subsurface injection of dairy pond sludge compared to surface application. In the deeper layer (60–100 cm), however, low NO_3-N amounts (0–8 kg ha^{-1}) indicated low N leaching from the Kotkanoja field. After ploughing the grass stand, the SMN amount was greater in the plots where slurry had been previously injected ($p<0.01$) compared to surface–broadcast plots.

3.2.2 Surface runoff losses

The volume of surface runoff was small and it was formed on an even grass field (III–IV). The highest surface runoff was measured in spring and autumn outside the growing season. The average surface runoff (70–94 mm yr^{-1}, Table 6) agreed with other Finnish findings, indicating that there had been deep percolation (drainflow) as well. On a nearby grass field, the surface runoff was 85–250 mm yr^{-1} (Turtola and Jaakkola 1995, Turtola and Paajanen 1995, Uusitalo et al. 2007b).

Surface runoff volumes can, however, be many times higher than these findings, if a drainage system does not function well or there is no drainage system (Turtola and Paajanen 1995, Bilotta et al. 2008). Soil compaction caused by heavy machinery such as slurry spreaders or forage harvesters on wet soil decreases the water infiltration capacity, thus increasing the surface runoff (Alakukku 1997). After ploughing the grass field, the surface runoff was around 30% lower than before (Table 6) since the water holding capacity is higher for ploughed fields than for grass fields.

The annual losses of TP (1.0 kg ha^{-1}) and TN (2.5–2.9 kg ha^{-1}) in surface runoff were small from grass when moderate amounts of cattle slurry were applied once in summer (Table 6). The losses increased after biannual applications, the losses being 2.4 kg ha^{-1} yr^{-1} TP and 6.2 kg ha^{-1} yr^{-1} TN. Injection of slurry decreased the respective losses by 73% and 57% (Table 6). These results agree with findings in Norway, where surface runoff losses of NH_4-N, TN and TP were about 4, 8 and 4 kg ha^{-1}, respectively, 14 months after autumn application of semi liquid cow manure (60 t ha^{-1}) to grassland (Uhlen 1978). The TP losses in surface runoff from slurry broadcast plots were higher than the estimated average losses (0.6–1.4 kg TP ha^{-1} yr^{-1}, Vuorenmaa et al. 2002) in surface runoff and drainage water from Finnish cultivated fields. The small amount of NO_3-N (<0.7 kg ha^{-1}) was consistent with studies by Uhlen (1978), Turtola and Kemppainen (1998), Ridley et al. (2001), Smith et al (2001) and Saarijärvi (2008).

The highest nutrient losses were measured from broadcast slurry plots in October 1998 after slurry application to wet soil followed by heavy rainfall (38 mm during 5 days). The mean TP and TN losses were 4.4 and 13 kg ha^{-1} yr^{-1}, respectively, from the broadcast slurry, and half of the TP load was transported during those first five days after application. This agrees with earlier studies where incidental P losses have represented up to 50–98% of the measured P losses in runoff from fields where rainfall interacted directly with fertilizer or manure spread on the soil surface (Withers et al. 2003). This study also indicated that regarding incidental P losses, P release from previously applied slurry would be more important than a high soil P status. This opinion was confirmed with high DRP concentrations (average 0.4–2.0 mg L^{-1}) in surface runoff water from broadcast plots, whereas the estimated DRP concentration based on soil P according to Ekholm et al. (2005) was 0.6 mg L^{-1} from the field (Table 3).

In the Kotkanoja field, a 10 m wide non-manured buffer zone probably decreased TP and TN losses from slurry-amended grass. In the USA, McDowell and Sharpley (2002) showed the decline of P concentration to be up to 70–90% when surface runoff water from a manured field was purified by a 10 m wide buffer zone. In a field study by Heathwaite et al. (1998), the reductions of TN and TP were 75 and

Table 6. Periodical mean surface runoff and losses of TP and TN on the plots where slurry was either broadcast (B) or injected (IN) or where only mineral fertilizer was applied (C) before and during study phases in the Kotkanoja field (III–IV). Mean annual losses in parentheses.

