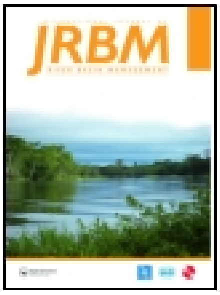

International Journal of River Basin Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trbm20

Cost-effective targeting of riparian buffers to achieve water quality and wildlife habitat benefits

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Accepted author version posted online: 22 Jan 2014.Published online: 21 Feb 2014.

Intl. J. River Basin Management iFirst, 2014, 1–13

Research paper

Cost-effective targeting of riparian buffers to achieve water quality and wildlife habitat benefits

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ABSTRACT

This study develops an integrated economic, hydrologic, and ecological modelling framework to examine cost-effective targeting of riparian buffers to achieve water quality and wildlife habitat benefits. The framework is empirically applied to the Canagagigue Creek watershed in Ontario, Canada to compare the economic costs for establishing riparian buffers under three alternative environmental and ecological constraints: sediment abatement only, habitat improvement only, and riparian buffer acreage only. The results show that riparian buffers targeted for achieving sediment abatement goal are not effective in improving habitat quality. Similarly, riparian buffers identified through habitat improvement goal achieve less sediment abatement as compared to those targeted in the sediment abatement scenario. The trade-offs suggest that agricultural stewardship programmes with joint water quality and habitat improvement goals may need to allocate funds independently for targeting two pools of riparian buffers: for improving water quality only or for improving habitat only.

Keywords: Cost-effectiveness; integration; riparian buffers; water quality; wildlife habitats

1 Introduction

Riparian buffers as a beneficial management practice have been widely established across landscapes to mitigate adverse environmental effects of agriculture. While riparian buffers play an important role in filtering agricultural pollutants and improving water quality, the vegetative (tree, shrub, and grass) buffers also increase natural cover in agricultural watersheds and therefore contribute to improving wildlife habitat quality (Qiu and Dosskey 2012). From this point of view, establishing riparian buffers has the potential to provide both water quality and wildlife habitat benefits. However, riparian buffers with higher water quality benefits are not necessarily effective in providing wildlife habitat benefits and vice versa. Furthermore, economic costs, e.g. forgone cropping returns, are associated with establishing riparian buffers and these costs are often spatially variable within an agricultural watershed. In developed market economies, agricultural stewardship programmes typically provide financial incentives to farmers for establishing riparian buffers in order to compensate for the private costs. Because of the heterogeneity across vast agricultural regions, a policy question that arises is which riparian areas should be targeted for buffers to achieve both water quality and wildlife habitat benefits at least costs. This question demands an understanding of not only the trade-offs between economic costs and water quality/wildlife habitat benefits but also the trade-offs between water quality and wildlife habitat benefits.

Received 21 June 2013. Accepted 27 December 2013.

ISSN 1571-5124 print/ISSN 1814-2060 online
http://dx.doi.org/10.1080/15715124.2014.880710
http://www.tandfonline.com

Previous studies have examined targeting of conservation tillage (Fox *et al*. 1995), land retirement (Khanna *et al*. 2003, Yang *et al*. 2003), and riparian buffers (Qiu and Prato 1998, Yang and Weersink 2004, Qiu 2009, Qiu *et al*. 2009, Dosskey and Qiu 2011, Dosskey *et al*. 2011) in agricultural watersheds with various approaches. They have shown that targeting specific locations for implementing conservation practices can achieve cost-effectiveness of stewardship programmes. However, these studies typically used water quality indicators as environmental goals without explicitly considering wildlife habitat benefits. Babcock *et al*. (1996, 1997) examined the cost implications of alternative criteria such as costs only, benefits only, and benefit to cost ratios in targeting land retirement to achieve multiple environmental benefits including wildlife habitat benefits. However, these studies typically focus on a large region such as the entire USA. They do not examine the relationship between water quality and wildlife benefits and the role of wildlife benefits in targeting land retirement at watershed scale.

