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REPORT

Environmental Services Provided from Riparian Forests in the Nordic Countries

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Abstract Riparian forests (RF) growing along streams, rivers and lakes comprise more than 2% of the forest area in the Nordic countries (considering a 10 m wide zone from the water body). They have special ecological functions in the landscape. They receive water and nutrients from the upslope areas, are important habitats for biodiversity, have large soil carbon stores, but may emit more greenhouse gases (GHG) than the uplands. In this article, we present a review of the environmental services related to water protection, terrestrial biodiversity, carbon storage and greenhouse gas dynamics provided by RF in the Nordic countries. We discuss the benefits and trade-offs when leaving the RF as a buffer against the impacts from upland forest management, in particular the impacts of clear cutting. Forest buffers are effective in protecting water quality and aquatic life, and have positive effects on terrestrial biodiversity, particularly when broader than 40 m, whereas the effect on the greenhouse gas exchange is unclear.

Keywords Biodiversity · Greenhouse gas exchange · Riparian forest buffer · Surface water quality · Clear cutting

INTRODUCTION

Riparian forests (RF) growing along streams, rivers and lakes have special functions in the landscape as the interface between the terrestrial and the aquatic ecosystem (Malanson 1993). The forest types along water bodies cover the whole continuum from those on dry sandy soils to wet peat dominated soil. The wet riparian zone has been subject to some research, whereas the drier forests next to water have received less attention.

The RF are habitats for a large number of forest species including many of the rare species that depend on water and as such serve as important areas for biodiversity (Darveau et al. 1995; Hylander 2004). Forests cover shade streams and moderate water temperature for the benefit of aquatic life. The litter production from the trees is important for stream food webs and stream production (Wallace et al. 1997) and has similar effects in small forest lakes (Sand-Jensen and Staehr 2007). Further, plant cover reduces erosion and stabilises stream banks.

The RF receive and process water, sediment and nutrients transported from upslope areas, and usually function as effective sinks for sediment and nutrients, thus regulating the nutrient loading to the aquatic system (Luke et al. 2007; Mayer et al. 2007). With ample supply of water and nutrients, RF may support high plant productivity and carbon (C) sequestration. However, in boreal and temperate forests most of the ecosystem C is stored in the soil. The soil C storage is largely dependent on soil moisture conditions and is generally increasing towards wetter conditions. Per unit area RF may thus hold greater C pools and sequester more C than upland forests. On the other hand, wet soils are potential sources of other greenhouse gasses (GHG) such as methane and nitrous oxide that have GHG warming potentials which are 25 and 298 times higher than CO_2, respectively, at a 100-year time horizon (Forster 2007).

Owing to the nutrient sink function of RF it is often recommended to maintain a strip of unmanaged vegetation as a buffer zone to protect water bodies from nutrients released from upslope forest management or agriculture activities. Today, areas adjacent to streams and rivers are often left unharvested in forest management practice in the Nordic countries (Photo 1).

Photo 1 Buffer zone left between a lake and a clear cut in Finland. *Photographer*: Erkki Oksanen, METLA

The design and efficiency of riparian buffers for control of nutrient transport to surface water are relatively well studied outside the Nordic countries (Broadmeadow and Nisbet 2004) especially in agricultural landscapes (Mayer et al. 2007; Sabater et al. 2003; Polyakov et al. 2005). However, other functions of buffer zones are rarely discussed. For instance, forested buffers may serve as refuge for biodiversity dependent on continuity in the landscape. Retained forested buffers may also enhance the biomass-C storage at a landscape level through their effect on forest age-class structure. They may possibly affect soil C storage through reductions in erosion and, e.g. through less decomposition due to lower soil temperatures in their shade. Their net GHG balance is, however, not well known (Maljanen et al. 2009). Further, forested buffers might have an aesthetic function especially for visitors on lakes. Although there are obvious ecological benefits, these need to be weighed against an economical loss that forest owners experience for setting aside buffer zones.

The European Union implements a new legislation based on the Water Framework Directive (2000/60/EC) in the coming years, and as such the interest in buffer zones as a measure in surface water protection may increase both in forestry and in the agricultural landscape where stream restoration could include establishment of RF buffers. The Nordic Council of Ministers has expressed a special interest in protection of forest waters in the Selfoss declaration (Selfoss Declaration 2008).

In this article, we describe the role and function of RF. We review literature on nutrient sinks, habitats, GHG exchange and C storage in RF. Our intention is to offer a synthesis balanced across the three functions rather than a comprehensive review of the vast information that is available for some of the functions. The aim is to provide knowledge for wise management and to evaluate the pros and cons as regards this special fraction of the forest area. We focus on the Nordic countries with climates ranging from Atlantic temperate to northern boreal. We have limited the analysis to the terrestrial functions and thus excluded the analysis of the influence on the aquatic life, which deserves a separate synthesis.