Period	Runoff			TP			TN		
	mm study period^{-1} (mm yr^{-1})			kg ha^{-1} study period^{-1} (kg ha^{-1} yr^{-1})					
	B	IN	C	B	IN	C	B	IN	C
July 1995–June 1996 (Before slurry applications)	75	80	73	0.5	0.4	0.4	2.0	1.6	1.8
June 1996–June 1998 (Annual slurry application)	150 (75)	160 (80)	140 (70)	2.0 (1.0)	2.0 (1.0)	1.6 (0.8)	4.9 (2.5)	5.8 (2.9)	4.3 (2.1)
July 1998–Oct. 2000 (Biannual slurry application)	210 (90)	220 (94)	170 (73)	5.5 (2.4)	1.5 (0.6)	1.2 (0.5)	14.5 (6.2)	6.2 (2.7)	3.5 (1.5)
Nov. 2000–Dec. 2001 (After ploughing grass field)	64 (55)	78 (67)	60 (51)	2.3 (1.9)	1.8 (1.5)	1.1 (0.9)	3.0 (2.5)	4.9 (4.1)	2.4 (2.0)

10%, respectively, by a 10 m wide unfertilized buffer zone below an adjacent slurry-amended source field.

3.2.3 Field balances

In the slurry-amended plots, the net TP balance was around 10 and 50 kg ha^{-1} yr^{-1} in Phase I and II, respectively (III). In other Finnish studies, the P balances have been from 8 to 13 kg ha^{-1} yr^{-1} (Kainuun Maaseutukeskus et al. 2000, Antikainen et al. 2005, Virtanen & Nousiainen 2005, Uusitalo et al. 2007a). The high balances were due to the high P inputs (44–48 kg TP ha^{-1}) in slurry in the Kotkanoja field. According to a meta-analysis of Valkama et al. (2009), maximum grass yields have been obtained in Finnish soils with a P input of 13 kg ha^{-1} yr^{-1}.

During Phase I (annual slurry application), the net balance of TN was 4–72 kg ha^{-1} yr^{-1} in the slurry-amended plots, taking into account the TN uptake of above-ground grass biomass, NH_3 volatilization and TN losses in surface runoff. In the mineral fertilization plots, the balance was negative (IV). In Phase II (biannual slurry application), the TN balances were very high, 210–290 kg ha^{-1} yr^{-1}, due to high inputs (370–400 kg ha^{-1} yr^{-1} TN) in the slurry plots. These field balances were higher than the early Finnish estimates of N surpluses (30–109 kg N ha^{-1} yr^{-1}) (Kainuun Maaseutukeskus et al. 2000, Antikainen et al. 2005, Virtanen and Nousiainen 2005). The low NH_3 volatilization and slightly higher slurry amounts in injection explained partly the higher TN balances in plots where slurry was injected.

The high TN balances show that a large part of the TN inputs was not taken up by the above-ground grass biomass, volatilized as NH_3 or detected as surface runoff or SMN. This agrees with the findings of MacDonald and Jones (2003) who pointed out that 20–70% of the N inputs to agricultural systems may be unaccounted for. Part of the slurry N might have volatilized as NH_3, stayed in organic form, been stored in roots, immobilized in soil soon after application due to decomposition of fatty acids in the slurry (Kirchmann and Lundvall 1993, Sørensen and Amato

2002), denitrified and evaporated into the air or leached into deeper soil layers.

3.3 Mitigation of surface runoff losses by buffer zones

3.3.1 Pasture and direct drilling

There were no clear differences in the amounts of TS and nutrients in surface runoff between plots with and without buffer zones in the Lintupaju pasture, although the infiltration was higher in the GBZ and VBZ than in grazed NBZ where the soil was more compacted from the trampling of cows (Pietola et al., 2006). The losses of TS, TP, PP and TN in surface runoff from rotationally grazed grass (VI) were smaller than those earlier measured from the tilled field (V). Only the DRP load (0.3–0.4 kg ha^{-1} yr^{-1}) was higher from the pasture than from the tilled soil (VI). The DRP losses were highest in spring 2003 before grazing and in spring 2006 after application of Roundup the previous autumn (VI). Elevated DRP losses in runoff from the plants treated with glyphosate was also found in the studies of Ulén and Kalisky (2005) and Uusitalo et al. (2007b). The high DRP load in spring 2003 was probably due to the dry and warm autumn in 2002 (VI).