A few studies have examined the impacts of agricultural stewardship programmes such as the US Conservation Reserve Program (CRP) on wildlife habitat benefits. For example, Roseberry *et al.* (1994) used geographic information system (GIS) and a habitat suitability index model to assess the effects of land retirement on bobwhite habitats (*Colinus virginianus*). They revealed that contribution of land retirement to bobwhite habitat quality depended on the amount of retired land and its vegetation suitability for bobwhite use, the habitat suitability of remaining cropland, and the spatial arrangements of retired cropland in association with existing bobwhite habitat patches. Patterson and Best (1996) examined the linkage of bird abundance and nesting success with vegetation arrangements such as structure and composition on retired crop fields. The results showed that the retired land had contributed to an increase in abundance of some bird species on the study site in central Iowa. Egbert *et al.* (2002) used seven fundamental landscape metrics to estimate wildlife habitat improvement for post-CRP fields. These metrics included the number of patches, mean patch size, patch density, edge density, mean shape index, nearest neighbour distance, and interspersion/juxtaposition index. The results indicated that wildlife habitat quality was improved in terms of increasing habitat amounts and de-fragmenting habitats after enrolling CRP land. Several studies also developed indexes including water quality and wildlife benefits to examine the cost-effective targeting of conservation buffers on agricultural landscapes (Qiu 2010, Qiu and Dosskey 2012). These studies demonstrated that agricultural stewardship programmes have contributed to wildlife habitat quality on the landscape. However, the magnitude of contribution also depends on spatial arrangement of existing natural area and the additional stewardship lands.

This study extends previous research to develop an integrated economic, hydrologic, and ecological modelling framework to examine cost-effective targeting of riparian buffers to achieve multiple environmental and ecological benefits. Within the modelling framework, a farm economic model is used to quantify the forgone cropping returns from establishing riparian buffers. Two hydrologic models are employed to estimate the corresponding water quality benefits in terms of off-site sediment abatement. An ecological model is applied to quantify the wildlife habitat benefits measured by reduction in the least costs for wildlife movement from establishing riparian buffers. Finally, a GIS-based mathematical programming model is developed to integrate data from various sources and examine cost-effective targeting of riparian buffers to achieve both water quality and wildlife habitat benefits.

The next section outlines a conceptual framework for the conservation planner's decision problem in improving cost-effectiveness of agricultural stewardship programmes. The empirical application section of the paper begins by describing the Canagagigue Creek watershed study area located in Southern Ontario, Canada. This area is selected because it is currently experiencing water quality problems from suspected agricultural non-point sources and riparian buffers are being established as one of the beneficial management practices in the watershed. This watershed is also within the range of about 20 wildlife species that have been officially designated 'at risk' in Canada. The economic costs of riparian buffers are quantified and sediment abatement and wildlife habitat improvement benefits are estimated. Then cost-effective targeting of riparian buffers in the agricultural watersheds under alternative constraints such as sediment abatement only, wildlife habitat improvement only, and riparian buffer acreage only are examined. The paper concludes with implications and challenges in modelling and designing agricultural stewardship programmes.

2 Conceptual framework

Establishing riparian buffers in an agricultural watershed involve private costs in terms of forgone cropping returns and riparian investment (planting and maintenance costs). Agricultural stewardship programmes typically provide financial incentives to compensate farmers' economic losses from conservation actions. Because of the heterogeneity of cropland within a watershed, the spatial distribution of economic costs, water quality benefits, and wildlife habitat benefits could be very different. The trade-offs exist not only between economic costs and water quality/wildlife habitat benefits but also between water quality and wildlife benefits. The conservation planner's decision problem is to target land for establishing riparian buffers such that both the water quality and wildlife habitat benefits could be achieved at least costs.

To set up the conceptual framework, an agricultural watershed is delineated into N sub-catchments based on surface hydrology. For each sub-catchment i, where $i = 1, 2, \ldots, N$, five land management options j are specified, which refer to establishing riparian buffers with widths of 0, 5, 10, 15, and 20 metres on each side of the drainage network in the sub-catchment. That is, $j = 1, 2, \ldots, 5$ and the base scenario is $j = 1$, the land management option without buffer. These options are defined because the Rural Water Quality Program in the study area is providing financial incentives to farmers for establishing riparian buffers of at least 10 feet or 3 metres along water courses (Ryan, personal communication, 2010). Literature also shows that riparian buffers need to be wider to be effective in filtering sediment and nutrients from agricultural fields (Dillaha *et al*. 1989, Schmitt et al. 1999, Qiu and Dosskey 2012).

