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Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation

Benjamin Christen*, Tommy Dalgaard

Aarhus University, Institute for Agroecology, Blichers Allé 20, DK-8830 Tjele, Denmark

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ABSTRACT

Buffer strips on agricultural land have been shown to protect surface water quality by reducing erosion and diffuse pollution. They can also play a key role in nature conservation and flood risk mitigation as well as in the design of bioenergy landscapes resilient to changes in climate, environmental pressures from intensive agriculture and policy developments. Use of conservation buffers by farmers outside of designated schemes is limited to date, but the increasing demand for bioenergy and the combination of agricultural production with conservation calls for a much wider implementation.

This paper reviews the biophysical knowledge on buffer functioning and associated ecosystem services. It describes how a three-zone buffer design, with arable fields buffered in combination by grassland, short rotation forestry (SRF) or coppice (SRC) and undisturbed vegetation along water courses, can be incorporated into farming landscapes as productive conservation elements and reflects on the potential for successful implementation.

Land use plays a much greater role in determining catchment hydrology than soil type: shelterbelts or buffer strips have markedly higher infiltration capacity than arable or pasture land. Root architecture of trees, shrubs and herbaceous plants differs between species and is important for the extent of hydrological changes after establishment. Riparian buffers retain 30–99% of nitrate N and 20–100% of phosphorus from runoff and shallow groundwater. Buffers are also highly effective for pesticide removal and farmland biodiversity conservation with a high potential for low-input fuel, feed, or fibre production. Landscape amenities, sporting opportunities, and a display of land stewardship are additional benefits.

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1. Introduction

1.1. Background

In the 1980s, research into riparian buffers and other landscape elements planned to reduce nonpoint-source pollution, and potentially produce biomass for bioenergy, really began to develop [1,2]. In the following 30 years, with the raised nature

protection concerns and energy prices, an impressive amount of studies have been published on the subject, enough to recently warrant a comprehensive review or meta-analysis every few years on the details of buffer functions for specific contaminants like N [3], P [4,5], sediment [6], a mix of these [7,8] or the potentials for bioenergy production from biomass [9,10].

Despite deep insights into nutrient cycling and contaminant pathways, the answer to one question remains elusive:

* Corresponding author. Tel.: +45 8715 4761.

E-mail address: benjamin.christen@agrsci.dk (B. Christen).

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'How widely applicable are the effects we observed?' [1] p. 1474. What can be said with certainty is that, apart from the added benefit of low-input biomass production opportunities, managed buffers do have a positive effect for water quality conservation although the exact quantification on larger scales has been unattainable so far.

1.2. Why install buffers for biomass production?

The reasons for installing buffers for environmental protection and thereby creating bioenergy production landscapes in the meantime remain as important as ever: the eutrophication of streams, lakes and estuaries that threatens ecosystems and fisheries in coastal waters through algal blooms and oxygen depletion events (hypoxia) has been brought down by action plans and monitoring programs such as found in Denmark [11,12], but the problem of hypoxia in shallow waters receiving nutrient inputs from intensive agriculture like in most of the Baltic Sea has proved to be persistent [13]. As the EU Water Framework Directive [14] demands good ecological status of water bodies by 2027 at the latest, further reductions in nutrient losses are needed; a goal which in many areas will be hard to achieve with existing best management options. With rising energy prices, the future shortage of fossil energy sources and the threatening climate changes, new measures that combine environmental protection with renewable energy production and carbon sequestration for the mitigation of greenhouse gas emissions are required [15]. One way to meet these challenges may be a rethinking of farming systems into combined food and bioenergy production landscapes.

1.3. Aim

This paper aims to (i) review the biophysical knowledge on buffer functioning relevant for designing efficient and environmentally friendly biomass production buffers in conjunction with reflections on landscape impacts and on-farm decision making, and (ii) present buffer designs to be implemented in a real bioenergy landscape scenario and the potential benefits thereof to farmers.

2. Methodology

An extensive, desk-based literature review was conducted to establish the current knowledge on

- 1 Hydrological effects of tree planting and buffer establishment
- 2 Buffer functioning for mitigation of surface water pollution by nitrogen, phosphorus and pesticide leaching, focussing on how the biophysical processes influence practical design considerations such as buffer structure, slope, width and placement
- 3 Biodiversity effects of introducing linear, semi-natural landscape features like shelterbelts and buffers and partially substituting high-input annual crops with low-intensity perennials
- 4 Biomass yields of multipurpose grasses and suitable SRC and SRF tree species

- 5 Socio-ecological factors related to buffer establishment like landscape perceptions and farmer decision making regarding landscape management.

Based on these findings and considering the available space and probable production aims for biomass and timber in two Danish research landscapes at Bjerringbro/Hvorslev sub-catchment of the river Gudenå, central Jutland (9°40'13.2018" E, 56°20'27.7039" N) and Norsminde Fjord catchment, eastern Jutland (10°14'02.8130" E, 56°00'39.5032" N) along with the properties of typical farm equipment and forest service provider machinery, 7 distinct buffer layouts were designed. These viable designs were then analysed for their potential benefits to farmers in the areas of environmental regulations, farm economics, time management and personal interests and preferences. To verify the findings, design viability and compatibility with farmers' interests, a 0.2 ha trial site was established.

3. Findings: biophysical knowledge and environmental effects

3.1. Hydrology

For surface runoff, land use is the defining parameter for the hydrology of any area. According to Bachmair et al. [16], it determines soil structure and infiltration capacity to a much higher degree than soil type and is the reason for fundamental hydrological differences between e.g. fields and forests. Landscape structures like shelterbelts or buffer strips therefore change the local hydrology. If placed at the bottom of a slope, a shelterbelt preferentially takes up water from lateral flow, leading to a drying effect for the slope above the shelterbelt and an increase in its ability to absorb moisture during autumn rewetting [17]. Runoff is reduced and infiltration on the slope is enhanced, reducing the amount of nutrient loss. As long as the soil is not saturated, surface runoff reaching a shelterbelt/upland buffer is caught in a sink-for-runoff effect as former fields and areas used for grazing planted with trees have an up to 20 or 60 times higher infiltration capacity respectively [18,19]. Living tree roots provide fast pathways for water into deeper soil layers [20,21] and enhance water holding capacity by adding substantial amounts of organic matter as well as increasing soil porosity [22]. The changes happen within a timeframe of only a few years [19,23]. Marshall et al. [24] conclude, from a study in mid-Wales, that landscape structures such as fenced off shelterbelts in the uplands therefore have the potential to reduce the flashy response character of catchments to heavy rainfall events and mitigate flood peaks and flood-related damages.