DEFINITION, CHARACTERISTICS AND PROCESSES OF RF

Hydrologically, RF are to a large extent discharge areas through which water flows before reaching surface water. RF are often characterised by a high ground water table and superficial subsurface flow created by ground water exfiltration. Overland flow may occur at high flow events. Often peat is accumulated, but mineral soils with thin organic layers can prevail as well.

As such, RF may span the whole continuum from waterlogged to dry conditions and they are located next to natural water bodies such as rivers, brooks, ponds, lakes and seas. Vegetation on RF can vary from the riparian type of field- and bottom vegetation including *Sphagnum* spp. and sedges to upland vegetation characteristic for dryer areas as well as vary from open areas via bushes to forested types. The distribution between overland and subsurface flow in RF exerts a control over the water protection functions related to the export of suspended solids and dissolved nutrients. This distribution varies according to seasonal and spatial conditions.

AREA OF FORESTS BY THE WATER

In order to evaluate the importance of RF in the Nordic countries, we calculated a rough estimate of the potential area of RF in each of the Nordic countries. We collected data on the length of streams and rivers as well as of lake shorelines based on 1:50,000 scale maps (Table 1). We assume that shorelines have the same frequency at forest land as other land uses, so that the fraction of forested shoreline is equal to the fraction of forest land in each country. We used a width of 10 m along the shoreline (at both sides for streams and rivers) to estimate the potential RF area. The relevant width varies with local conditions such as soil type, slope, and character of the water body, but when used as a buffer zone the width is often 10 m or more. If 20-m-wide strips were considered, then the areas of RF calculated in Table 1 would simply double. The estimated total area of RF in the five countries is 1.5 million ha or 2.3% of the forest land, ranging from 1.1% in Finland to 3.9% in Norway.

The shorelines areas are probably underestimated since the detail of 1:50,000 scale maps do not include all brooks

Table 1 Potential area of RF in the Nordic countries determined from maps at 1:50,000 scale

Country	Total stream + river length (Shore Length Data Sources 2008) km	Lake shoreline (Shore Length Data Sources 2008) km	Potential riparian area[a] 1000 ha	Total land area[b] 1000 ha	Total forest area[b] 1000 ha	Potential RF[c] 1000 ha	RF fraction of total forest area %
Denmark	68936	24906	163	4243	636	24	3.8
Finland	53510	214896	322	30447	23302	246	1.1
Iceland	69998	n.a.	140	6254	144	3	2.2
Norway	450897	295176	1197	30625	12000	469	3.9
Sweden	313453	411946	1039	41162	30785	777	2.5
Total					66867	1520	2.3

[a] 10 m on each side of streams, rivers etc. and 10 m around lakes

[b] FAO statistics

[c] Assuming a similar frequency of shoreline in forests and in the country as a whole

and small streams. Further, other wet parts of the forest such as depressions with water-saturated conditions and temporary open water, which also in part may have similar functions as the RF, are not taken into account by this method. In Finland, 1.3 million km of peatland ditches exists which in part may have similar functions as the natural streams since they transport water to rivers; however, it is not known if all ditches are indeed intact and functioning. If these ditches were considered in the calculation, then 10% of the forest area in Finland would be RF. Data on such ditches were also available for Sweden (0.36 million km) and Iceland (0.3 million km) which if included would increase the RF area fractions to 4 and 12%, respectively. In all, 2.3% of the forest area is a conservative estimate of the RF area in the Nordic countries.

WATER PROTECTION FUNCTION OF RF

Water transports a small proportion of the nutrient stocks present in the terrestrial part of the catchment to surface water, and this transport takes place through RF (Fig. 1a). The magnitude of water and nutrient transport depends on the area of upland that drains through the RF. The nutrients entering the RF can be taken up by the riparian vegetation or microbes, sorbed by the soil matrix, or deposited if attached to particles or exported to surface water.

Owing to the uptake and sorption processes, RF can function as a nutrient sink, i.e. the import of nutrients into RF is greater than the export, and the nutrient loading to surface water is reduced. When the upslope area draining through the RF is covered with forest, the nutrient transport into RF is rather small (Fig. 1a). In some cases, RF can act as a source of nutrients, e.g. in peat covered RF where the nutrient release through mineralisation exceeds the nutrient uptake and sorption (Cirmo and McDonnel 1997). A large