The loads of TP (0.7 kg ha^{-1} yr^{-1}) and TN (< 2 kg ha^{-1} yr^{-1}) were small, since the fertilizer applications were moderate and the stocking rate (≤ 0.6 AU ha^{-1} yr^{-1}) was low on the rotationally grazed Lintupaju field (VI). Also on the Kotkanoja field, the TP load was some 0.7 kg ha^{-1} yr^{-1} during grazing (≤ 0.5 AU ha^{-1} yr^{-1}) and there were no differences in TP loads between the grazed and non-grazed 10 m wide buffer zones (Uusi-Kämppä & Palojärvi 2006). These results agree with the findings of Haan et al. (2003) who observed in Iowa, USA, that buffer zones and rotational grazing of cattle can greatly control erosion and nutrient losses from pastures compared to perennial grazing. On the other hand, Hay et al. (2006) observed in California, USA, that the effectiveness of buffer zones for reducing sediment and nutrient transport from irrigated pastures may be questionable due to slope, high runoff volumes and channelled flow.

The losses of TS and PP in surface runoff from the directly drilled plots were higher than from pasture but lower than from conventionally tilled clay field (VI). The GBZ and VBZ decreased the losses of TS, TP, PP and TN (Fig. 8) in autumn, but had no significant effect on these losses in spring. There was no difference in DRP loads between treatments, with the exception of the lower load from the VBZ in autumn (VI). The reason for the lower DRP load in the VBZ was the lower surface runoff than in the GBZ and NBZ due to good infiltration in the VBZ (Pietola et al. 2006). During the first direct drilling years, the DRP losses did not increase substantially in surface runoff, although the P_{Ac} started to increase on the soil surface of the NBZ.

3.3.2 Mitigation processes in buffer zones

Deposition has been considered to be the most important mechanism retaining eroded soil and particle-bound nutrients in buffer zones, whereas infiltration of water into buffer zone soil is efficient for dissolved nutrients. On conventionally tilled soils, the losses of TS and PP declined by 50% in the buffer zones, and the retention capacity for TP loss was 36 and 28% in the GBZs and VBZs, respectively (V–VI). In other Nordic Countries, the retention of TP ranged between from 51 to 97% in the buffer zones (Uusi-Kämppä et al. 2000). In the USA, Dillaha et al. (1989) observed that 4.6 and 9.1 m wide grass buffer strips decreased the losses of suspended solids by 70 and 84%, respectively, and TP losses by 61 and 79%, respectively, on silt loam soil. The capacity of the GBZ and VBZ to decrease TN loads (62 and 48%, respectively; Fig. 8) in conventional tillage was as good as in the studies of Dillaha et al. (1989) and Lee et al. (1999) where 6–9 m wide buffer zones retained 46–73% of the incoming TN in surface runoff water. Infiltration of N into deeper soil layers, uptake by plants and denitrification are the main mitigation processes for N in buffer zones (Hefting 2003).

The retention capacity of buffer zones is better for coarse particles than for fine ones (e.g. Daniels and Gilliam 1996, Krongvang et al. 2005, Syversen and Borch 2005). The retention of particles was the highest in the upper part of the buffer zones on silty clay soil (Syversen et al. 2001). Thus, even a narrow buffer zone may retain coarse particles well, while a wide buffer zone is needed to retain small clay particles. The removal of TS was probably greater in the American and Norwegian studies due to the coarse soils as compared to the soil in the Lintupaju field. In addition to erosion caused by the kinetic energy of raindrops, the risk of erosion due to diffusion of fine clay particles is high in Finnish clay soils if freshly tilled soil stays wet for long periods (Alakukku & Aura 2006).

The retention capacity has also been reported to be better for pollutants bound to soil particles than for dissolved pollutants (e.g. Magette et al. 1989). In the Lintupaju field, the retention of PP was some 50%, but the retention efficacy for DRP was poor (V–VI). Infiltrated water transports nutrients within a buffer zone into deeper soil layers and sometimes into a subdrainage system or even into ground water. In the USA, NO_3-N was found to increase in drainage water in a buffer zone retaining nutrients from a feedlot runoff (Bhattarai et al. 2009).

In surface soil as well as on the walls of cracks and pores, DRP is adsorbed by Al and Fe oxides. In Finnish forests, over 90% of the trapped P was found to be adsorbed in buffer zone soil during spring runoff