The hydrological effect of trees is species dependent as the root architecture and penetration capability varies substantially (Fig. 1), affecting water uptake rate and distribution of infiltrating water.

The influence of tree evaporation on groundwater is dependent on season, height of the water table and slope of the aquifer. Ryszkowski and Kędziora [25] showed, on a sandy soil in Poland, that water uptake from the groundwater table (as opposed to other available water in the soil matrix) by

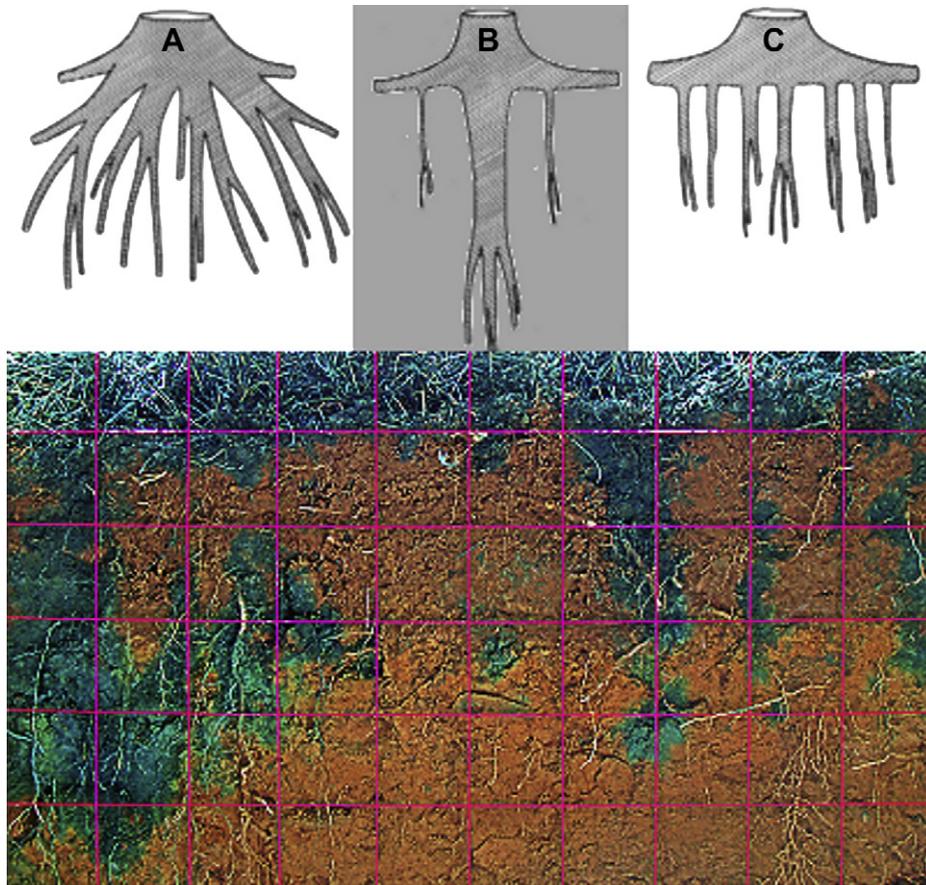


Fig. 1 – The three major root system classes: (A) diffuse heart shaped, (B) taproot, (C) sinker [37] compared to photographs of a type A root from Downey Birch (*B. pubescens*, left) and a type C root from Common Ash (*F. excelsior*, right). Root architecture under fenced off shelterbelt on stony clay soil revealed by application of dye solution (Brilliant Blue FCF 4 g l⁻¹) equivalent to 80 mm precipitation over duration of 8 h. One box is 10 × 10 cm (after [20]).

shelterbelts varied between 18 and 37% of overall tree water use at the beginning of the growing season to 30–50% in summer. In their study of 10 m wide shelterbelts, an aquifer slope of 4% or 1% translated to an uptake of groundwater influx of 18% or 68% respectively. According to Burt et al. [26], in general the groundwater table is lower under a shelterbelt than under the adjoining fields, creating an influx of groundwater towards the shelterbelt. In prolonged dry periods this can in the case of riparian buffers lead to a reversal of the hydraulic gradient between stream and buffer with surface water infiltrating into the buffer zone.

3.2. Nitrogen

The effectiveness of riparian buffers in retaining or removing nitrate-N (NO₃⁻) through plant uptake or denitrification has been shown to be in the range of 30–99% regardless of buffer composition, although buffers combining grass and trees tend to be more effective than buffer strips consisting only of herbaceous vegetation [3,25,27–32]. It has been shown that some riparian grass-buffers turn into a net source of NO₃⁻ after a few years if there is no removal of biomass [33]. Evidence points into the direction of tree or grass-tree buffers displaying the same behaviour [34].

Denitrification is efficient under suboxic conditions and with readily available organic carbon; it can remove 30 kg ha⁻¹–170 kg ha⁻¹ of NO₃⁻ [35,36]. Burt et al. [26] describe the process as of special importance during winter when the water table in riparian buffers tends to be high enough to induce suboxic conditions in the upper soil layers of flat stream banks which are rich in organic matter. Buffers on steep slopes will therefore usually not be very effective at denitrification. Trees enrich the lower soil layers with organic carbon due to their deep root network and various root exudates [37]. Autumn leaf fall is also likely to play a role in reducing NO₃⁻ leaching as it adds considerably more C than N to the upper soil layers and increases the potential for other N-immobilising processes [28]. This effect is enhanced by a high C/N ratio in the leaf litter [38] as found in tree species like birch (*Betula* spp.), poplars (*Populus* spp.) and many conifers.

Species-specific N-uptake values have not been studied much to date. Tufekcioglu et al. [38] measured long-term N-immobilisation (harvestable N) of 37 kg ha⁻¹ a⁻¹ in living and dead biomass of poplars (*Populus* spp.) in a buffer strip. Uri et al. [39] showed that the N-uptake of silver birch (*Betula pendula* L.) increases significantly with increasing soil NO₃⁻ levels and varies between 5.5 and 10.5 kg per metric ton of dry matter (DM) produced. 41–62% of the assimilated N is found in

the leaf biomass and is therefore not immobilised. With an average N-uptake of $175 \text{ kg ha}^{-1} \text{ a}^{-1}$ for young birch (*Betula* spp.) trees on former arable land [40] this means an annual N-immobilisation between 103 kg ha^{-1} and 67 kg ha^{-1} . Fortier et al. [41] also showed large variation of N-uptake dependent on available NO_3^- with poplar hybrids (*Populus* spp.) at different sites accumulating between $47 \text{ kg ha}^{-1} \text{ N}$ and $490 \text{ kg ha}^{-1} \text{ N}$ in woody biomass over 6 growing seasons. How species-specific C/N ratios in leaves or needles influence N-immobilisation in this context has apparently not been published.