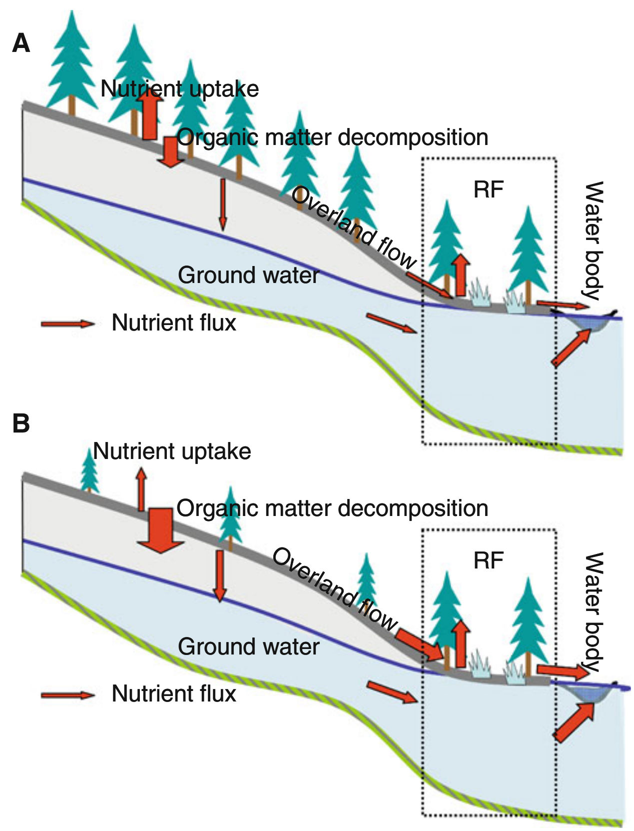

Fig. 1 Conceptual view of nutrient fluxes through the RF (**a**) before and (**b**) after clear cutting in the area upslope of the RF. Clear cut increases the flow of water and nutrients into the RF. A fraction of the nutrient flux can be taken up by vegetation and microbes or absorbed in the soil matrix of the RF. Evapotranspiration is deceased after the cut and thus the ground water table might rise somewhat, which then again may increase the risk of overland flow and erosion in wheel tracks or other micro-topographic furrows

portion of the dissolved organic carbon (DOC) entering the stream channel in boreal forests originates from the riparian zone (Ågren et al. 2008).

When the forest land upslope of the RF is subject to management operations such as harvesting, soil preparation or fertilisation, the influx of nutrients to the RF increases (Fig. 1b). In this article, we focus on clear cutting and potential subsequent soil scarification for regeneration or planting that are the most common management operations affecting RF. The increased nutrient influx into RF after clear cutting is due to (i) reduced evapotranspiration from the cut area leading to an increase in runoff (Andréassian 2004; Sørensen et al. 2009) and an elevated groundwater table in the RF (deeper snow cover and faster melt rate at the cut area further enhance runoff generation during snowmelt); (ii) reduced nutrient uptake by vegetation and increased organic matter decomposition enhancing nutrient leaching; (iii) exposure of soils to surface runoff increasing erosion risk (e.g. Ahtiainen and Huttunen 1999). The efficiency of RF to reduce nutrient export depends on soil and topographical characteristics of RF, hydrological pathways, vegetation and microbial activity and dimensions of RF in relation to the upslope area. We discuss these factors and the main retention processes in RF for reducing loads of suspended solids, nitrogen (N), phosphorous (P) and DOC. The processes and retention mechanisms of N and P discussed are applicable in connection with fertilisation, where RF are important buffers for avoiding direct application of fertilisers in surface water (Binkley et al. 1999).

Buffering impacts from clear cuts

After clear cutting and soil preparation, part of the soil surface is no longer covered by vegetation but consists of bare mineral soil. As a result, the risk for erosion and transport of suspended solids on the disturbed surfaces increases (Ahtiainen and Huttunen 1999), especially in wheel tracks, furrows and damaged stream banks. A RF buffer zone can decrease the export of suspended solids by decreasing the flow velocity of overland flow, and by increasing water infiltration into soil, thus enabling particle sedimentation. The sedimentation rate depends on flow velocity, particle size and particle density. The flow velocity of overland flow decreases with decreasing slope and increasing amount of vegetation and litter on the soil surface (Järvelä 2002, 2002b). When the flow velocity is sufficiently small compared with the sedimentation velocity, suspended particles can be deposited. Because the sedimentation velocity is proportional to particle radius squared, coarse particles are easily retained in RF. However, the deposition of silt and clay fractions and fine organic particles is unlikely, since the time required for their sedimentation is longer than the retention time in a typical 3–30 m wide RF. Fine sediment deposited to RF is easily resuspended during subsequent overland flow peaks. Prevention of sediment transport should not be based on countermeasures targeting sedimentation alone. The export of suspended solids is most effectively reduced when all overland flow is infiltrated into soil. Currently, little is known about the contribution of mineral versus organic particles in the suspended solids that are transported through or deposited in RF.