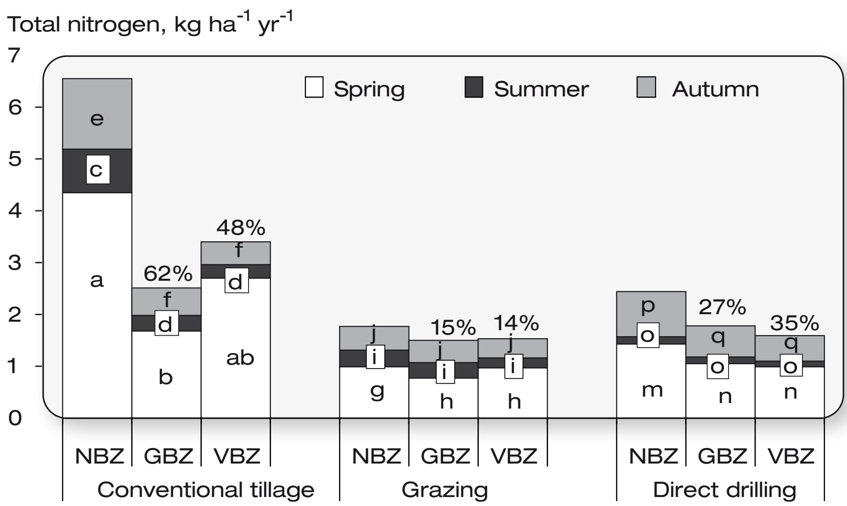

Figure 8. Estimates for total nitrogen in surface runoff during conventional tillage, grazing and direct drilling (VI). Different letters in the bars indicate significant difference at $p < 0.05$ for NBZ, GBZ and VBZ in different seasons. GBZ = 10 m wide grass buffer zone; NBZ = no buffer zone; VBZ = 10 m wide vegetated buffer zone growing natural herbs and shrubs. Percent of retention efficacy is given above the columns.

(Väänänen et al. 2006). Adsorbed P may, however, later be desorbed from the soil particles, enhancing DRP losses. For example at Lintupaju, the VBZ changed from a P sink to a DRP source in spring. The 2 cm thick soil surface layer might be saturated by P, in which case P was released into surface runoff water (V–VI). In spring, low temperature, low salt and P concentration in the melting water, and high solution to soil ratio may also favour P desorption from the soil (Yli-Halla and Hartikainen 1996). The change of filter (0.45 µm) to a finer one (0.2 µm) in 1995 did not decrease the level of DRP, which agrees with the findings of Turtola (1996).

The uptake of P and N by buffer zone vegetation is an excellent way of retaining soluble P and N. The above-ground biomass must, however, be harvested to remove the nutrients from the buffer zone. At Lintupaju, the DRP loss in surface runoff from the unharvested VBZ plots was 60% higher than from the NBZ and harvested GBZ during conventional tillage (V–VI). An increase in DRP in buffer zones has been found by some other studies, too, (e.g. Osborne and Kovacic 1993, Daniels and Gilliam 1996). Yet, in most other studies, mostly performed during the growing season, the retention of DRP has been good (e.g. Vought et al. 1991, Puustinen et al. 2005, Watts and Tobert 2009).

Buffer zones can sometimes lead to increased release of P to waters, since the establishment of buffer zones enhances soil P cycling, increasing soil P solubility and the potential to leach into waters (Stutter et al. 2009). At Lintupaju, a substantial decrease in the P content of above-ground plant material (6.1 kg ha^{-1}) was detected in the VBZ after the first frost in autumn (Räty et al. 2009). In a laboratory experiment, the extraction of TP in leachates from the above-ground biomass of the buffer zones was high (1.6 and 3.1 kg ha^{-1} in the GBZ and VBZ, respectively) after three freeze-thaw cycles, mostly as DRP (Uusi-Kämppä 2007). High P losses from dried and frozen plant residues have been found in several studies (e.g. Singer and Rust 1975, Timmons et al. 1970, Sharpley 1981, Ulén 1984, Bechmann et al. 2005).

For practical agriculture, however, the introduction of buffer zones may have a smaller effect on the net DRP losses in surface runoff due to a smaller ratio of buffer zones to source fields than presented in our study (1:6). The DRP losses can be decreased by mowing and removing the residue from the buffer zones. Grazing is a possible way of harvesting the biomass from buffer zones. The animal unit should not be too high, and rotation grazing is more advisable than grazing for the whole pasture season (Lounais-Suomen ympäristökeskus et al. 2006). Grazing during the first year after establishing a buffer zone is not recommended, due to the compaction of soil (Rasa et al. 2007). The retention capacity of the buffer zone with limited vegetation cover was also poor in the Lintupaju field during the first year (Uusi-Kämppä and Yläranta 1992).

3.3.3 The efficacy of buffer zones in different situations

The efficacy of buffer zones depends on several factors such as the source field itself (e.g. bare vs. plant-covered, slurry applications to soil surface, outdoor feedlots), the width and slope of the buffer zone, type of soil and buffer zone vegetation, ratio of source area to buffer zone and intensity of surface flow (Syversen 2002, Liu et al. 2008).