Apparently, biodiversity effects on N-uptake in buffer strips have also hitherto not been published. Species choice for buffer establishment therefore can only be informed by growth potential and, if known, rooting behaviour to maximise utilization of the available rooting space.

Drainage negates most buffer effects as N removal by either plant uptake or denitrification is dependent on the residence time of water in the buffer strip [4,26,42–44].

A negative side-effect of denitrification is the production of nitrous oxide (N_2O), a powerful greenhouse gas (GHG). As Davidson and Firestone [45] described with their 'Leaky Pipe' model, N may leave a buffer system in various ways, one of which is in the form of N_2O emitted from the soil surface to the atmosphere. Hefting et al. [46] showed that permanently N-saturated buffers, woodland to a higher degree than grass, can be very conducive to this process. Also, plant species able to actively transport gases via aerenchyma like alders (*Alnus* spp.) or reed meadow grass (*Glyceria grandis* L.) provide direct pathways for N_2O effluxes from lower soil layers, bypassing the upper soil layers which have been shown to regulate soil surface N_2O fluxes and equalize the spatially highly variable N_2O production in the subsoil [47]. So far it has not been possible to calculate N_2O emissions from buffer zones on a landscape level, mainly because of the process heterogeneity in riparian zones which has been conceptualized as 'hot spots and moments' of retention, degradation and production [48]. To our knowledge there are no studies published on the GHG balance of fossil fuel substitution by biomass for bio-energy production in buffers and the accompanying increase in N_2O emissions. Likewise, there seems to be no comparative data on N_2O emissions further down the system, especially in coastal bottom waters where high nutrient loading induces the narrow band of limited oxygen-availability where N_2O production peaks, an effect widely observed in the Baltic Sea.

3.3. Phosphorus

The effectiveness of buffer strips in retaining P varies between 20% and 100% [29,31,49–51] with the main P losses due to streambank erosion and sediment-bound particulate P in runoff, although losses through drainage and leaching of soluble P due to a high groundwater table also play important roles [52,53]. Decreasing sediment particle size decreases the amount of particulate P that can be retained in buffers. Diebel et al. [49] state that 25% of the clay fraction in a given sediment load cannot be buffered as the fine particles remain in suspension and reach watercourses with the part of field runoff that does not infiltrate. Since P preferentially binds to clay minerals they calculate that 20% of the sediment P load is unbufferable if 10% of the sediment is of the clay fraction. In

areas having predominantly clay-soils it is therefore important to minimize the loss of P as most of it will be unbufferable.

Very flat areas pose another difficulty for buffering P, as runoff follows microtopography resulting in slow flowing rivulets and ponds across fields, keeping fine particles in suspension and washing P from plant surfaces. For this case, Sheppard et al. [54] recommend asymmetric, strategically placed perennial vegetation.

A grass strip containing stiff stemmed grass that cannot be flattened by runoff is seen as an essential component of any buffer strip designed to capture sediment and thereby particulate P in most studies [4,6,32,54–56]. The grass strip reduces runoff velocity and spreads the runoff more evenly, facilitating better infiltration and sediment capture.

According to Cooper et al. [33], most P is retained in the upper 5–10 cm of the soil where particulate P is slowly transformed into soluble, biologically active P. Conditions favourable for denitrification and therefore NO_3^- removal also speed up this transformation process [4]: unmanaged riparian buffers without regular biomass removal soon start to leach soluble P [54,57,58], turning the problem of N in estuaries and coastal waters into a problem of P in rivers and lakes.

Herbaceous biomass removal should take place at least once a year before the first frost as P in decomposing plant material is rapidly transformed to soluble P by freezing/thawing cycles [59]. Published harvestable amounts of P for grasses in riparian buffers are between 10 kg ha^{-1} and 15 kg ha^{-1} for a single yearly cutting [5,57,60]. Sheaffer et al. [61] report a P-uptake of 72 kg ha^{-1} for reed canary grass (*Phalaris arundinacea* L.) on a wastewater application site with extreme NO_3^- availability. Although multiple cuttings and extensive grazing are mentioned in some studies as a way to achieve nutrient removal, apparently no data on the actual net effect has so far been published.

P immobilisation values for woody biomass published range from $1.5 \text{ kg ha}^{-1} \text{ a}^{-1}$ to $15 \text{ kg ha}^{-1} \text{ a}^{-1}$ [5,39,41,57], the high variability between the studies resulting from differences between near-boreal and temperate climate zones as well as different tree species and site-specific N-availability. P-uptake does not seem to increase under conditions of high P availability [39].

3.4. Pesticides

Pesticide trapping efficiency is difficult to generalize, as different pesticides have different properties regarding solubility, sorption characteristics and mobility under different hydrological conditions [62]. According to Otto et al. [63], grass strips of 4–6 m width are the most effective buffer type to retain many different pesticides with efficiency close to 100%. Lin et al. [64] measured grass strip efficiency of up to 80% for retaining and degrading 'Atrazine' (2-chloro-4-(ethyl-amino)-6-(isopropylamino)-s-triazine). C4 plants were more suitable for degrading this pesticide than C3 plants and degradation correlated with microbial activity. Other pesticides like 'Isoxaflutol' (5-cyclopropyl-4-(2-methanesulphonyl-4-trifluoromethylbenzoyl)isoxazole) are degraded abiotically and species composition has no influence on the process. Most pesticides sorb preferentially to dead organic material: cutting the grass strip without biomass removal increases

effectiveness. The same is true for leaf litter [50]. Not removing the biomass will lead to nutrient leaching, so it may be a matter of timing to achieve both pesticide retention and nutrient removal. Lowrance et al. [65] calculated pesticide trapping efficiency from runoff reaching the watercourse while still above ground to 2–6% m⁻¹ buffer strip and close to 100% after infiltration in the buffer zone using 'Alachlor' (2-Chloro-N-(2,6-diethylphenyl)-N-(methoxymethyl)acetamide).

