Europ. J. Agronomy 32 (2010) 103–111

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Multiple functions of buffer strips in farming areas

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ARTICLE INFO

Article history:
Received 4 July 2008
Received in revised form 4 March 2009
Accepted 14 May 2009

Keywords:
Buffer strip
Hedgerow
Multi-function

ABSTRACT

Buffer strips (BSs) are strips interposed between fields and streams that intercept and treat the waters leaving cropland, and so are a useful tool for reducing agricultural diffuse pollution in lowland areas. If properly vegetated and managed, they can also produce wood for burning, act as sinks for atmospheric CO_2 and enhance the landscape beauty.

The paper presents an analysis of the different functions of BS and reviews the more important data from research programmes conducted over the last decade in Veneto Region (North-East Italy). Over a period of 3–5 years, in two experimental sites, young BS reduced total runoff by 33%, losses of N by 44% and P by 50% compared to no-BS. A mature BS was able to abate both NO_3–N and dissolved phosphorus concentrations by almost 100%, in most cases having exiting water that satisfied the limit for avoiding eutrophication. The BS also proved to be a useful barrier for herbicides, with concentrations abated by 60% and 90%, depending on the chemical and the time elapsed since application. Considering the CO_2 immobilized in the wood and soil together, the different BS monitored stored up to 80 t ha^{-1} year^{-1}.

The BS caused negligible disturbance to maize, soybean and sugarbeet yields. The hedgerows, particularly if composed of trees taller than 6 m, positively influenced the aesthetic value of the territory, improving its perceived naturalness and screening the man-made elements.

Lastly, through a multi-objective analysis, opportunity costs were estimated to support the public decision-maker in determining the subsidies to be paid to encourage farmers to plant BS.

1. Introduction

Buffer strips are riparian vegetated filter zones, interposed between fields and streams, which intercept and treat the waters leaving cropland, thereby being a useful tool to reduce agricultural diffuse pollution in lowland areas (Dillaha et al., 1988; Heathwaite et al., 2000; Dosskey, 2001; Benoit et al., 2004). Designed to remove sediment and bound pollutants from surface water (Young et al., 1980; Muños-Carpena et al., 1999), if properly vegetated and managed, they can produce wood for burning, act as sinks for atmospheric CO_2 and enhance the beauty of the landscape. Buffer strips are hence typical multi-functional elements in farming systems.

Analyzing the above functions in more detail, there are five general ways through which buffers reduce non point source (NPS) water pollution from cropland (Dosskey, 2001): (1) by reducing surface runoff from fields, (2) filtering surface runoff from fields (Van Dijk et al., 1996), (3) filtering groundwater runoff from fields, (4) reducing riverbank erosion, and (5) filtering pollutants from stream water. The pollutant abatement achieved in runoff water varies with width, pollutant type and chemical form (Daniels and Gilliam, 1996; Schmitt et al., 1999; Abu-Zreig et al., 2003). The effect is usually highly satisfactory, with abatements of 70–90% for suspended solids, (Neibling and Alberts, 1979; Abu-Zreig et al., 2003; Benoit et al., 2004), 60–98% for phosphorus (Duchemin and Madjoub, 2004; Borin et al., 2005; Dorioz et al., 2006) and 70–95% for nitrogen (e.g. Delgado et al., 1995; Heathwaite et al., 1998; Parkyn, 2004). Grassed buffer strips are also a way to reduce pesticide transfer by surface runoff from farmed fields to streams (Lacas et al., 2005). Buffer effect depends on external factors, such as runoff volume and features of the area originating the runoff (e.g. slope, size, land use), and also the type of buffer, in terms of its composition, age and width (Chaubey et al., 1994; Vought et al., 1995).

Because of high soil moisture and nutrient availability, riparian zones are often highly productive sites for growing trees (Megahan et al., 1981; Gibbons, 1988; Kinley and Newhouse, 1997), which, in addition to removing pollutants, may be used as a harvestable crop, providing, among other products, a renewable fuel source, timber, pulp, paper, or industrial chemical feed stock. This crop value provides the land owner with a quicker return on the investment in setting aside land for a tree buffer strip (Walbridge, 1993; Schultz et al., 1994). Researchers in Iowa (Schultz et al., 1994) suggested a design for producing fuelwood in riparian areas based on

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doi:10.1016/j.eja.2009.05.003

selected fast-growing tree species (hybrid poplar, green ash, silver maple, black walnut, ninebark, red osier dogwood). These trees are grown as short-rotation woody crop systems producing biomass for energy in 5–8 years and timber products in 15–20 years (except black walnut, which is grown on a 45–55 year rotation). Moreover, these species reproduce vegetatively from stump or root sprouts, and develop large root systems for rapid nutrient uptake and soil stabilization. The faster growing species will not become over competitive because they can be harvested on a short-rotation.

One characteristic of riparian woodlands that has been less appreciated is their potential to sequester large amounts of C in vegetation and soil. Increased soil moisture at lower slope positions may influence forest productivity and modify decomposition processes in the soils, favouring C accumulation (Kimmins, 1987).