In this study, the efficiency of buffer zones was due to 1) trapping of the buffer zone and 2) reduced tillage area. In the GBZ and VBZ plots, the area of the source field was 17% smaller than in the NBZ plots. In addition, the steep slope was cultivated in the NBZ, whereas it was under grass in the GBZ and VBZ. This study site was different from most of the others where the source fields have had the same size in each treatment plot. This site was chosen since it is typical of real farms in south-western Finland – the steep slopes along water courses are either cultivated or protected by buffer zones.

The climate also puts great strains on buffer zones. In boreal areas, buffer zones do not always work well in spring due to poor grass cover and frosted soils (VI–VI). In the Aurajoki field with high P_{Ac}, buffer zones were effective in retaining sediment, PP and DRP also in winter and spring (Puustinen et al. 2007). The efficiency of buffers was better when autumns were dry and the soil was covered by permanent snow in winter compared to rainy autumns and warm winters (Puustinen et al. 2007). In addition, the contact time between nutrients in water and soil surface is short due to the high volumes of melt water in spring. In a Finnish forest, only 16% of ^{32}P added in spring was retained by 25–50 m wide buffer zones (Väänänen et al. 2006).

In fields where DRP losses into surface runoff water are high, new innovations to retain P in the soil of source fields as well as buffer zones are needed. Buffer zones amended with drinking water treatment residues or gypsum for retaining DRP have been studied recently (Wagner et al. 2008, Watts and Torbert 2009).

4 General conclusions

From the forested feedlots the TP and TN losses in the ditch water were 0.9–1.4 and 4–16 kg ha^{-1} yr^{-1}, respectively, during the first penning years. At the beginning, nutrients were retained by forest soil, but if the exchange sites of the soil become saturated, e.g. with NH_4-N or phosphorus, nutrient losses from the feedlot area will increase. The feedlots may become polluting areas, if penning with high stocking rate (>5 AU ha^{-1} yr^{-1}) is continued for years and the dung is not removed. The mean concentrations of TP (up to 3.0 mg L^{-1}) and TN (370 mg L^{-1}) in percolation water from lysimeters were observed in high-input areas, such as bedded and feeding areas. The annual amounts of NH_4-N (560 kg ha^{-1}) and TN (670 kg ha^{-1}) were great in percolation water. Movement of nutrients, especially NO_3-N, into deeper soil layers and finally into groundwater is, thus, probable from high-input areas. Removing dung from the bedded and feeding areas decreases the nitrogen and phosphorus losses to water.

The annual losses of TP, DRP and TN were 2.4, 1.7 and 6.2 kg ha^{-1}, respectively, (Table 6) from the grass field with biannual slurry broadcast to soil surface. Shallow injection of slurry into the soil decreased the losses of TP, DRP and TN in surface runoff by 73, 80 and 57%, respectively. The TP, DRP and TN losses in surface runoff were highest, 4.4, 3.6 and 13 kg ha^{-1} yr^{-1}, respectively, after slurry surface application to wet soil in autumn 1998, in which case half the loads were transported during the first 5 days after application. The TP load in surface runoff from a slurry-amended grass field exceeded the average annual TP load of 0.6–1.4 kg ha^{-1} from Finnish fields, whereas the TN load fitted into the average TN losses of 8–15 kg ha^{-1} (Vuorenmaa et al. 2002).

Buffer zones interposed between source areas and watercourses are efficient in decreasing losses of sediment and nutrients, especially from conventionally tilled fields. In a 70 m long clay soil field, 10 m wide buffer zones decreased losses of TS, TP, PP and TN in surface runoff by 50, 30, 40 and 50%, respectively. On pasture, the sediment and nutrient losses were smaller than on the tilled soil and, thus, the requirement for buffer zones on pastures is less than on tilled soil. The retention capacity of buffer zones for DRP was low both on pasture and tilled soil. In conventional tillage, the DRP load even increased 90% on the VBZs during spring runoff.

According to the formulas presented by Ekholm et al. (2005), the estimated plant-available P in soil and the DRP concentration in surface runoff were close to those measured during the first experimental years (Table 3). There are, however, no measured values for P_{Ac} and DRP after 20 years loading to compare with the estimated values. At all the sites, DRP may also have been leached from the dung and thus the measured DRP concentrations have been higher than those estimated. At Tohmajärvi, however, the measured DRP concentration might be lower than the estimated one due to dilution of the feedlot runoff with waters from virgin forest.