Often used buffer species like poplar (*Populus* spp.) and willow (*Salix* spp.) are known for their ability to take up a wide range of pollutants, including pesticides and their degradation products, and immobilize them in woody parts of the tree [66].

3.5. Buffer placement and establishment

Tomer et al. [67] describe buffer placement as the aspect that first and foremost determines if nutrient retention will be in the range of 10–30% or 70–100%. Riparian buffers should be placed along 1st and 2nd order streams after studying local hydrology, physically surveying local microtopography and soil type and avoid a purely map based standardized buffer design which is likely to be ineffective [54]. This is confirmed by Vidon et al. [48], who show the importance of localising 'hot spots' for nutrient retention and mobilisation in the landscape as well as 'hot moments' in the course of a year where pulses of nutrient exchange activity occur. Schmitt et al. [68] advised against buffers consisting only of grass strips, as they found that non-sediment-bound pollutants in runoff were not retained effectively. To which degree vegetation increases surface porosity and infiltration capacity is more important than actual buffer width [31]. This is supported by Mayer et al. [3], who also describe buffer width as less important.

Schultz et al. [43] describe establishment of a 20 m wide riparian buffer consisting of trees along the stream, a row of shrubs and a 7 m grass strip. 10 years later on, the system is described as efficient, easy to maintain and resilient to floods and other disturbances [32]. They dealt with the existing tile drains by rearranging the drains and collecting the outflow in a wetland with an area of 1% of the drained upland. Existing drainage will always have to be dealt with, as it negates most buffer effects. Grass strips should, according to Liu et al. [6], ideally have a width of 6 m and a slope of around 9% for optimal runoff dispersion and sediment retention. Stiff stemmed species that form mats are best suited, but forage grasses or grass mixtures for other purposes can also be used. Including catch crops like oilseed radish (*Raphanus sativus* L.) in the establishment phase may be beneficial to quickly soak up excess nutrients as it has very deep roots and a growth potential of up to 10 t ha⁻¹ DM [69]. Other suitable species in this respect are rye (*Secale cereale* L.), ryegrass (*Lolium perenne* L.), white mustard (*Sinapis alba* L.), chikory (*Cichorium intybus* L.) and woad (*Isatis tinctoria* L.), which will all help to establish ground cover, suppress aggressive weeds and prevent NO₃ leaching [70].

3.6. Biodiversity

Apart from removing pesticides from runoff, buffer strips can reduce the need for pesticide applications by harbouring beneficial species [71,72]. Species dispersal between wooded areas and cropland is mostly one-sided from field to woodland,

but establishment density is not high enough to create a problem of weeds spreading back later [73]. On the contrary, having a seed bank of non-harmful herbaceous plants close by reduces the establishment-opportunities for harmful weeds [74]. Stream shading by mature trees and shrubs together with addition of litter and debris creates a better habitat for aquatic organisms including fish [32]. According to findings by Piessens et al. [75], edge effects between landscape elements are measurable in a transition zone of up to 8 m, putting streams behind a 10 m wide productive buffer out of the direct influence from arable fields, thereby creating semi-natural conditions. Probably more important than these immediate effects is the way in which a landscape-level implementation of buffer strips would increase biodiversity by altering the landscape mosaic. This positive effect is attributable to an increase in edge-habitats at the interface (ecotone) between different habitats that generally are believed to be more species-rich as they may offer sustenance to species from both adjoining habitats as well as species particular to the specific ecotone [76]. Marshall et al. [77] conclude that management of landscape structure is equally important to habitat creation as landscape type and boundary structures have a statistically significant influence on species diversity. Modern land management has often reduced or removed the ecotones through contrast sharpening between landscape elements [78], as can be seen at the sharp interface of arable land and forestry plantations. Establishing three-zone buffers reintroduces the fuzziness at the edges of different land uses. Diversity in the forms of agriculture together with the connectedness of different semi-natural landscape elements are both important factors for biodiversity in agro-ecosystems [79] and productive buffers provide both.

The biodiversity effects of bioenergy crops are also mainly positive, be it energy grasses, SRC or SRF. Soil community biodiversity will benefit strongly from the presence of tree roots over large areas as root inputs play an important role in shaping the trophic composition in soil food webs [80]. *Miscanthus* and reed canary grass (*P. arundinacea* L.) offer very good foraging areas for seed eating birds in winter on the precondition that the field structure with boundaries and hedges is retained according to Semere and Slater [81]. They also found that small mammals profit from the good ground cover and that the field margins surrounding the biomass crops support high plant biodiversity, most likely due to low agrochemical inputs and untreated headlands. Thus, although a few open-field bird species are likely to be negatively affected and biomass crops may not attract any new species [82], they will be beneficial to most other species already present in semi-natural landscape elements.

4. Findings: biomass production in buffers

4.1. Grassland

Grass strips can be used for extensive grazing, production of fodder (hay, silage), biogas feedstock or biomass for bioenergy generation. Mixtures based on common ryegrass (*L. perenne* L.) or clover grass mixtures are likely to yield 2–10 t ha⁻¹ DM in a buffer strip setting [10,83] which would be sufficient for the

above uses. Reed canary grass (*P. arundinacea* L.) is a promising multipurpose species in areas where it is not considered invasive, as it forms dense mats, is stiff stemmed, can be used for grazing early in the growing season and is able to grow well on most soils. Christian et al. [60] report yields of 6–12 t ha⁻¹ DM for southern England dependent on provenience. Sheaffer et al. [61] describe high responsiveness of reed canary grass to N-fertilization, which will be considerable in a buffer strip.

4.2. Short Rotation Forestry or coppice

Short Rotation Forestry (SRF) with a mix of species has its optimal rotation time for biomass production between 12 and 30 years depending on the species used [84–94]. This is also valid for willow (*Salix* spp.) and poplar (*Populus* spp.), but these species can be harvested with much shorter intervals in short rotation coppice (SRC), 1–5 years or 4–10 years respectively, making them easier to use in farming systems built on yearly rotations. All species suitable can be coppiced at least 2–3 times before the stubs die off or yields decrease significantly. Harvest should only happen after leaf fall as not to weaken the plants too much. Under the assumption that most buffer strips will be placed on fertile soils with a high influx of nutrients and dependent on species combination and growing conditions, an annual DM yield estimate of 5–8 t ha⁻¹ (6–18 m³ ha⁻¹) for SRF and up to 16 t ha⁻¹ (39 m³ ha⁻¹) for willow/poplar SRC can be made using data available in the

literature (Table 1). If the nutrient influx should decrease it is unlikely to reduce yields of woody biomass for the first ten years after establishment on ex-arable soils as the soil will be saturated with nutrients and even fast growing trees have much lower requirements than crops [95].