In sub-catchment i with land management option j, the buffer area along the water course has an area of A_{ij} hectares and the forgone cropping returns from establishing riparian buffers are defined as R_{ij}. The off-site sediment abatement is denoted as S_{ij}, which is the reduction of sediment transported to the drainage network of the watershed. The wildlife habitat benefits in terms of reduction in the least costs for wildlife movement from establishing riparian buffers are represented by H_{ij}. In the base scenario without riparian buffer, $A_{i1} = 0$, $R_{i1} = 0$, $S_{i1} = 0$, and $H_{i1} = 0$ because no change in land management has been made. With a limited budget, the conservation planner's decision problem is to identify one of the five buffer options (including no buffer option) in each sub-catchment such that the economic costs are minimized for achieving specific goals of water quality and wildlife habitat improvement. To choose among the five buffer options we introduce a convex combination (weight) variable Z_{ij}, where $0 \leq Z_{ij} \leq 1$ with $\sum_{j=1}^{5} Z_{ij} = 1$ for each sub-catchment i. The mathematical programming model that determines cost-effective targeting of riparian buffers in the watershed is as follows:

$$\text{Min} \sum_{i=1}^{N} \sum_{j=1}^{5} R_{ij} Z_{ij}, \tag{1}$$

s.t.

$$\sum_{i=1}^{N} \sum_{j=1}^{5} A_{ij} Z_{ij} \geq \overline{A}, \tag{2}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{5} S_{ij} Z_{ij} \geq \overline{S}, \tag{3}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{5} H_{ij} Z_{ij} \geq \overline{H}, \tag{4}$$

$$\sum_{j=1}^{5} Z_{ij} = 1 \text{ for all } j = 1, 2, \ldots, 5, \tag{5}$$

$$Z_{ij} \geq 0 \text{ for all } i, j, \tag{6}$$

where $\overline{A}$ is the riparian acreage goal in stewardship programmes, $\overline{S}$ is the amount of sediment abatement, and $\overline{H}$ is the reduction of the least costs for wildlife movement as specified in the environmental and ecological goals. Besides required constraints (5) and (6), the above model with additional constraints (3) and (4) identifies sub-catchments to establish riparian buffers for achieving joint benefits of off-site sediment abatement and wildlife habitat improvement. The mathematical model also can be modified to have either additional constraint (3) or (4). These modifications will simplify the model into examining spatial targeting of riparian buffers to achieve sediment abatement goals only or wildlife habitat goals only. The riparian acreage scenario with constraint (2) only can also be specified to target riparian buffers to achieve acreage goal while minimizing economic costs. A comparison of these targeting scenarios will provide insights for effective stewardship programme design.

3 Empirical applications

A GIS-based modelling framework has been developed to implement the conceptual framework (Figure 1). Within the framework, a farm model is used to estimate economic costs for establishing riparian buffers in the study watershed. Two hydrologic models are employed to estimate sediment abatement benefits of riparian buffers. An ecological model is applied to quantify the habitat benefits in terms of reduction in costs of inter-patch movement for wildlife. A GIS-based mathematical programming model is developed to spatially target riparian buffers to minimize the economic costs for achieving specific sediment abatement and wildlife habitat benefits in an agricultural watershed. The procedure for the empirical application is described below.

3.1 *Study area*

The Canagagigue Creek watershed drains an area of 146 square kilometres (14,600 hectares) in the central portion of the Grand River Basin in Ontario, Canada (Figure 2). About 79% of the land is used for agricultural purposes with 12% in forest, 8% in pasture, and 1% in open water. The elevation in the watershed ranges from 320 to 470 metres, and 97% of the area has a slope of less than 10%. There are five types of soil present: Guelph,

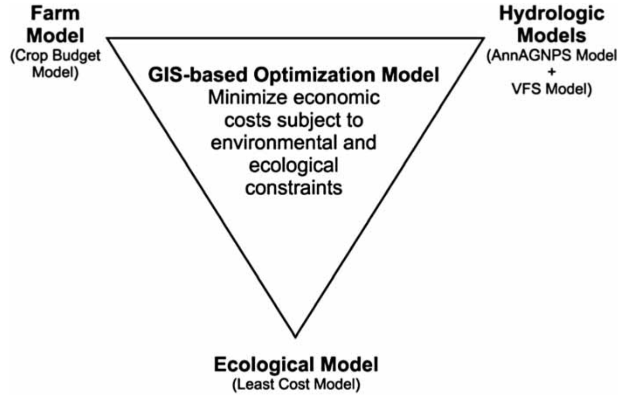

Figure 1 The integrated economic, hydrologic, and ecologic modelling framework for targeting riparian buffers in agricultural watersheds.