The European Landscape Convention signed in Florence in 2000 states that “landscape means an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors”. The rural landscape can be considered as the visual appearance of agrarian ecosystems. A close relationship exists between the landscape and primary activities, and landscape can be considered one of the main agriculture externalities. During the last decades, the European Common Agricultural Policy (CAP) evolution and innovations in agricultural technology have vastly altered the Italian landscape. CAP strategies strongly modified the relative prices of agricultural products, while more capital-intensive agricultural practices required major land transformation. Fields were enlarged and many typical land layouts with perennial vegetation were abandoned. Hedgerows, tree plantations, natural meadows, mulberry trees and numerous lowland woods gradually disappeared from the plain. These changes also increased nitrogen release and leaching. Over the same period there has been increasing demand for outdoor recreation activities. This demand is closely connected to landscape features, the preservation and creation of which is becoming more central under the reformed CAP. Since rural landscape is an agro-forestry positive externality, and given its nature as a pure public good, economic farm incentives can increase social welfare.

Methods have been set up, and applied many times, to evaluate the visual quality of the landscape, in order to give an economic value (Daniel and Boster, 1976; Gobster and Chenoweth, 1989; Brown and Daniel, 1991; Gregory and Davis, 1993; Lothian, 1999; Daniel, 2001). These methods are based on the principle that when the landscape inspires positive feelings, such as security, relaxation, pleasure and happiness, it is subjectively considered as being of high quality. On the contrary, when it elicits states of stress, fear, insecurity or limitation, etc., it is subjectively considered of low quality (Buhyoff et al., 1994). Buffer strips, especially those with trees and shrubs, connote a more sustainable landscape (Dorioz et al., 2006).

If buffer strips can offer these positive externalities, attention also has to be paid to the possible negative interference with crop productivity to assess whether planting them is economical. Regarding this, experimental trials in the Philippines and other locations revealed depressed yield in some systems with hedgerow intercropping, due to competition for sunlight, nutrients and soil moisture (Garrity et al., 1995; PCARRD, 1992; Lal, 1989). However, these data refer to narrow alleys between the hedgerows. No data are available in the literature about the effect of edge buffer strips with trees on field crop productivity.

From the economic point of view, timber production and CO_2 accumulation present a direct trading value that is variable, but easily determined. On the contrary, pollution control and landscape amelioration are positive externalities that require the application of an adequate economic analysis to support the decision-maker in designing proper public interventions. This is therefore a key issue in the planning and implementation of sound policies at the territorial scale.

This paper presents an analysis of the different functions of buffer strips and offers the more important data from research programmes conducted over the last decade in Veneto Region (North-East Italy).

2. Methodology

The research activity consists of a core field experiment and a series of studies conducted at two scales: field ancillary experiments and territorial surveys (Table 1). The experimental data have been utilized in a Multiple Objective Programming (MOP) model to assess how different environmental policies can be implemented to maximize economic return and environmental targets (pollution control and landscape quality improvement).

A description of the research is given below, but the specific references obviously provide more details.

2.1. Field experiments

2.1.1. Field description and activity

The Legnaro core experiment is ongoing at the Padova University Experimental Farm (45°12′N, 11°58′E, 6 m a.s.l.) and mainly concerns the effect of buffer strips on surface water quality (Borin et al., 2005). CO_2 fixation and timber production have also been evaluated. The experimental site is a rectangular field, with a 35 m long 1.8% slope down towards a ditch. During the period 1998–2002, a 6 m wide buffer strip (BS), composed of two rows of regularly alternating trees (*Platanus hybrida* Brot.) and shrubs (*Viburnum opulus* L.) was studied in comparison with no-BS. Each treatment had two replications. To measure runoff volumes and collect water samples, collector systems with multi-pipe divisors were designed and installed in early 1998 (Morari et al., 2001) according to Brakensiek et al. (1979) and Hudson (1993). The collector system consisted of a metal gutter 1.5 m wide and a double-split runoff divider that separated total runoff volume from each plot to a storage tank at 81:1 ratio. Water volume fractions collected in the tank were measured to calculate total volume and samples were taken once a day (time-dependent) for analysis during each runoff event. During sampling

Table 1
Ten years of research on buffer strips in Veneto Region: projects, locations and experiment duration, studied functions.

	Core experiment	Ancillary experiment	Ancillary experiment	PRIN VBS	PRIN ecological network	PRIN Agripark
Location	Legnaro	Marano	Mogliano	Veneto Region	Veneto Region	Veneto Region
Years	1998–present	1997–1999	1999–2005	2002–2003	2003–2004	2004–2005
Surface runoff pollutants control	*		*	*		
Subsurface flow pollutants control	*	*				
Plant growth and production	*		*	*		
Soil C accumulation	*	*	*	*		
Landscape quality				*		
Crop yield losses	*				*	*
Economic evaluations				*		*

the water in the tank was stirred; 2 L samples were stored at 4 °C until analysis. The concentrations of total suspended solids (TSS), nitrogen (total N, NO_3–N) and phosphorus (total P and PO_4–P) were determined, allowing the losses to be calculated. Runoff volumes, nutrient and TSS concentration data were multiplied to give the mass transport of each constituent and each time interval.

All the *Platanus* plants (81) were cut and harvested in autumn 2003, after the first growing cycle, and productivity was measured. Plants were analyzed for C content. For each plant the total wood was weighed and moisture content measured to determine the dry matter production. These measurements were also taken on a hedgerow 20 years older, composed of 51 *Platanus* plants, growing on the same farm and harvested in autumn 2002. This was the third time the hedgerow had been cut after planting.