There was a relationship between the mean P_{Ac} (0–2 or 0–5 cm) and flow-weighted DRP concentration in surface runoff from agricultural fields with slurry application and grazing (Fig. 5). On the contrary, the feedlot sites (Tohmajärvi and Ruukki) did not fit as well as the agricultural fields. The ammonium acetate extraction might give too high P_{Ac} values for acid soils. Water extraction might have been a more suitable method for the forest soil samples and given more accurate values for plant-available P.

Further research is still needed:

1. Different management practices to retain nutrients in feedlot soils and for the purification of feedlot runoff waters before discharge into the environment should be studied. For example, soil amendments, such as gypsum ($CaSO_4$ x $2H_2O$), Fe-gypsum and granulated ferric suphate (Ferix-3), can retain P in the soil, but more research is needed on their use in feedlots and their possible risks to animal welfare.

2. Losses of DRP from grass fields and buffer zones will probably increase in future due to increased rainfall and multiple melting events in winter. Freezing and thawing cycles will increase DRP losses and therefore the retention efficiency for DRP in buffer zones should be increased via new innovative methods. For example, Fe and Ca compounds have been found to decrease DRP and TP concentrations from buffer zone surface runoff in rainfall simulation experiments (Uusi-Kämppä et al. unpublished).

5 Practical implications

To mitigate P and N runoff losses from forested feedlots, bedded and feeding areas should be established on upward slopes and sufficiently far from open ditches, watercourses and ground water areas. Nutrient losses can be cut by establishing a dense floor (e.g. concrete) on high-input areas and removing dung regularly from it. The low-input areas can be divided into sections which are penned in rotation, so each part will be evenly loaded. Some of the recommendations presented in this thesis as well as in the introductions of the Ministry of the Environment (1989, 2009) are also suitable for the exercise of cattle, equine and other animals such as poultry, wild boars and alpacas as well as reindeer penning in North Finland.

Broadcasting slurry on wet soil before predictable heavy rainfall, too near watercourses or on fields sloping steeply to watercourses should be avoided to decrease the losses of nutrients by surface runoff. Moderate application rates of slurry given during the growing season, good application methods (i.e. injection of slurry instead of broadcasting) and sufficient non-manured buffer zones between a source field and a ditch or watercourse decrease losses from slurry amended grass. Most of these ideas have already been included in the Government Decree 931/2000 (Finlex 2000). Injection of slurry may, however, increase nitrogen losses in drainage water.

Buffer zones are most important in decreasing sediment and nutrient losses in surface runoff from conventionally tilled soils. They are also useful on grassed and directly drilled soils, since application of nutrients and agrochemicals is not allowed in the buffer zones. The above-ground biomass in the buffer zones should be cut and the residue collected annually to remove trapped nutrients and decrease DRP losses into surface runoff water from frozen and thawed plant residues during the spring runoff. Harvesting also hinders the increase in plant-available P in the soil surface of buffer zones and thus decreases DRP losses into water. The removal efficiency of buffer zones increased during the first two years. After that the efficiency was predicated on the weather in the different seasons and on the management of the source field. Although the losses in surface runoff can be decreased by buffer zones, the losses may increase in drainage water due to infiltration of surface runoff water in the buffer zones.

The continuous growth of cattle farms and their concentration in certain agricultural areas increases the risk for nutrient losses in these regions. Especially repeated slurry applications with high field N and P budgets or rearing cattle in the same feedlot year after year increases N and P losses into water. Moreover, in coarse-textured soils, common in central and western Finland, the losses of N and P into drainage water and ground water may be higher than those measured on clay soil in southwestern Finland.

To estimate DRP losses to surface runoff from untilled soils (e.g. grassed or directly drilled soils) by soil sampling, the samples should be taken from the uppermost soil layer (e.g. 0–2 cm) as this is the part which has most efficient contact with the surface runoff. As P_{Ac} tends to decrease with depth, soil samples taken from the 0–20 cm layer do not reveal the P enrichment of the top soil. The soil P status can best be described by dividing the plough layer into a few layers and analysing the P_{Ac} values separately. Sharpley et al. (1986) also showed that there is a relationship between the soil P concentration of the top 1 cm of surface soil and the DRP concentration in runoff from cropped and grassy watersheds. The formula of Ekholm et al. (2005) is suitable for predicting DRP concentration from sites treated with manure. However, the formula may not fit in situations where a high P input to the soil surface is continued for several years. The formula fitted well on agricultural soils, but some limitations occurred in acid forest soils.

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