Clear cutting usually leads to elevated export of N to surface waters for a period of several years (Ahtiainen and Huttunen 1999; Grip 1982; Nieminen 2004; Löfgren et al. 2009). The most important processes occurring in RF that can decrease the N export are vegetation uptake (Silvan et al. 2005; Palviainen et al. 2007), retention to soil and assimilation to soil microbes (Silvan et al. 2003; Palviainen et al. 2004) as well as gaseous N fluxes from soil to the atmosphere (Regina et al. 1998; Silvan et al. 2002; Maljanen et al. 2003). Nitrogen export depends on the mobility of N fractions including ammonium (NH_4^+), nitrate (NO_3^-) and dissolved organic N (DON). Ammonium and DON mobility are reduced by chemical sorption in soil, whereas the sorption of NO_3^- is weak. RF decreases the export of NH_4^+ and DON to a larger degree than the export of NO_3^- (Kokkonen et al. 2006; Laurén et al. 2005). RF most effectively decreases N export when water is infiltrated into soil allowing adsorption in soil and uptake by vegetation and microbes. Nitrogen leaching can be decreased by denitrification, under anoxic moisture conditions and sufficiently high pH near the soil surface. Denitrification usually takes place near the margin between upland and RF (Jacks and Norrström 2004). The N retention in RF is limited during spring flood, when flow retention time is low (Laurén et al. 2005), and during winter periods, when vegetation uptake is absent.

The export of P to water bodies increases after clear cutting and soil preparation (Grip 1982; Nieminen 2004) as a result of an increase in soluble P compounds in soil solution and a simultaneous decrease in the uptake of soluble P by the vegetation. In addition, P can be released from logging residues, litter and other organic matter (Palviainen et al. 2004), from mineral weathering (Stevenson and Cole 1999), and under reducing conditions from P storage bound to Fe and Al compounds (Jensen et al. 1999). The transport of P through the RF decreases due to chemical sorption to soil, especially to Fe and Al compounds (Giesler et al. 2002; Väänänen et al. 2006), and due to uptake by understory vegetation and microbes (Silvan et al. 2004). Some P reaches the stream, especially outside the growing season when the biological activity is low (Väänänen et al. 2006). An uncut forested buffer between the clear cut area and the receiving surface water is found to be effective in mitigating P leaching from clear cuts (Niemelä 2001; Laurén et al. 2009) (Box 1; Fig. 2).

Dissolved organic C in soil water can be transported to water courses, where it can deteriorate water quality as a

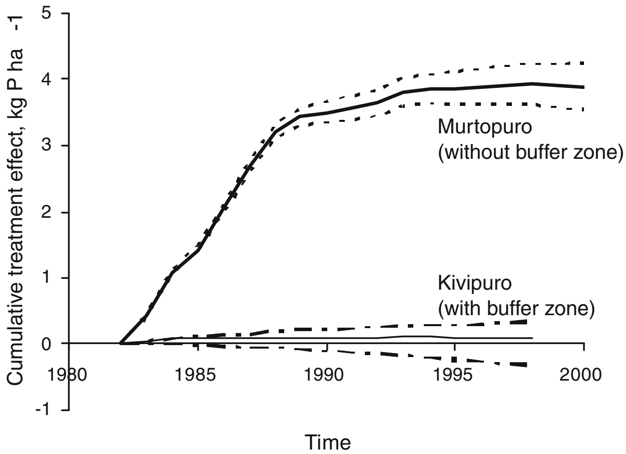

Fig. 2 The cumulative increase in P export to the stream comparing catchments with and without a buffer (including 95% confidence limits for the treatment effect). During the first 3 years after cutting, the increase without buffer was 1.4 kg ha^{-1} year^{-1} of catchment area. Background leaching was 0.1–0.2 kg ha^{-1} year^{-1} (modified from Laurén et al. 2009)

result of increased chemical oxygen demand (COD). Clear cutting increases decomposition of organic matter and the release of DOC into RF. Clear cutting in the upland area raises the ground water level in the RF, thus increasing the runoff and DOC export from the RF to the water courses. Rising ground water level can change RF into a source of C. RF can reduce the C export to water bodies when the water passes through mineral soil horizons that allow sorption of DOC into soil matrix. Further, rising ground water tables could potentially lead to greater fluxes of toxic methyl-Hg from the riparian zone (Bishop et al. 2009).

Managing buffer zones for water protection

The properties of an ideal RF buffer zone are partly contradictory with respect to the real prevailing conditions. Ideally, the soil should be a rather thin, permeable mineral soil that efficiently retains P and does not provide excessive pools of mineralisable N, and that directs the water as a subsurface flow through the rooting layer. In order to avoid overland flow, the area of the RF should be proportional to the size of the upslope treated area. The retention time in RF should be long enough to enable the physical, chemical and biological reactions and short enough to avoid prolonged saturation of the soil. The retention in the RF should work throughout the year and during the flow peaks. In an ideal situation, vigorous vegetation takes up nutrients and binds them into biomass for long periods of time. Such vegetation is composed of, e.g. trees and dwarf shrubs whose woody biomass decomposes slowly by fungi-dominated decomposer organisms that also immobilise nutrients.