In 2003, soil samples were collected and analyzed for C content to determine the CO_2 fixation of the buffer strip. Three samples for each BS were taken at two depths (0–5 and 20–25 cm) and the C accumulation in the soil was calculated comparing the amount in 2003 with the amount at the start of the experiment in the BS. The comparison was also made in the normally cultivated soil, where 14 samples were collected at the same depths.

Yields of maize (2000), soybean (2001) and sugarbeet (2002), grown in the field and sown in rows parallel to the buffer, were measured at increasing distances from the BS to determine the possible detrimental effect of the hedgerow on crop yield. In maize, sown with a distance between rows of 0.8 m, the distances from the buffer were 0, 4, 8, 12, 16, 20, 24 m; at each distance, along a crop row, three sections 10 m long were harvested to measure the productivity. In soybean and sugarbeet, sown at an inter-row distance of 0.5 m, the sampling distances were 0, 2, 4, 7, 13, 25 m, with three sections of 10 m being sampled at each distance.

2.2. Ancillary experiments

Mogliano (45°33′N, 12°14′E, 8 m a.s.l., province of Treviso) ancillary experiment gathered further information on the pollutant control in runoff water, collecting 60 surface water samples during the period 2003–2005. The BS, planted in 1999, was formed by one line of trees and a strip of grass, for a total width of 4 m. To measure runoff volumes and collect water samples, the same facility described for Legnaro was installed in the BS and at the border of a field without BS. Total N, NO_3–N, total P, PO_4–P and suspended solids were determined. Observations were also made on the tree growth and CO_2 accumulation in the soil in the first year after BS planting, following the same procedure as that described for the Legnaro experiment.

Marano (45°27′N, 12°07′E, 4 m a.s.l., province of Venice) ancillary experiment studied the role of mature (more than 20 years old) riparian BS in abating NO_3–N, PO_4–P and herbicides in the shallow water table. The BS was composed of one line of trees (1 m wide) and a 5 m strip of grass. The excess water came from an irregularly shaped field of approximately 6 ha, draining into two streams running along its longer sides (Borin and Bigon, 2002; Borin et al., 2004). During the monitoring period (1997–1999), 28 samplings were done in 8 observation wells (4 in the field and 4 after the BS), for a total collection of about 220 water samples. In addition, C accumulation was determined in the BS soil by comparing the C content with that in the field.

2.2.1. Laboratory analysis

In all the experiments, water samples were analyzed as follows.

Suspended solids were separated by centrifugation at a relative centrifugal force (RCF) of $14.0 \times g$ for 5 min and dried for 48 h at 55 °C. Total P (inorganic and organic) was determined by oxidation of unfiltered samples with potassium persulfate, and analyzing at 885 nm wavelength on the spectrophotometer after colour development with an ammonium molybdate–ascorbic acid–antimony method (Genchi, 1990). To determine PO_4–P, the same colour development method was used on filtered samples and analyzed at 885 nm wavelength on the spectrophotometer (Genchi, 1990).

Nitrate (NO_3–N) was determined in filtered samples with the salicylic acid method and spectrophotometer analysis (Cataldo et al., 1975). Total N (inorganic and organic) was determined in unfiltered samples by oxidation with potassium persulfate (Genchi, 1990) and, after colour development with the salicylic acid method, samples were analyzed at 410-nm wavelength on the spectrophotometer (Cataldo et al., 1975). N and P were analyzed using an Ultrospec 2000 UV–vis spectrophotometer, Pharmacia Biotech (Biochrom) Ltd. Ammonium (NH_4–N) was determined by the specific electrode method (Martillotti et al., 1987).

For herbicide analysis, the water samples were first filtered by using SPE (Lichrolut) extraction cartridges; the molecules were then removed from the cartridges and analyzed by HPLC under the following conditions: wavelength 210 nm, flux 1.0 mL min^{-1}, column temperature 30 °C. Absorption spectra and absorbance values of all the examined compounds were determined prior to analysis.

Soil organic C was determined with the Walkley–Black method.

2.3. Territorial surveys and economic evaluations

The surveys aimed to assess the contribution of hedgerows to rural landscape aesthetic value (Tempesta, 2006). For this purpose, a preliminary classification was made of the landscape into units or types. After having quantified some land use parameters that can affect landscape aesthetics (for details, see Table 4), interviews were conducted, with the aim of revealing people's preferences. The level of appreciation of the landscape was defined by proposing photographs to each interviewee on which he expressed a judgement, using a rating scale that gave a visual aesthetic index (VAI). Pictures were used because studies conducted in the USA have highlighted that there is generally no divergence between the evaluation of a photo and an evaluation made in the countryside or in woodland (Hetherington et al., 1993), although there is some difference of opinion among researchers (Scott and Canter, 1997; Palmer and Hoffman, 2001). In all the studies a multivariate function was then calculated relating VAI score and landscape elements. The regression coefficients were taken as a measure of the aesthetic importance of any landscape element, positive values meaning appreciation.