Leaving an undisturbed zone of vegetation on the stream side of riparian buffers will occasionally provide low quality timber of larger dimensions, but the zone itself will likely only have conservation value. Harvesting of biomass from the rest of the buffer can be done without temporary deterioration of stream water quality, provided no bare patches of soil are left [96].

5. Findings: buffers, landscape perceptions and management

5.1. Landscape perceptions

Structured, open landscapes with hedges and small woodlands are appealing to most people: mixed deciduous trees are commonly associated with ‘nature’ and there is a preference for ‘peaceful’ landscapes. Peaceful landscapes are never wilderness, but managed in a non-obvious manner, either infrequently or non-mechanized like short rotation forestry, old forest grazing areas or extensively used meadows [97,98]. Buffer strips usually resemble natural structural landscape

Table 1 – Maximum biomass yield potentials from tree species suitable for short rotation forestry and short rotation coppice for which yield data were attainable [39,84–88,90,92–95,113–123]. Performance assumptions of m³ and dry matter (DM) yield for fertile soils without nutrient or water limitations, as expected in riparian buffer zones.

Tree species	Latin name	Age of max. mean annual increment ^a	Max. mean annual increment, m ³ ha ⁻¹	Mean DM wood density, kg m ⁻³	Max. mean annual DM, t ha ⁻¹
Field Maple	<i>Acer campestre</i> L.	15–25	7	750	5.3
Sycamore	<i>Acer pseudoplatanus</i> L.	30	11	590	6.5
Black Alder	<i>Alnus glutinosa</i> L.	15–20	15.5	490	7.6
Grey alder	<i>Alnus incana</i> L.	12–16	18.5	490	9.1
Green Alder	<i>Alnus viridis</i> L.	unknown ^b	5	570	2.9
Silver Birch	<i>Betula pendula</i> L.	15–30	11	630	6.9
Downey Birch	<i>Betula pubescens</i> L.	15–30	8	680	5.4
Hornbeam	<i>Carpinus betulus</i> L.	20–30	5	770	3.9
Common Ash	<i>Fraxinus Excelsior</i> L.	40–50	7	670	4.7
Poplar hybrids	<i>Populus deltoides</i> L.	unknown ^c	39	410	16
	based and other hybrids				
Aspen	<i>Populus tremula</i> L.	unknown	16	450	7.2
Aspen hybrids	<i>Populus tremula</i> L. based	unknown	23	450	10.3
Bird Cherry	<i>Prunus avium</i> L.	30	9	580	5.2
Common pear	<i>Pyrus communis</i> L.	10–15	7	680	4.8
Pendunculate Oak	<i>Quercus robur</i> L.	40	7	670	4.7
Sessile Oak	<i>Quercus petraea</i> L.				
Red oak	<i>Quercus rubra</i> L.	25	8	670	5.4
Black Locust	<i>Robinia pseudoacacia</i> L.	15	11	730	8.0
Willow hybrids	<i>Salix viminalis</i> L.	unknown ^d	27	520	14.0
	based and other hybrids				
Lime	<i>Tilia cordata</i> L.	30	11	520	5.7
	<i>Tilia platyphyllos</i> L.				
White Elm	<i>Ulmus laevis</i> L.	20–25	7	640	4.5

a Harvest age for best utilization of growth potential.

b Not commonly used for production purposes.

c Commonly 4–10-year SRC/SRF.

d Commonly 3–5-year SRC.

elements, are managed extensively and may thus meet these criteria of acceptability for the wider public.

Gradual implementation may not even be noticed by most people as the agricultural landscape changes constantly: Kristensen et al. [99] found that 8.4% of a 5000 ha agricultural area in southern Denmark underwent land use change over a period of 5 years, including removal of 14 km of shelterbelts and establishment of 20 km new shelterbelts.

5.2. Farmers' decision making regarding landscape management

On the one hand, even though the linkages between agricultural practices and coastal water quality seem obvious when viewed from an ecosystem perspective, these linkages are not commonly recognized by land managers [100]. On the other hand, many farmers may be interested in the development of new ways of land management, especially if they deal with cost effective ways of preserving their resource base like maintaining soil fertility and minimising erosion [101]. The relationship between farm economics and landscape management is also rarely straightforward. A choice experiment study on energy crops in Sweden revealed that although willow growing would yield the highest income, it would not provide farmers with maximum utility as other factors like landscape impact and crop characteristics played an important role [102]. Also, because the farm and the farming landscape are an expression of the farmer's and his family's identity [103], economics alone is not able to explain all aspects of farm management. Battershill and Gilg [104] illustrate this by the finding that the same policy framework may have very different effects depending on the farmer: some farmers in their study on the uptake of environmentally friendly farming practices described Common Agricultural Policy (CAP), local or regional regulations, obligatory set-aside and general financial constraints as hindering the development, others as helping it. Thus, structural considerations are often not as important as attitudes and beliefs, as shown by farmers under financial pressure who intensify production while others in the same situation continue to extensify due to attitudinal commitment.

Regardless of the level of diversification on a farm, most farmers are interested in new land management practices when they hear of them, making research into farming systems and dissemination of knowledge in the research process a driver of land use change in itself [105]. Highly visible changes in landscape management practices that will alter the landscape mosaic (e.g. like installing shelterbelts and buffer strips on a larger scale) often require a local successful example set by a respected farmer [106]. 'Successful' in this context rarely refers to economic success but to a display of farming skill: Burton [103] describes farmers gauging each other's activities by the regularity of landscape features they produce, general appearance of crops or livestock and increases in yield; the latter more as a source of personal pride than for financial reasons. From this perspective, profitability is less important for a farmer's standing in the farming community than tidiness of the farm appearance. Regular landscapes tell a generation spanning success-story to farmers and are highly symbolic environments on a par with their economic value. The status of

a whole farming family may thus change when new practices are being adopted that change the landscape appearance.

Risk, effectiveness, time demand and the professional challenge associated with new land management and conservation practices can be equally or more important than economics [107]. Rigid measures, for example agri-environmental schemes that only require compliance [108], are of little interest to those farmers who have a focus on rational, efficient production and want to display 'good farming practice' that is measurable in things like straightness of tramlines, crop health or absence of weeds [109].