In reality, the RFs often include wet peat soils, where the fluctuation of the ground water table controls the fluxes of N and P more than in mineral soils. The ground water table affects redox conditions that control the retention capacity of P. In peat soil, the pool of undecomposed organic matter is considerable, providing a vast potential for the formation of nutrient export to water bodies. Moreover, there is a risk of overland or superficial flow because of low hydraulic conductivity in deeper peat layers.

The protection of water quality is largely sustained by avoiding disturbances in the RF such as soil damage and elevated ground water levels. The management of the whole forest area must be carefully planned from a water perspective as well to achieve water protection goals in full. For instance, the location of logging roads and landings determines how off-road driving is performed adjacent to water. Knowledge on the environmental effects of different forestry operations and forest hydrology provides the basis for taking adequate countermeasures against adverse effects of forestry on water.

When aiming at good water protection, all measures that cause substantial erosion should be avoided on the management area and in the RF. Also, physical disturbance of the water body itself should be avoided; thus, water courses should preferably not be crossed by machinery, but when this is inevitable necessary precautions should be taken (cf. Ring et al. 2008). Site preparation methods that minimise the disturbance of soil and at the same time guarantee vigorous development of the new tree generation should be chosen. The forest cover of the RF should be kept as undisturbed as possible and the width of the buffer zone wide enough to allow time for sedimentation, i.e. increasing the width at increasing slopes. By avoiding rut formation both in the RF buffer zone and in upland areas many of these problems could be diminished.

Box 1 An intact RF buffer zone reduced suspended solids and nutrient export to water bodies after forest clear cutting in Finland

The effect of clear cutting on leaching to water bodies was studied in eastern Finland from year 1979 and onwards by a paired catchments approach. In 1983, clear cutting was performed on 56–58% of the area in two catchments (Murtopuro and Kivipuro), and in 1986, soil preparations were performed. The first catchment was cut without any water protection measures, whereas in the second, an intact RF buffer zone with the width of 30-50 m was left between the cut area and the stream. In the Murtopuro catchment suspended solids, N and P leaching increased due to the treatment. However, in the Kivipuro catchment with the RF buffer zone, none of the factors increased (Ahtiainen and Huttunen 1999; Laurén et al. 2009). The measured effect on P is illustrated in Fig. 2.

TERRESTRIAL BIODIVERSITY IN RF

There are two main arguments for the importance of RF for terrestrial biodiversity. First, RFs are supposed to host species that are adapted to these special conditions and, therefore, are found primarily within these zones. Secondly, RFs represent important forest habitat for generalist forest species. As such, RF may enhance landscape connectivity and act as important reservoirs of forest biodiversity, in otherwise heavily managed forest landscapes (Darveau et al. 1995; Hylander 2004).

Riparian forest species

Wet RF buffer zones harbour a special set of species not found in upland forested areas (Sabo et al. 2005; Hylander 2006; Sabo and Soykan 2006). In a meta-analysis of 47 studies worldwide (no Nordic studies included) on species richness and composition in both riparian and upland habitats it was found that RF did not host more species than upland habitats. However, the species pools found in RF were different from the species pools in upland habitats. The turnover (change) in species pools between riparian zones and upland habitats was found to be consistently high and significant. In fact, the proportional increase in regional species richness due to riparian habitats was on average 38% (Sabo and Soykan 2006). Furthermore, the displacement of species from riparian to upland zones was stronger for plants than animals and stronger in dry than wet climates (Sabo et al. 2005). Animals are mobile and can take advantage of seasonally varying microclimates and riparian resources and may therefore utilise both riparian and upland areas. Plants on the other hand, are sessile organisms and are therefore forced to cope with the local environment. The high degree of species turnover in dry climates probably reflects the more pronounced environmental gradients in dry climates such as soil humidity, water temperature and seasonal variation in moisture. These patterns of RF having different species, but not a higher mean number of species, are supported by a study on wood fungi in Finland (Komonen et al. 2008) where the authors also found that flat riparian sites harboured more species than sloped riparian sites.

Water and adjacent wet ground may function as fire-breaks and refuges in a natural landscape. Thus, one may argue that these environments and the organisms that live there are less adapted to disturbances such as clear cutting than other environments (e.g. Angelstam 1998). However, we have found no study confirming that riparian species in general are less tolerant to clear cutting than upland species. In fact, the opposite was found in a study comparing old (never clear cut) and young (30–50 years after clear cutting) riparian and upland habitats (Dynesius et al. 2009). Greater differences were found in bryophyte (moss and liverwort) assemblages between old and young stands. This difference was higher for upland than for riparian sites indicating higher resilience in riparian than in upland forests.