A modelling approach based on Multi Objective Programming was lastly used to analyze the trade-off between the quality of the environment and an economic index, namely farmers' income (Thiene et al., 2007, 2008). MOP, which belongs to the Multicriteria Analysis techniques (Romero and Rehman, 1989; Tempesta and Tiene, 2004; Hung et al., 2006), provides useful information within this decision-support context, by identifying and evaluating possible alternatives. In this specific case, three decisional criteria were identified: a criterion of private relevance (gross income of the farm) and two of public relevance (landscape quality and nitrogen losses associated with the different crops in the study area). The compromise solutions among the different objectives were identified using MOP. Mathematically, this is a problem of constrained optimisation that can be formalised in compact form as:

$$\underset{X}{Eff}(Z_1, Z_2, Z_3) \qquad XA \leq \bar{b} \tag{1}$$

where Z_1, Z_2 and Z_3 represent the objectives, X the set of decisional variables, A the matrix of the technique, i.e. the set of technical coefficients, b the vector of the availability. The operator *Eff* expresses the fact that the methodology permits the acceptable efficient solutions to be identified, i.e. those characterised by different attainment levels of the three objectives but that cannot be improved further; given the availability of resources, the improvement of a criterion is always and only obtainable on condition that at least one other is reduced. *Eff* therefore identifies the technically possible set of solutions that together constitute the efficient frontier, which is a representation of the results of the objectives in the space. There being three objectives, the frontier takes the form of a plane in a three-dimensional space in which the axis represents a criterion. Each configuration in the space of the objectives is associable to a point in the space of the alternatives, i.e. a particular combination of land uses.

The model, which was applied using the experimental data of nitrogen abatement and aesthetic value, quantifies the farmer's loss of income when he implements actions that achieve both water quality and landscape beauty. Farm allocation to different cropping systems associated to each point of the estimated efficient frontier is also provided by the model.

This approach suffers from the many and well-known limitations associated to the linear programming approach, results appear to be sensitive to the assumptions that need to be made about inputs, and it does not take into account the dynamic effects being restrictively based on a short run period. Nevertheless it provides reliable information to the policy maker by estimating the opportunity cost at a farm scale, that is by allowing to easily take into account local economic and environmental input and output factors.

3. Results

3.1. Pollutant losses control

In the main experiment, during the period 1998–2002 the BS reduced total runoff by 78% compared with no-BS, in which cumulative runoff depth was 231 mm over 5 years.

The filtering effect of the BS reduced total suspended solids, particularly after the second year, when the median yearly concentrations ranged from 0.28 to 0.99 g L^{-1} in no-BS treatment and were lower than 0.14 g L^{-1} with 6.2S buffer. The combination of lower concentrations and runoff volumes significantly reduced TSS losses from 6.9 to 0.4 t ha^{-1} over the entire period.

A tendency was observed to increased concentrations of all forms of N (total, nitrate and ammonium) while passing through the BS, but total N losses were reduced from 17.3 to 4.5 kg ha^{-1} in terms of mass balance. On the contrary, P concentrations were unmodified (soluble P), or lowered (total P) by the BS, reducing total losses by about 80%. The effect on total P, composed mainly of sediment-bound forms, was related to particulate settling when passing through the BS (Borin et al., 2005).

In the Mogliano ancillary experiment, the total runoff measured in the period 2003–2005 was about 97 mm without BS and 61 mm with BS. The pollutant concentrations in runoff water showed that the BS effect was evident in reducing both the median values and dispersion indices (first and third quartiles) for all pollutants, except total P (Table 2). The total cumulative losses of all pollutants were quite low compared to other experiments (Borin et al., 2005), but were reduced by 7% (PO_4–P) to 88% (soluble solids) by the BS.

The research conducted at Marano showed the efficacy of the mature BS in controlling pollution in the shallow subsurface flow (Fig. 1). Both NO_3–N and dissolved phosphorus concentrations were reduced by almost 100% passing through the BS and in most cases the exiting water satisfied the limit for avoiding eutrophication. The significant reduction already observed at the border between the field and grass strip suggested that the perennial plants forming the BS, particularly the trees (Borin and Bigon, 2002), might have developed their root systems within the field. According to this, we could conclude that the zone of influence of this BS goes beyond its simple width. Since the 6 m wide BS permitted an abatement close to 100% of the pollutants we can recommend this width to obtain significant water amelioration.

The BS also proved to be a useful barrier for herbicides, with concentrations abated by 60% and 90%, depending on the chemical and the time elapsed since application.

3.2. Timber production

On average, one *Platanus* plant gave 49 kg of d.m. wood at the first cycle of utilization; at maturity this production reached 160 kg. Considering 1 ha of hedgerow 5 m wide, with a single line of plants at 2 m intervals, production reaches 49 and 160 t, respectively.

3.3. Buffer strip system as C sink

The C immobilized in the wood was 104 kg per single plant in the first growing cycle and three times higher at maturity. Assuming the previous plant density, yearly total C sequestration ranges from 20 t in the young hedgerow to 50 t in the older one.

Moreover, both at Legnaro and Mogliano the soil under the BS accumulated organic C with respect to the values at the time of planting, while during the same period the concentration in the arable soil reduced (Table 3). As a consequence, at Legnaro and Mogliano, in the first period after planting, the soil under the BS immobilized 7.2 and 9.3 t ha^{-1} $year^{-1}$ of CO_2, respectively. In the same sites, the arable soil emitted 8 and 33 t ha^{-1} $year^{-1}$ of the CO_2 as organic matter oxidation.

At Marano, where data regarding the organic matter concentration in the soil at the time of BS planting are not available, the BS soil immobilized 2.3 t ha^{-1} $year^{-1}$ with respect to the arable soil. Hence, the yearly ratio of CO_2 immobilization in the long term is lower, suggesting that the organic matter accumulation process is more intensive in the period immediately subsequent to the change of land use.