6. Synthesis: designing energy landscapes with buffers for biomass

Vegetated buffer zones will reduce the losses of nutrients and pesticides from agricultural land and may help to manage the nutrient and water cycles, mitigate flooding, enhance carbon sequestration, mitigate greenhouse gas emissions through fossil fuel substitution and play a role in enabling a net energy production from agriculture [15]. Thereby, buffers for biomass in temperate climate agricultural landscapes have a large potential for sustainable production of forage, fodder, biomass for bioenergy and sometimes timber. Based on the findings from the literature review in the previous sections, we suggest the implementation of energy landscapes with three-zoned buffers for biomass, as described in the following.

6.1. Three-zoned buffers for biomass (based on Schultz et al., [43])

As the most suitable buffer design, we suggest a three-zone structure consisting of a grass strip along the arable field or pasture, a zone with shrubs, short rotation forestry (SRF) or short rotation coppice (SRC), and a third zone along the lower edge or stream bank consisting of permanent and largely unmanaged woody vegetation.

6.1.1. The grassland strip

The grass strip slows and spreads runoff, filters sediment, resists erosion by rill flow common in row crops, takes up nutrients during the growing season and furthers denitrification. It can be used to produce energy grasses, hay and silage, pasture for extensive grazing and biogas feedstock.

6.1.2. The woodland strip

SRF/SRC provides the best conditions for infiltration of runoff and thereby retention of suspended sediment particles and removal of dissolved pollutants, immobilizes nutrients in woody biomass and greatly enhances denitrification potential. Production options for SRC are woodchips, for SRF additionally firewood, pulpwood and in case of more careful long-time management also sawlogs for parquet, furniture and special uses.

6.1.3. The undisturbed zone

The undisturbed zone reduces bank erosion, protects the buffer structure during flood events, buffers maintenance

operations in the other two zones, immobilizes nutrients in woody biomass, has a high denitrification potential and can enhance stream ecology by shading and addition of debris and litter. Occasionally it may produce low quality timber of larger dimensions, mainly usable as firewood or for chipping.

6.2. Hydrology measures

If space is limited due to the value of cropland as in most temperate European agricultural settings, there are options to slim the structure, although the focus then is conservation: a ditch can replace the grass strip and act as sedimentation basin from which overflowing water seeps through the buffer towards the stream; the buffer may be a combined structure composed of shade tolerant grasses and trees with light foliage such as birch (*Betula* spp.) or oak (*Quercus* spp.) provided the lower branches are removed to reduce shading.

Dealing with drainage is the most important issue as the presence of tile drains negates most buffer effects by providing a fast bypass for water to the stream. Rerouting the drains into a constructed wetland is an elegant but costly solution. Breaking the drains and collecting the water in a ditch on the field side of the buffer is a promising and cheap approach, the function is as described above. In flat areas it may be a good idea to create the ditch in the middle of a buffer consisting of species with high water demands to prevent waterlogging in the field in the growing season. Standing water in the ditch will also enhance denitrification.

Species choice seems not to be limited by nutrient uptake characteristics and should be guided by local growing conditions, management goals and, if possible, rooting behaviour to achieve effective utilization of the available rooting space.

Riparian buffer strips can be supplemented with upland buffers in the form of shelterbelts following the contour lines to delay the hydrologic response time during heavy rainfall events. Apart from reducing runoff and erosion by acting as a sink for overland flow, another benefit of additional contour buffers would be to capture sediment-bound P before it reaches the riparian zone where the conditions for turning particulate P into leachable, biologically active P are favourable.

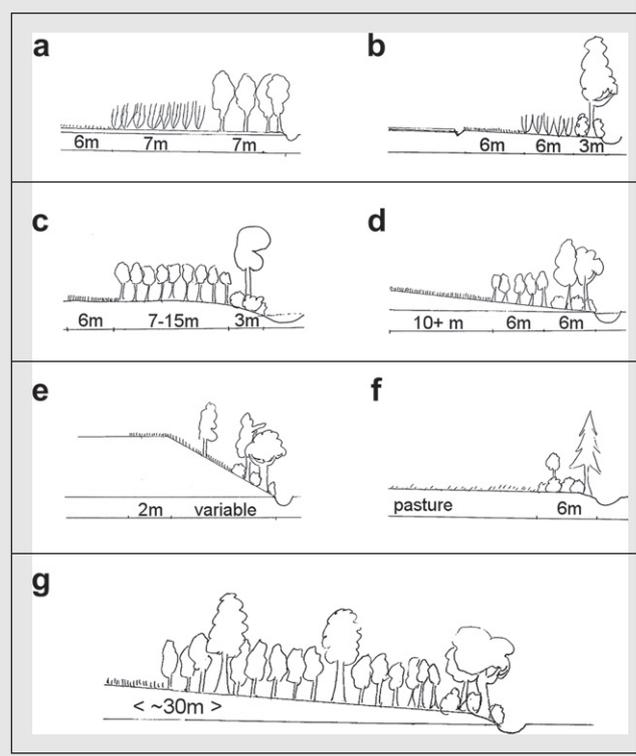
6.3. Buffer design scenarios

Depending on topography, production goal, harvesting technology, local markets, conservation aim and personal preferences, many different buffer designs can be created.

6.3.1. High energy yield buffers on very low slopes

On mainly flat areas (some slope towards the stream is necessary) the buffer system can be optimized for high energy yield and a high degree of mechanisation without compromising buffer functioning by using fast growing grass, SRC and SRF species with a zone-width adjusted for standard grass harvesting equipment, willow/poplar coppice machinery and harvester crane reach. Species options include reed canary grass (*P. arundinacea* L.), willow hybrids (*Salix* spp.), poplar hybrids (*Populus* spp.), grey or black alder (*Alnus incana* L., *Alnus glutinosa* L.) (Table 2, Fig. a).

Table 2 – Implementation options for productive three-zone buffers between arable fields and water courses. Suggested zone-width is adjusted for standard harvesting equipment, production goal and buffer function. Fig. a: high energy yield buffer with energy grass, willow/alder SRC and SRF on very low slope optimized for fully mechanized harvesting on areas with low erosion risk, therefore very small undisturbed zone; Fig. b: ditch for drainage water retention, high yield energy grass, poplar/alder SRC/SRF and undisturbed zone; Figs. c and d: multipurpose buffers on varying slopes with grass mixtures and multi-species SRF; Figs. e and f: extensive systems for limited grazing/browsing and firewood production for on-farm use, Fig. g: multipurpose woodland buffer with long-term focus on forestry options consisting of grass mixture, multi-species SRF and combined higher value timber production (e.g. ash, cherry, sycamore, other hardwoods).