Many terrestrial species are favored by tree retention in RF as compared to clear cutting. Forest songbirds in British Columbia benefit from buffers >30 m in width, whereas at widths <15 m they were replaced by generalist and open-habitat species (Haag 2002). Studies on mosses and liverworts indicate that even with 10–15 m wide RF buffer zones along each side of a stream only edge habitat occurs (Hylander 2005). Probably an intact RF zone of 40–50 m is sufficient to avoid edge effects, such as changes in air and soil moisture and temperature, in the most interior parts. Using snails as indicators a 10 m wide buffer zone may be sufficient since these organisms may survive in hollows and crevices, especially if the site is wet or moist. Thus, species that are dependent on moisture may be more tolerant to edge effects at wet than at mesic sites (Hylander et al. 2004). This is contradictory to certain guidelines that promote wider strips at moist sites. Aspect is also important, since North-facing edges suffer less from edge effects than south-facing (Hylander 2005; Åström et al. 2007). The location of the buffer in the landscape in relation to prevailing winds should be considered in making decisions on the width, especially in the case when only on side of a stream is cut and the other side of the stream is left untouched.

Forest generalist species

Even though there is a considerable change in species compositions between RF and upland forest, many generalist forest species are commonly found within the RF. Riparian buffer zones may therefore act as important areas for these species. RF are found to be utilised more frequently by songbirds than upland forests, both during the breeding and during the fall migration periods (e.g. Mosley et al. 2006). As an example, neotropical migrant songbirds were captured more frequently in mist nets located perpendicular to the streams during both breeding and fall migration. These results indicate that streams may act as movement corridors for forest birds (Machtans et al. 1996). The general value of corridors for dispersal has been questioned (Machtans et al. 1996; Simberloff and Cox 1987; Gustafsson and Hansson 1987; Niemelä 2001; Öckinger and Smith 2008). Several factors may influence the general value of corridors. First, actively dispersing species, such as birds, mammals and insects are thought to benefit more than passively dispersed species, such as fungi, bryophytes and lichens. Secondly, the spatial context of the corridor in relation to the landscape matrix appears to be important (Öckinger and Smith 2008; Lindenmayer and Franklin 2002).

Managing buffer zones for biodiversity

There is strong supportive evidence that RF buffer zones are important for landscape biodiversity. They host species that are rare elsewhere and they support landscape connectivity and may thus act as reservoirs for generalist species. There is no strong supportive evidence that these habitats are less tolerant to disturbance than upland habitats. Their significance as movement corridors for dispersing species is unclear and needs to be researched more.

The overall recommendation for buffer zone management is to leave as much forest as possible along streams and lakes. The wider the strip the better it is for biodiversity. However, this is a recommendation of little value to forestry. Another way of addressing the problem is to ask how a given area of forest should be left along a water course. Should it be short and wide, or narrow and long? That depends on the aim. If the aim is to create corridors, then the obvious recommendation is narrow and long. If the aim is to secure habitats for moisture-dependent organisms, then the recommendation would be to concentrate on wide buffer strips along certain forest types or habitats, rather than leaving a long thin strip along all riparian zones (Komonen 2009). As argued by Hylander (2004) the area per se and the quality of the RF may be important for terrestrial biodiversity. Acknowledging that buffer zones of up to a width of 40 m are sometimes necessary to maintain pre-logging species composition (e.g. Whitaker and Montevecchi 1999), it is be better to leave certain forest types or habitats as buffer zones, than to have fixed buffers throughout the landscape. In a Nordic context, Hylander (2004) recommends three types of sites which should be prioritized with respect to wider RF zones: (i) sites with erosion prone fine sediments which can represent a threat to fish fauna if it is eroded into the rivers, (ii) wet and moist sites which can experience changes in hydrology if the soil is disturbed or compacted as a result of off-road driving and (iii) sites with woody debris and boulders which inhabit species requiring a moist microclimate, such as species on dead wood and rocks.

As mentioned in the introduction, forest buffer zones are important for the aquatic biodiversity which is an argument for keeping at least partial canopy cover over streams, though probably with less requirements for the width than for the terrestrial biodiversity. Changes of tree species from broadleaf to (exotic) conifers in the RF may have significant negative effects on the in-stream biodiversity (Friberg 1997). Thus, recommendations on RF buffer management include retention of the natural (often broadleaved) tree species at the site and selective cutting of exotic species.

CARBON STORAGE AND GREENHOUSE GAS DYNAMICS IN RF

Trees are responsible for the forest C uptake and intermediate storage, but the main long-term storage of C is in the soil. In boreal climates 80% of the forest ecosystem C is stored as soil organic C (SOC) (Dixon et al. 1994). Studies of CO_2 exchange as well as C storage in forests have mainly focused on upland systems, and thus less is known about these processes in RF.