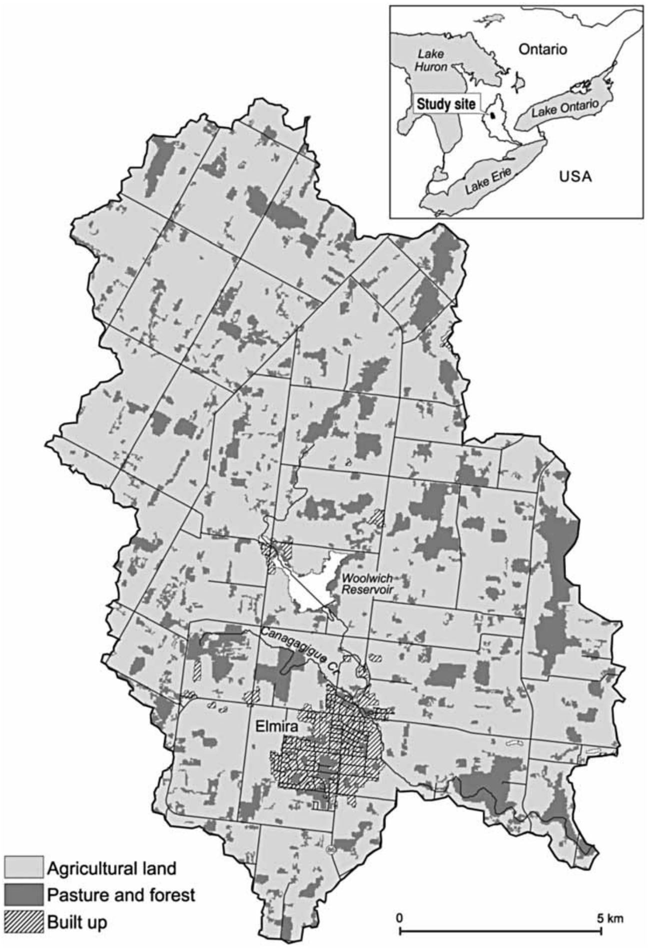

Figure 2 Distribution of land use in the Canagagigue Creek watershed.

Harriston, Dumfries, Burford, and Waterloo (mostly in 'Podzols' group of Food and Agriculture Organization soil classification). Most of the soils are suitable for cropping but have high erosion potential (Grand River Conservation Authority 2002).

The typical crop rotation in the region is corn, soybean, and winter wheat. The study year is 2000 because the most reliable hydrologic data and model validation are obtained for that year. The watershed is divided into 122 sub-catchments based on surface hydrology, 92 of which have row crops, small grains, or forages. Riparian buffers are only considered for the 92 sub-catchments with agricultural land use. Based on the conceptual framework the riparian buffers specified in agricultural sub-catchments have widths ranging from 5 to 20 metres and represent between 216 and 867 hectares or between 1.9% and 7.5% of the agricultural land in the watershed. Please note that the riparian buffer along streams in this study is only one type of conservation buffers, which may include grass waterway, filter strip, and vegetative cover along non-perennial streams (Qiu *et al*. 2009).

3.2 *Economic costs of riparian buffers*

The economic costs for establishing riparian buffers are represented by the forgone cropping returns incurred, which determine the minimum financial incentives that need to be provided to farmers for retiring their land from production. Riparian establishment costs such as purchase of tree saplings and grass seeds, and associated labour and maintenance costs are assumed to be uniform across spatial locations and therefore not included in spatial targeting of riparian buffers. A farm economic model or crop budget model is used to estimate cropping returns in the Canagagigue Creek watershed. This model can be expressed as follows (Just *et al.* 1982):

$$R = \mathrm{TR} - \mathrm{TVC}, \tag{7}$$

where R represents the cropping returns, TR is the total revenue, and TVC denotes the variable costs in crop production.

We obtained soil-based crop yield data from AGRICORP, the crop insurance company in Ontario. Specifically, farm-specific crop yield data are overlaid with soil polygon data to generate crop yield data for each soil polygon. The revenue data are estimated for each soil polygon by multiplying crop yields with prices in year 2000 (OMAF 2003, 2013). Estimating variable costs is based on a 243-hectare (600-acre) representative farm in consultation with business analysts in the Ontario Ministry of Agriculture and Food (OMAF 2013). The variable production costs are defined as expenses on seed, fertilizer, chemical, fuel, machinery, marketing fee, crop insurance, trucking, labour, interest on operating, and other miscellaneous expenses. The variable costs are estimated for corn, soybean, and winter wheat production separately and are assumed to be uniform across the watershed since most of the cost items are based on custom rates. The cropping returns for each crop based on soil polygons are calculated by subtracting variable costs from cropping revenue. The average annual returns for each soil polygon are the simple averages of cropping returns for corn, soybeans, and winter wheat.