Existing drains can be dealt with by breaking them with a ditch on the field side of the buffer from where the water then seeps through the buffer towards the stream. As buffer integrity is very important to avoid severe erosion problems when using this method, an undisturbed zone with a longer rotation time should be included. Species options for the resulting wet conditions: reed canary grass (*P. arundinacea* L.), willow hybrids (*Salix* spp.), poplar hybrids (*Populus* spp.), grey or black alder (*A. incana* L., *A. glutinosa* L.), aspen (*Populus tremula* L.), downy birch (*Betula pubescens* L.), white elm (*Ulmus laevis* L.) (Table 2, Fig. b). The grass strip may be replaced by the ditch acting as sedimentation basin depending on local conditions. At the lower end of a catchment, the drainage water yield from the upland can make this approach unfeasible. Constructed wetlands or filters may be the only usable option.

6.3.2. Multipurpose buffers on low to intermediate slopes

Where a buffer system of lower management intensity and with more production options is desired, a multipurpose buffer based on grassland species and SRF can be established. Energy grasses can be replaced by forage or wildlife mixtures or mixtures optimized for use in biogas plants. Choice of species is limited only by local soil conditions. With increasing slope, the grass strip needs to be widened and the species should be more stiff stemmed to resist the increasing runoff amount and velocity. SRF production options range from woodchip over firewood and pulpwood to medium quality sawlogs (Table 2, Figs. c and d).

6.3.3. Extensively managed buffers

On steep slopes the main buffer aim will be prevention of erosion and loss of particulate P in runoff. Scattered trees with light foliage over stiff stemmed grass can be used to maximize infiltration capacity. Energy production is limited to firewood for on-farm use with an option for limited grazing and browsing. Species options: silver birch (*B. pendula* L.), sessile or pendunculate oak (*Quercus petraea* L., *Quercus robur* L.), black locust (*Robinia pseudoacacia* L.), field maple (*Acer campestre* L.) (Table 2, Fig. e).

Extensive pasture systems on any slope can be amended with buffers designed for production of firewood and timber for on-farm use without limitations on species choice. These buffers consist of a mixture of trees and shrubs and are largely undisturbed (Table 2, Fig. f).

6.3.4. Woodland buffers

Where space is not too limited and actual forestry is of interest, a historical land management system redesigned for use in a productive buffer zone is an option with added high

conservation value. It consists of a grass strip with a wildlife or forage grass mixture and SRF in the understorey with valuable and well-maintained trees evenly spaced throughout the buffer. Production options range from woodchip to veneer, depending on management intensity. Species options for high value production: bird cherry (*Prunus avium* L.), sycamore (*Acer pseudoplatanus* L.), silver birch (*B. pendula* L.), common ash (*Fraxinus excelsior* L.), black alder (*A. glutinosa* L.), oak (*Quercus* spp.) (Table 2, Fig. g).

6.4. On-farm costs and benefits of the energy landscapes approach

In summary, to compare costs and benefits of the seven types of three-zoned buffers presented in Table 2, the energy balances (i.e. the net energy yields) and gross margins of the buffer systems were estimated per hectare and compared to standard winter wheat production (Table 3). Indicative energy balances were derived from Dalgaard et al. [15,110], together with economic figures from The Danish Advisory Service [111] and yield estimates from Jørgensen et al. [112,9]. The results show net energy yields between 48 and 104 MJ ha⁻¹ a⁻¹, corresponding to 32–69% of the net energy yield from winter wheat for Combined Heat and Power (CHP) and gross margins between 91 and 267 € ha⁻¹ a⁻¹ (675–1988 DKK, conversion factor 7.44 on 09/05/2012) corresponding to 15–44% of the gross margin from standard winter wheat production. Consequently, the valuation of the other benefits listed for buffers should be compared to those of the substituted crop production, together with the energy balances and gross margins of Table 3. For example, the Water Framework Directive [14] in the EU and other regulations concerning water quality

Table 3 – Estimated conservative key figures and overall energy balances (i.e. the energy yield minus the energy input) and gross margins for the seven types of three-zoned buffers illustrated in Table 2 (Fig. a–g), compared to standard winter wheat production.

Production system (% of area):	Buffer land use types						Overall energy balance (MJ ha ⁻¹ a ⁻¹)	Overall gross margin (€ ha ⁻¹ a ⁻¹) ^f
	In rotation	Grass/clover ^a	Pasture	SRC	SRF ^b	Undisturbed ^c		
Winter wheat ^d	100%						150	605
a) High energy yield		30%		35%	35%		104	267
b) High energy yield + drainage ditch		35%		35%		30%	76	259
c) Multipurpose, intermediate slope			30%		55%	15%	66	177
d) Multipurpose, pronounced slope			50%		25%	25%	48	227
e) Extensive, steep slope			20%		70%	10%	74	151
f) Extensive, slope independent			70%		20%	10%	53	303
g) Woodland, slope independent					90%	10%	83	90
Key figures:								
Dry matter yield (t ha ⁻¹ a ⁻¹)	10	8	5	9	6	0		
Energy yield (MJ ha ⁻¹ a ⁻¹) ^e	170	90	55	150	100	0		
Energy input (MJ ha ⁻¹ a ⁻¹)	20	14	5	10	8	0		
Energy Balance (MJ ha ⁻¹ a ⁻¹)	150	76	50	140	92	0		
Gross margin (€ ha ⁻¹ a ⁻¹) ^f	605	538	403	202	101	0		

a For biogas.

b Including firewood and timber production.

c Including ditches.

d Energy yield for CHP.

e Metabolisable energy yield for pasture grassing.

f Converted from DKK with factor 7.44 from 09/05/2012.

conservation require new developments in farming systems if targets are to be met. Best management practice solutions in the existing systems have mostly been exhausted and there are several reasons why energy landscapes with buffers could be attractive to farmers.

Farm economics – price volatility in biomass is low, providing a stable source of income that will be increasingly competitive as fossil fuels get more expensive. Taking land out of the yearly crop rotation will lead to savings on fuel and fertilizer, using the herbaceous biomass as feedstock in a biogas plant will also lead to production of fertilizer, further reducing demand. This option is especially attractive for organic agriculture as it reduces dependence on off-farm sources of (non-organic) manure. There are possible savings on agrochemicals due to the beneficial effects of shelterbelts, hedgerows and buffer strips on pest antagonists. For livestock farmers it can lead to savings in animal housing costs as the animals can stay out for longer periods of the year due to the shelter effect of established buffers. In non-sensitive areas installation of effective buffers may allow farming intensification or at least maintenance of the status quo on the remaining land. The value of sporting rights for hunting and fishing will increase as wildlife diversity and game and fish numbers increase along with improved landscape aesthetics.