Owing to the influx of water and nutrients from the upland, a higher C uptake and biomass production may be hypothesised for the RF compared to the upland, although water logging may constrain plant growth in wet parts of the RF. Studies from France and Canada did, however, not find evidence for such a difference in the biomass C pools between upland and RF (Eglin et al. 2008; Hazlett et al. 2005).

The SOC content in soils depends among other things on the hydrological characteristics of the soil and a 45% increase in SOC was found in moist compared to dry podzols in Sweden (Olsson et al. 2009). A detailed study along two streams in France revealed increasing SOC stocks towards the stream and at wet conditions (Eglin et al. 2008) and a study from Canada found thicker organic layers and more SOC in the RF compared to the upland (Hazlett et al. 2005). The main reason for increased SOC under wet conditions is that decomposition of organic matter is limited by lack of oxygen, thus soil respiration (CO_2 efflux) decreases when the ground water table is close to the surface (Laine et al. 1996; Jungkunst et al. 2008).

The emissions of the strong GHGs, CH_4 and N_2O, are known to increase under wet conditions. The N_2O emissions peak at intermediate soil moisture and increase at acidic conditions, whereas the CH_4 emissions largely occur at water saturated conditions (Maljanen et al. 2003, 2009; Jungkunst et al. 2008; Christiansen, in review). Although wet soil conditions may only prevail in a minor part of a catchment such as the RF area, the emissions are high enough to be important at the catchment or landscape level. In a forest area in Germany, N_2O emissions were estimated to double (Jungkunst et al. 2004) and CH_4 estimated to change from a small sink to a source (Fiedler et al. 2005), when the actual distribution of upland and wet soils were accounted for compared to when the upland measurements were taken as average for the area.

The increased CH_4 and N_2O emissions in the RF may be fully compensated by the reduced CO_2 efflux in the RF; however, this observation is based on only a few studies (Laine et al. 1996; Jungkunst et al. 2008; Jungkunst and Fiedler 2007). Saari et al. (2009) recently showed that sedimentation ponds in peatland forest buffers with high N loads can be potential hot spots for N_2O emissions. Thus, the full GHG budgets in forest catchments is further complicated by the fact that terrestrial produced N_2O, CH_4 and CO_2 dissolved in soil water may be transported to and released from the water body (Fiedler et al. 2005). Also, the fate of terrestrial DOC needs to be considered in a catchment or landscape GHG balance. It is therefore not surprising that different authors have reached different conclusions as to whether or not RF areas are important sources of GHG at a landscape level (Maljanen et al. 2009; Fiedler et al. 2005; Saari et al. 2009).

Managing buffer zones for C storage and GHG balance

The objective when managing RF zones should generally be not to change the C storage or the GHG sink or source function of the ecosystem. Changes happen along with different management schemes, and changes in GHG exchange are to a large extent governed by operations performed outside the RF zones. The GHG balances are more likely to be affected at the wet peatland soils than at dryer RF soils. In the following section potential effects on RF GHG exchange after clear cutting, when cutting the RF versus leaving it as a buffer, are discussed based on theoretical considerations, since we have found no studies on this subject.

Clear cutting will decrease the vegetation C stock. Therefore, there is an initial positive effect on the standing C stock if RF buffer zones are left standing, both at a local and at a landscape level. The positive effect on the aboveground C storage can last for decades depending on the site productivity. Increased increment downslope of clear cuts were found at two out of six investigated sites (Lundell and Albrektson 1997), presumably due to increased water and nutrient availability. Eventually, an unmanaged RF zone will reach a stage where net biomass accumulation becomes slow or even negative. What happens with SOC is not well understood, but it has recently been shown that old-growth upland forests generally are C sinks long after their net aboveground C storage has gone down (Luyssaert et al. 2008).

Clear cutting increases the runoff, which is likely to raise the ground water table, especially in RF zone (Fig. 1b). This will most probably lead to an extension of the discharge areas with alternating redox potentials in the soil and a larger area with water saturated soil in the RF. This could theoretically increase the emissions of CH_4 (larger RF fraction being a source) and of N_2O (more intermediate wet areas and increased dissolved N inputs), but the soil respiration may be reduced by lack of oxygen in those same wet areas. Since these potential effects are caused by water level changes from cutting the upland forest, this is not expected to differ if the RF is cut or left as a buffer zone. However, if the RF area is cut, the shading will change, and the soil temperature may increase. Since the emission of CH_4 and N_2O as well as the soil respiration (CO_2 efflux) all increase with temperature, these changes could lead to higher GHG emission from a cut RF than when it is kept as a buffer zone. We are not aware of any studies that have looked at this indirect effect.

The RF zone thus seems to be important for GHG exchange, and the balance among the different processes needs further attention. Experimental verification is particularly needed to identify whether RF buffer zones make a difference on GHG exchange.