The economic costs of riparian buffers are then estimated by overlaying soil-based cropping returns data with riparian buffer boundaries to obtain forgone cropping returns. The total economic costs for the 5-, 10-, 15-, and 20-metre widths of riparian buffers are \$79,260, \$160,470, \$240,836, and \$321,626 per year with average costs between \$367/hectare and \$370/hectare. The economic costs of riparian buffers are spatially variable across sub-catchments. For example, the acreage/cost ratios of 20-metre riparian buffers range from 1 to 7 hectare/\$1000. There are 58 buffer segments with acreage cost ratios below 3. These buffers account for 65.6% of the total area for the 20-metre buffer area but constitute 77.5% of the total forgone cropping returns. The other 34 buffers with cost ratios between 3 and 7 comprise 34.3% of the 20-metre buffer area but share only 22.5% of the total economic costs (Table 1). The pattern indicates that the majority of the riparian buffers are located in areas with high land productivity and therefore with high forgone economic costs.

3.3 *Sediment abatement benefits of riparian buffers*

The annualized Agricultural Non-point Source Pollution (AnnAGNPS) model is identified as the watershed hydrologic

Table 1 Distribution of forgone cropping returns by sub-catchments in the Canagagigue Creek watershed with 20-metre riparian buffers

Range for acreage/cost ratio (ha/$1000)	Number of sub-catchments	Buffer area (ha)	% of total buffer area	Forgone cropping returns for area ($)	% of total forgone cropping returns
1–2	8	70.2	8.1	36,029.0	11.2
2–3	50	498.4	57.5	213,242.9	66.3
3–4	14	123.9	14.3	36,062.3	11.2
4–7	20	174.6	20.1	36,292.2	11.3
Total	92	867.1	100.0	361,626.3	100.0

model for the study. Developed by the US Department of Agriculture, the AnnAGNPS model has been widely applied in various watersheds to estimate the water quality impacts of agricultural management practices (Yuan *et al*. 2003). In the AnnAGNPS model, the basic modelling units are sub-catchments. However, riparian buffers only comprise a small portion of sub-catchments. While the AnnAGNPS model focuses on simulating the watershed process of sediment and nutrient movement, the pollution filtering of riparian buffers is a local process. The sediment abatement of riparian buffers is estimated using a field-scale hydrologic model, Vegetation Filter Strip (VFS) model, in conjunction with the AnnAGNPS model. The VFS model is an event-based model designed to estimate the outflow, infiltration, and sediment trapping efficiency of vegetation buffer strips (Parsons and Muñoz-Carpena 2002).

The implementation of the AnnAGNPS model begins by dividing the Canagagigue Creek watershed into 122 sub-catchments based on surface hydrology. The input parameters are derived from five data-sets: climate, the Digital Elevation Model, drainage network, land use, and soil. With the input data collected, the AnnAGNPS model is run to simulate daily runoff, on-site erosion, sediment yield, and sediment loading for the Canagagigue Creek watershed in the cropping season of 2000. The simulation results are validated based on observed runoff and sediment loading data obtained from the Grand River Conservation Authority for an upper and lower location within the watershed. The calculated correlation coefficient between observed and simulated values is 0.96, indicating a good match between the trends of the two sets of data. For a typical 5-year storm event (69.6 mm rainfall during 24 hours on May 18, 2000), the predicted sediment loading at the watershed outlet is 76.1 tonnes while the observed sediment loading is 109.3 tonnes, representing an underestimation of 30.3%. This discrepancy is within the acceptable range of hydrologic model predictions (Mitchell *et al*. 1993).

AnnAGNPS simulation results for the typical five-year storm event are used as inputs to the VFS model. The choice of storm event before the crop season and the maximum extent of bare ground represent the time period for which the environmental benefits of riparian buffers are at a maximum. Data for six AnnAGNPS model output parameters are used as inputs to the VFS model: peak runoff, time to peak, total runoff, storm hydrograph, sediment concentration (average), and sediment median particle size. For each sub-catchment, the VFS model estimates sediment outflow before and after the vegetation buffer strip is established. The difference between the two outputs is defined as the sediment abatement benefits achieved by a vegetative buffer strip, which are defined in widths of 5, 10, 15 and 20 metres.