3.4. Yield losses

The relative yields of maize, soybean and sugarbeet, expressed as % of the maximum yields measured in the field, were slightly influenced by the distance from the hedgerow (Fig. 2). In particular, for maize and soybean, losses were only noticeable in the first 4 m

Table 2
Mogliano ancillary experiment: pollutant concentrations and losses in runoff water with buffer strip (BS) and without (no-BS) (cumulative values, 2003–2005).

Pollutants	Total N		NO_3–N		Total P		PO_4–P		Total suspended solid	
Treatments	no-BS	BS	no-BS	no-BS	no-BS	BS	no-BS	BS	no-BS	BS
Concentrations (mg L^{-1})										
Median	1.7	1.9	0.8	0.5	0.2	0.3	0.1	0.07	5.0	5.0
First quartile	3.2	2.9	1.2	0.8	0.5	0.4	0.1	0.1	93.0	53.5
Third quartile	6.0	5.4	3.0	1.5	1.0	0.8	0.1	0.35	424.5	117.5
Losses (g ha^{-1})										
Total	2463	1374	1079	470	510	225	69	64	740,000	86,000

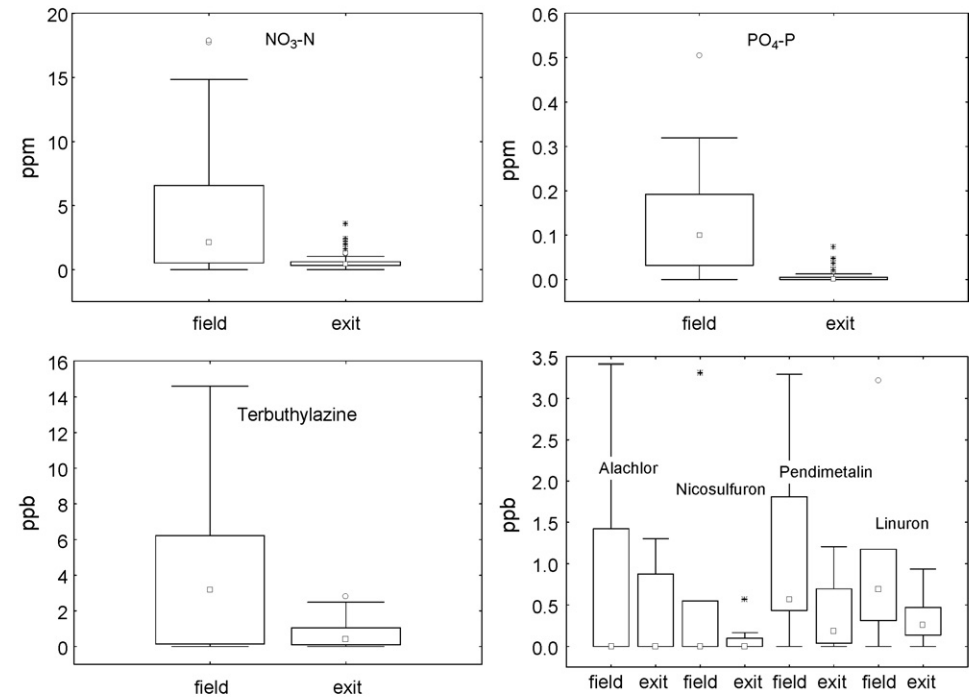

Fig. 1. Marano ancillary experiment: efficacy of the mature buffer in controlling pollution in the shallow subsurface flow, comparing concentrations in field and after the passage trough the BS (exit).

Table 3
Organic matter content (g 100 g^{-1}), mean and std error, in the top 0–0.5 m soil under buffer strips and in arable field in the different experimental sites.

Experimental site	Years	Field		Buffer	
		Initial	Final	Initial	Final
Mogliano	2	1.3 ± 0.08	0.86 ± 0.17	1.19 ± 0.08	1.27 ± 0.10
Legnaro	5	1.1 ± 0.12	0.82 ± 0.03	1.01 ± 0.12	1.18 ± 0.11
Marano	>20	n.a.	1.54 ± 0.05	n.a.	2.08 ± 0.34

of field from the hedgerow. The hedgerow disturbance was higher in sugarbeet because near the hedgerow the yield was less than 50% of that measured at 25 m from the hedgerow.

3.5. Hedgerows and landscape economic values

The multivariate regression coefficients showed that the visual aesthetic index is affected by many elements (Table 4). In general, all elements of the so-called "savannah like landscape" improve

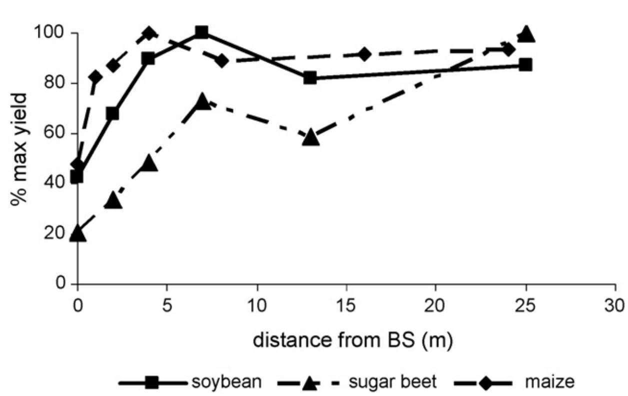

Fig. 2. Legnaro experiment: relative yields of maize, soybean and sugar beet, expressed as % of the maximum yields measured in the field at increasing distance from the buffer strips.

the value, e.g. hedgerows, meadows, scattered trees, woods and, if present, water and animals. On the other hand, man-made elements (modern buildings, pylons, asphalted roads, etc.) usually decrease the VAI. All the models highlight the importance of hedgerows, with those composed of trees taller than 6 m being more appreciated than those with smaller trees (3–6 m). The aesthetic effect of hedgerows, especially on the plain, is twofold: on the one hand they improve the perceived naturalness of the territory, on the other they can screen the man-made elements.