Time management – forestry or coppice work mainly falls into the period of lowest on-farm workload and, in the event of unfavourable weather or market conditions, can be postponed unlike crop management. Buffer management can be contracted out to service providers. At the same time, landscape structures like shelterbelts and buffers are useful in streamlining field layout.

Personal preferences – unlike most agri-environmental schemes in use today for promoting environmentally friendly farming, buffers for biomass are a production orientated system leaving the ‘how’ to the farmer and allowing for a sense of ownership. Many farmers also value hunting and fishing opportunities. The use of buffers creates a regular, park like landscape mosaic with neat boundaries and straight lines that looks peaceful and cared for. Additionally, this display of skill and good land stewardship is highly visible due to the height and extent of established buffer structures.

7. Discussion and future work programme

The described three-zone buffer systems are very versatile and can be adapted to fit into most farm settings and will have a positive effect on surface water quality even though the exact catchment wide effect is difficult to predict. However, although promising, what is still needed to inform policy-making is a thorough cost–benefit analysis of farm scale and landscape scale buffer implementation. Most important in this respect is data on possible yields of different suitable species in a buffer implementation along with research into optimization of buffer harvesting operations. Towards this aim, a research site of 0.2 ha was established in May 2011 on a farm in eastern Jutland using the buffer design defined in Table 2, Fig. b and Fig. 2. Species used are reed canary grass (*P. arundinacea* L.), grey alder (*A. incana* L.) for SRF and black alder (*A. glutinosa* L.) for stream bank protection in the undisturbed



Fig. 2 – Buffer construction. 3-zone buffer under construction May 2011 on farmland near Odder, eastern Jutland, Denmark. Layout following Table 2, Fig. b: drains broken by ditch in a distance of 10 m from the stream. Buffer structure side of ditch approximately 30 cm lower than field side to avoid ponding.

zone. Taking into account the factors described in the literature review findings, buffer layout and placement, conservation and production aim and future management were agreed upon between the authors, the land owner, the Danish agricultural advisory service, a forest service provider, a local entrepreneur and the municipality (Fig. 3).



Fig. 3 – Established buffer. Same site as Fig. 2, September 2011. Buffer is well-established with 3 m reed canary grass (already a darker shade of green where in direct contact with nutrient enriched drainage water), 6 m of grey alder and one row of black alder for stream bank protection. First benefit described by farmer is improved hunting as roe deer are attracted to the site. Right side: 30 cm deep mulching with straw to suppress weeds and promote tree growth was successfully tested on a part of the structure. [For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.]

Biomass energy production in buffer systems will have a much lower landscape impact than large plantations as buffers follow the topography. How all the different buffer types described under Section 6.3. can be placed into landscapes is currently being mapped in collaboration with local farmers for a 6 × 6 km agricultural research landscape in central Jutland, Denmark. Placing all buffer types along the few streams in the area of such a small landscape will not be economical but will illustrate the three-zone buffer system's versatility and provide the basis for a tentative calculation of the achievable nutrient retention in a real farming landscape. Furthermore, this will enable a first cost–benefit analysis and scenario building, including visualization of landscape impacts. Successful implementation will require a landscape scale approach, preferably with farmer cooperations to increase efficiency of management operations. If of sufficient quantity, most of the SRC- and SRF-related work can be contracted out to specialized service providers, saving the farmer investment in special equipment and personal effort. Buffers defined as productive multipurpose elements of energy landscapes rather than a single-purpose conservation measure may therefore be a viable way towards fulfilling conservation needs while respecting farmers' authority as land managers, especially since the focus is not on removing but using expensive excess nutrients in landscape structures that happen to prevent those nutrients reaching surface waters. This would also enable farmers to proactively diversify their farming operations with the side-effect of fulfilling legislative obligations under the EU Water Framework Directive [14]. Finally, using productive buffers does not equate to losing valuable farmland to unproductive conservation measures or large scale conversion of cropland to biomass production with perennials, both being something most farmers are keen to avoid.

One of the main obstacles to wider implementation of productive buffers is the artificial divide between forestry-related and agricultural policies that make the use of agroforestry practices unattractive due to the lack of specific grant-schemes or subsidies. Although the system can be designed to fit under some schemes, this is complex and unwieldy, depriving it of its main strength, versatility. This could be remedied relatively easily by adjusting agricultural policies towards supporting agroforestry practices. Another problem is the marketability of biomass for bioenergy from small scale, local production. This is mainly a problem of infrastructure thresholds: as an example, local district heating plants or combined heat and power plants can create a market for these products by upgrading their boilers to co-fire biomass and enter into long-term contracts with any interested farmers. The same holds true for biogas plants. A third way of increasing the use of buffers could be direct compensation for farmers for the provision of ecosystem services to the general benefit of local communities, tourism and fisheries, namely flood risk mitigation and restoration of water quality in lakes and coastal waters. Further research will focus on the possibility of the system being economically viable by itself on a landscape scale, eliminating the dependency on subsidies by offering an interesting way of diversifying a farm business.

8. Conclusion

Buffer strips on agricultural land designed for combined biomass production, diffuse pollution mitigation and biodiversity conservation using the versatile three-zoned design presented here offer a promising way forward towards achieving a higher degree of resilience and sustainability in temperate European agriculture where farmland is expensive and where unproductive buffer zones are an annoyance to most farmers. Carefully placed and established correctly they are efficient in reducing flood risk, sediment load and the leaching of nitrates, phosphorus and pesticides to surface waters. At the same time there is a substantial potential for the economical production of biomass for fuel, biogas feedstock and to a degree livestock feed that could become a valuable asset in on-farm nutrient cycling and farm business diversification; especially if agricultural policies dis-incentivising agroforestry systems were adapted to accommodate this kind of land use and farmer cooperatives were to be promoted. The presented buffer system has been shown to work in the field and provides the land manager with a design toolbox rather than a prescription, allowing for a much greater sense of ownership than most agri-environmental schemes in use today. Additionally, bioenergy production in buffers designed specifically for local conditions does not reduce the amount of cropland available for food production, increasing the chance for internalization of the system in day-to-day farming practice.

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