SYNTHESIS AND RECOMMENDATIONS

We estimated RF to account for at least 2.3% of the forest area in the five Nordic countries (1.5 million ha), which is an area comparable to twice the area of annual cuts. Our analyses reveal that RF is important for the protection of water quality and aquatic life but also for the protection of terrestrial biodiversity, and although small in fraction, the RF area may be as important for GHG exchange as the rest of the forest. It is thus necessary to recognise the special characteristics and functions of RF it self forest management and planning; not merely the use of RF as a buffer zone against impacts of upland management on the water body.

Our analysis of the information on the functions of a RF buffer in upland forest management, in particular clear cutting, revealed only positive environmental effects including benefits for biodiversity. However, not much is known about the GHG exchange in a buffer zone. A trade-off is the immediate economic loss experienced by the owner from leaving the buffer uncut. It also needs to be mentioned that there is a risk for wind throw in exposed buffers which then may reduce its water protection function (Grizzel and Wolff 1998). Careful planning of the management operations and observing the management recommendations that reduce erosion risks from the operations (Ring et al. 2008) may further reduce the impacts of the upland management and improve the effectiveness of the buffer.

Recommendations on the appropriate width of an effective buffer zone are difficult to give, since the local conditions (slope, upland area size, vegetation and hydrological characteristics) as well as the purpose of the buffer need to be taken in consideration. Various technical details on buffer width, designs and nutrient sink effectiveness can be found in (Luke et al. 2007; Mayer et al. 2007; Broadmeadow and Nisbet 2004; Polyakov et al. 2005). In general, vegetated buffer widths of at least 20–30 m are recommended to obtain benefits for water, biodiversity and GHG exchange.

Leaving a vegetated buffer after clear cutting may support the perception that buffer zones should be left unmanaged. However, what is important for water chemistry and the GHG balance is an active layer of vegetation that can provide a continuous sink for nutrients and CO_2. In some situations, it may thus be beneficial to manage RF to facilitate succession and multi-storied forest types as well as to cut exotic tree species. Thinning of the RF may best be performed when a new stand is already established on the upland, e.g. jointly with early thinning of the new stand. Harvesting operations in the buffer zone at the time of clear cut or later should be performed without allowing machinery to enter the buffer.

In the implementation of the EU Water Framework Directive at the catchment and landscape scale, the use of RF functions can be an important instrument and motivate new regulation of RF in the coming years. A compilation of current legislation, regulation and recommendations through certification standards and practices related to RF buffer zones is available for the five Nordic countries on www.nordicforestry-cares.org. In general, there was little legislation directly related to land areas close to streams, though a recent Danish regulation restricts the activities in a 2 m wide buffer zone along streams and lakes. The rules and recommendations on RF buffer zones are often not well developed. They can be spread widely in different regulations and recommendations, which at times can lead to contradictions. Norway is the Nordic country which has the most exact rules and outlines for how buffer zones should be kept and managed. Iceland, on the other hand, has not considered it at all. Current regulations and recommendations target the protection of the aquatic environment. Future developments should also include considerations of the terrestrial biodiversity and the GHG exchange issues.

Forested buffers could be used more widely in agricultural landscapes of Fennoscandia to reduce nutrient loads to waters. It applies to the catchment/landscape perspective introduced by the Water Framework Directive and can be an essential instrument in meeting water quality criteria. Forested buffers appear to be more widely used in controlling diffuse pollution in North America (Mayer et al. 2007). At the same time, forested buffers establish corridors that may benefit biodiversity and protect (and potentially enhance) C stored in wet soils and increase the C sequestration in the permanent vegetation.

The nutrient sink function and the physical protection on streams (bank stabilisation, temperature, and shade) are relatively well understood and documented, but mainly for conditions outside the Nordic countries. Although RF buffers are increasingly used in forest practise and required in certified forestry, there has been little monitoring of their effectiveness. Thus, a recent Swedish review called for more research in the Nordic counties (Lindegren 2006).

RF is not only important for stream biodiversity but also for the forest biodiversity along the water courses. As a general management recommendation for forest biodiversity, we suggest that priority is given to buffer zones of certain forest types and habitats. In a Nordic context, these are wet and moist sites, and sites with boulders and dead wood.

It is not clear to what extent RF should be prioritised, in relation to upland sites, during selection of sites for biodiversity. If the aim is to maximise the overall number of species protected then both upland and RF forests are needed. The required RF area of each forest type will depend on the ratio of species being confined to RF and upland forest, as well as the spatial turnover of species within each group. No Nordic studies have addressed these questions in any detail.

Data on the role of RF and RF buffers in landscape GHG budgets are sparse. Investigations of both vegetation and soil C storage as well as of the GHG exchange in RF gradients are needed to conclude on their importance. Experimental approaches including investigation of all functions at the same location(s) should be encouraged. These may also include research on how to manage RF areas in a long-term perspective.

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