3.5.1. MOP

Results obtained via the MOP modelling approach provide estimates of the opportunity cost that must be supported by the farmer in term of income losses to achieve increases in landscape quality and reduce nitrogen losses (Thiene et al., 2007, 2008).

Results from maximization of income and landscape quality are reported in Fig. 3 and Table 5. Each point of the efficient frontier is associated to a cropping system. Income maximization implies a low landscape quality associated with a simplified cropping system: maize, soybean and alfalfa equally distributed on the farmland. The landscape quality maximization determines a consistent cut in income (more than 450 € ha^{-1}) and the new allocation involves the almost entire substitution of traditional crops by meadow (more than half of the land) and alfalfa, which positively influence the landscape quality. The remaining land is mostly occupied by woodland, along with hedgerows and scattered trees. It is worth underlining that a notable increase in landscape value (22%) can be reached with a rather limited decrease in income (52 € ha^{-1}). It follows that the opportunity cost supported by the farmer for improving the environmental quality appears sustainable, especially within the perspective of the subsidies paid for specific agro-environmental actions.

The conflicting nature of income and reduction of nitrogen losses is well described in Fig. 4 and Table 6 since high earnings imply sizeable nitrogen leaching from the soil. Maximization of the income objective involves average losses of 28 kg of N per hectare, associated with a crop allocation that includes maize, soybean and alfalfa,

Table 4
Main results of six landscape evaluation studies in North-East Italy during the last 15 years. Dependent variable: visual aesthetic index (VAI)[*].

Land use and cultural–historical elements	Euganean Hills Natural Park (PD)	Venice lagoon basin plain	Udine province hill and plain	Veneto east plain	Veneto west plain	Veneto plain (computer imaging)
Horticultural field crops (%)	−0.069	−0.044	−0.035			
Uncultivated land (%)	−0.018	−0.032				
Arable crops (%)	−0.019	−0.017	−0.021	−0.014		
Meadows (%)	0.018	0.017	0.014		0.019	0.025
Cattle pasture (%)						0.031
Alfalfa (%)					0.028	
Orchards (young trees) (%)					−0.020	
Hedges (%)	0.060	0.024	0.028	0.050	0.015	0.066
Hedge height >6 m[a]					1.144	
Hedge height from 3 to 6 m[a]					0.607	
Wood (%)	0.006		0.036			0.041
Scattered olive trees[a]	1.069					
Ditches, streams[a]	0.619	1.482		2.318		
Scattered trees[a]	0.732	1.455	0.942		0.644	0.181
Tree rows[a]	1.225				0.941	0.643
Paths[a]	3.717	1.322				
High voltage pylons[a]	−2.346			−2.478	−2.638	
Sprinkler[a]					−1.022	
Modern buildings[a]	−0.709					
Non-visible morphology[a]	−1.417					
Historical field layouts	0.375					
Waste land (herbaceous)[a]	0.831					
Vineyard (%)			−0.014	0.059		
Tree rows (%)		0.032				
Asphalt road[a]		−1.809				
Pylons, urban buildings, etc.[a]		−0.850	−0.926			
Mulberries rows[a]			0.132			
Hills[a]			0.704			
Photograph quality[a]			0.736			
Constant	5.542	4.380	5.780	5.159	4.630	3.452
Adjusted *r* squared	0.43	0.62	0.63	0.25	0.75	0.26

[a] Dummy variables, land percentage otherwise.
[*] All the coefficients are significant at 0.1*p*.

the latter being high-earning following the CAP Mid Term Review. When the goal is to maximize the environmental objective with an almost complete reduction of nitrogen losses, there is a marked drop in income (approximately half).

This reduction of losses is reached by successive scenarios that involve an initial substitution of maize by soybean, as the latter associates a still high income with lower nitrogen leaching. Then wheat, the field crop with the lowest losses, substitutes first soybean and then alfalfa, expanding over much of the farmland. As the environmental objective becomes more pressing, there is a marked modification of the crop allocation, with the substitution of field crops by hedgerows. Analysis of the efficient frontier (Fig. 4) shows that the opportunity cost for reducing nitrogen losses by almost half is rather low (45 € ha^{-1}), and a nutrient reduction of almost 90% involves a loss of income of less than 200 € ha^{-1}. These are therefore modifications to the farming system that are both economically and environmentally sustainable.

Finally, investigating the three objectives together, new possible solutions with respect to the simulations with two objectives can be identified (Fig. 5). The usefulness of the information provided by this approach becomes clear when focussing on the generated solutions. For example, two solutions involve an analogous improvement in terms of attainable landscape quality (22.4%), but a doubling in terms of reductions in income (the first solution involves a loss of 53 € ha^{-1} and the second 100 € ha^{-1}). However, the latter reduces nitrogen losses by almost 60%, whereas they drop to 28% with the other.

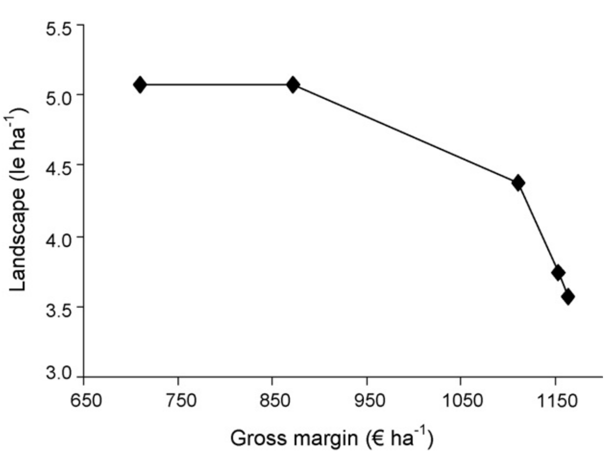

Fig. 3. Efficient frontier income-landscape for the land use combinations reported in Table 5.

4. Discussion

Planting wooded buffer strips in rural areas leads to environmental benefits and opportunities for farmers. According to the literature, the most relevant environmental effect of BS is the control of diffuse pollution leaving croplands, transported in the surface runoff and shallow subsurface flow. All the BS studied in the three experiments showed performances in abating total suspended solids, nitrogen and phosphorus similar to those reported in many studies (Kay et al., 2005). These substances are subjected to different fates in the BS: suspended solids are trapped by the grass (Dillaha et al., 1988; Dillaha and Inamdar, 1997), nitrogen can be abated by plant absorption and microbial activity leading to denitrification (Verchot et al., 1997) and dissolved P can be uptaken by plants and microbes (Welsch, 1991).

In one experiment, where the herbicides were also studied, the BS abated the concentrations of all the molecules that passed

Table 5
Solutions of the multi-objective analysis models. Criteria: income and landscape quality.

Gross margin (€ ha^{-1})	Var (€)	Landscape	Var (%)	Meadow area (%)	Alfalfa area (%)	Maize area (%)	Soybean area (%)	Trees area (%)	Hedgerow area (%)	Woodland area (%)	Systemic indexes			Subsidies (€ ha^{-1})
											Trees	Hedgerow-meadow	Meadow-woodland	
1164	0	3.574		0.0	33.3	31.6	35.1	0.0	0.0	0.0				455
1153	−10	3.742	4.7	0.0	33.3	32.2	33.5	1.0	0.0	0.0	1			450
1111	−53	4.373	22.4	15.0	33.3	0.6	48.1	1.0	1.9	0.0	1	1		441
872	−292	5.072	41.9	40.0	15.6	0.0	21.4	1.0	1.9	20.1	1	1	1	350
709	−454	5.079	42.1	50.1	10.5	0.0	0.0	1.6	5.1	32.9	1	1	1	275

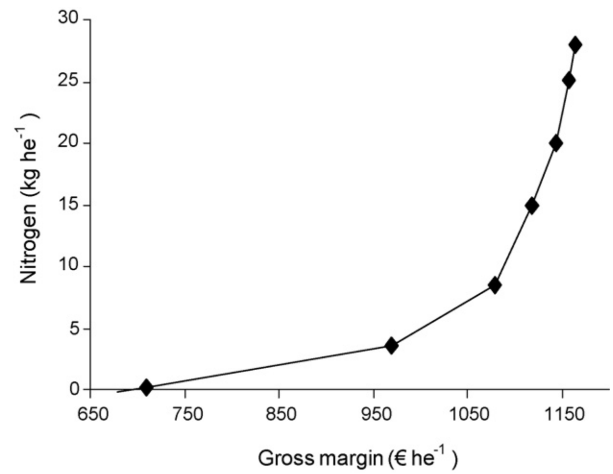

Fig. 4. Efficient frontier income-nitrogen for the land use combinations reported specified in Table 6.

through in the shallow water table by 55% and 95% depending on the chemical properties of the active ingredients (terbuthylazine, alachlor, nicosulfuron, pendimethalin, linuron). Other studies gave comparable results considering some herbicides belonging to the same families, as in example the findings of Patty et al. (1997) and Barnes and Kalita (2001) for atrazine or the findings of Popov et al. (2006) for metolachlor. The disappearance of these molecules can be related to different processes such as enhanced degradation (Staddon et al., 2001), plant uptake in the BS (Paterson and Schnorr, 1992) and absorption in the soil organic matter (Otto et al., 2008). The pollution control performance obtained with the BS in our experiments is of particular interest given that they were all only 4–6 m wide, a size that is suitable for the Italian rural landscape. With narrow BS it is hence possible to achieve a satisfactory protection of surface water bodies quality with a limited loss of cropland.

At the same time, the timber production can represent an interesting non-conventional opportunity for integrating the farmer's income. In our experiments *P. hybrida* was grown according to a scheme that involves the harvesting of wood every 5–7 years. Two situations were taken into account, comparing the yield of wood obtained in the first cycle of cultivation, harvested 6 years after plantation, and at plant maturity (more than 20 years old). In the second case, the wood production per plant was three times higher than in the first cycle, suggesting that the economic advantage increases over time. This information can be of help in changing the perception of wooded BS, which should be considered not only as "unproductive lands" functional for water cleaning, but as a productive part of the farm. At present, there is no consolidated market for wood in Italy, but the prospects are favourable because interest in renewable energy is growing due the scarcity of national sources and the Kyoto Protocol. The yearly production of wood that can be obtained from 1 ha of *Platanus* BS at the first cultivation cycle can supply the heating for a medium-sized house (500 m^3). Given that the average expense is around 2000 € if methane is used as energy source, a potential reference value of wood can be derived.

Moreover, the soil in the BS accumulates more organic matter than agricultural soils, because it is not subjected to the normal cultivation practices. As a consequence BS act as a sink of atmospheric CO_2 and can be considered as "diffused woodlands" within the framework of the measures supported by the Kyoto Protocol to reduce net C losses.

Considering the CO_2 immobilized in the wood and soil together, the BS can store up to 80 t ha^{-1} year^{-1}. The trading value on the CO_2 world market is rather variable (e.g. from 16 to 29 € t^{-1}, depending

Table 6
Solutions of the multi-objective analysis models. Criteria: income and nitrogen losses.

Gross margin (€ ha^{-1})	Var (€)	Nitrogen (kg ha^{-1})	Var (%)	Alfalfa area (%)	Wheat area (%)	Maize area (%)	Soybean area (%)	Trees area (%)	Hedgerow area (%)	Woodland area (%)	Subsidies (€ ha^{-1})
1164		28.0	0.0	33.3	0.0	31.6	35.1	0.0	0.0	0.0	455
1158	−5.7	25.0	−10.7	33.3	0.0	16.8	50.1	0.0	0.0	0.0	455
1143	−20.4	20.0	−28.6	33.3	16.8	0.0	50.1	0.0	0.0	0.0	455
1118	−45.2	15.0	−46.4	33.3	66.7	0.0	0.0	0.0	0.0	0.0	455
1078	−85.4	8.5	−69.6	33.3	61.8	0.0	0.0	0.0	5.1	0.0	432
970	−193.6	3.5	−87.5	0.0	94.9	0.0	0.0	0.0	5.1	0.0	432
709	−454.3	0.2	−99.3	0.0	62.0	0.0	0.0	0.0	5.1	32.9	282
679	−484.5	−0.1	−100.4	0.0	59.1	0.0	0.0	2.9	5.1	32.9	268

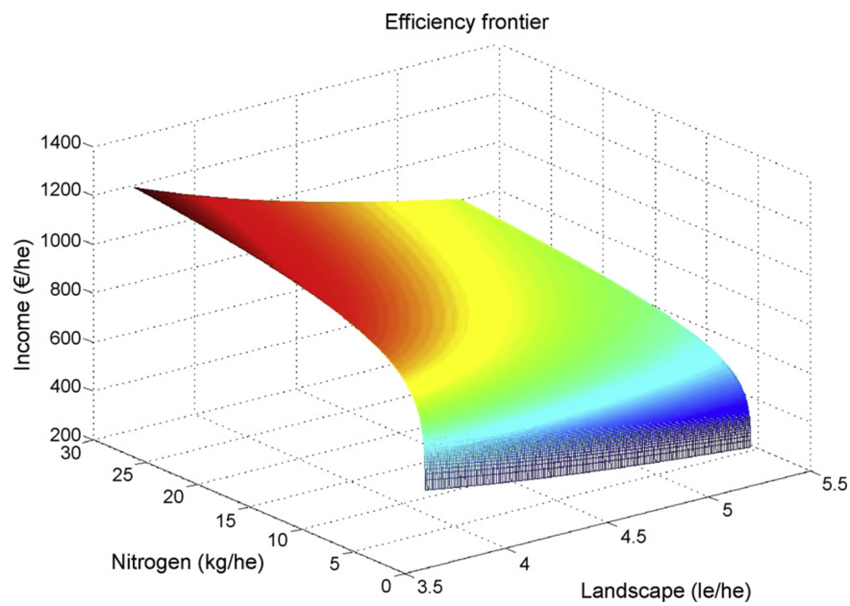

Fig. 5. Efficient frontier income, landscape and nitrogen releases.

on time and reference market, Pettenella and Ciccarese, 2007), but it can offer an interesting option for the farm income.

Lastly, the presence of hedgerows improves the population's perceived naturalness of the area.

Against these positive functions in the agro-ecosystems, a slight crop yield loss has been measured in proximity to the BS. This effect is likely due to the shading by the trees rather than to other processes like competition. As the soil in the field is ploughed every year, this disturbs the development of the tree roots in the upper soil profile, where most of the crop roots develop. The yield loss near the BS was higher in sugarbeet, followed by soybean and maize and this can be due to the age, and obviously size, of the trees in the BS: sugarbeet was cultivated 4 years after the BS had been planted, soybean after 3 years and maize after 2 years.

The results of the MOP model showed that without considering the opportunities offered by the sale of timber and the possible trading of CO_2 associated to C accumulation in the soil, allocating about 5% of the farmland to BS can achieve significantly reduced nitrogen losses with a reduction in gross margin of less than 100 € ha^{-1}. This could be the order of magnitude of a public subsidy given to encourage farmers in the planting and managing of BS.

5. Conclusions

The results demonstrate the importance and multi-functionality of buffer strips in the rural territory of the Veneto plain. Modern agriculture is called upon to offer two main functions to society: primary production and positive externalities. Buffer strips offer a good opportunity to satisfy both these targets.

Within the multi-functional role of agriculture, some aspects of hedgerows (e.g. timber production) have a straight monetary value, while others properly belong to the public sector. Within this framework, decision-makers need more information. The results show that estimated opportunity costs can support the public decision-maker in determining the subsidies to be paid to farmers to encourage them to pursue higher levels of environmental quality.

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