For the typical storm event, the total sediment yield in the watershed is 524.4 tonnes. Establishing riparian buffers along drainage network in agricultural sub-catchments leads to 159.5, 227.2, 265.6, and 289.0 tonnes of sediment abatement for buffers of 5-, 10-, 15-, and 20-metre widths, which represent 30.4%, 43.3%, 50.1%, and 55.1% of abatement over the base sediment yield. The pattern indicates decreasing sediment abatement efficiency as the widths of the riparian buffers increase. Similar to the economic costs, the sediment abatement of riparian buffers is also unevenly distributed across sub-catchments. For example, the sediment abatement/cost ratios of riparian buffers with 20-metre width range from 0.1 to 7 tonnes/$1000. Among the 92 riparian buffers, 77 of them have sediment abatement/cost ratios below 2 tonnes/$1000. These buffers comprise 85.1% of the total buffer area but contribute only 57.4% of the total sediment abatement. The other 15 buffers have sediment abatement cost ratios between 2 and 7 tonnes/$1000. They only account for 14.9% of the total buffer area but contribute 42.6% of the total sediment abatement (Table 2). The pattern shows considerably uneven distribution of sediment abatement among those buffers in the study watershed.

3.4 *Wildlife habitat benefits of riparian buffers*

Habitat connectivity is a critical measure of habitat quality within a landscape (With 1999, Tewksbury *et al*. 2002). Connectivity refers to the degree to which a landscape impedes or fosters wildlife movements among habitat patches (Forman 1995). The least cost distance (LCD) model has been identified to quantify wildlife habitat quality based on functional connectivity of habitats (Chardon *et al.* 2003). The LCD model specifies two landscape parameters – source patches and landscape friction. The source layer represents the best existing habitat patches for wildlife. The friction layer indicates the relative viscosity for inter-patch movement across all land cover types in the landscape. Based on the two layers, the LCD model calculates the least costs at

Table 2 Distribution of sediment abatement by sub-catchments in the Canagagigue Creek watershed with 20-metre riparian buffers

Range for sediment abatement/cost ratio (tonnes/$1000)	Number of sub-catchments	Area (ha)	% of total buffer area	Sediment abatement for area (tonnes)	% of total sediment abatement
0.1 – 1	56	546.7	63.0	78.7	27.2
1 – 2	21	191.2	22.1	87.3	30.2
2 – 3	9	71.8	8.3	54.5	18.9
3 – 7	6	57.4	6.6	68.3	23.7
Total	92	867.1	100.0	288.9	100.0

any point on the landscape for wildlife to travel from the nearest source patches (Verbeylen *et al.* 2003). If riparian buffers are added to the landscape then the habitat quality will improve in terms of connectivity between source patches. The wildlife benefits from establishing riparian buffers are defined as the reduction of the least costs for wildlife movement throughout the landscape.

In the LCD model, the source patches and friction values are established based on a guild of species instead of a single species. In the study area about 20 species of birds, mammals, reptiles, and insects are officially designated 'at risk', which include eleven bird species – passenger pigeon (*Ectopistes migratorius*), henslow's sparrow (*Ammodramus henslowii*), hooded warbler (*Wilsonia citrina*), least bittern (*Ixobrychus exilis*), black tern (*Chlidonias niger*), cerulean warbler (*Dendroica cerulea*), louisiana waterthrush (*Parkesia motacilla*), red-headed woodpecker (*Melanerpes erythrocephalus*), red-shouldered hawk (*Buteo lineatus*), short-eared owl (*Asio flammeus*), yellow-breasted chat (*Icteria virens*); four mammal species – eastern elk (*Cervus canadensis canadensis*), eastern cougar (*Puma concolor couguar*), American badger (*Taxidea taxus*), and southern flying squirrel (*Glaucomys volans*); two reptile species – eastern milk snake (*Lampropeltis triangulum triangulum*) and northern ribbon snake (*Thamnophis sauritus septentrionalis*); and two insect species – monarch butterfly (*Danaus plexippus*), and West Virginia white (*Pieris virginiensis*). After examining the distribution of natural areas and habitat requirements for associated wildlife species, all forest patches larger than 25 hectares are considered as source patches in the Canagagigue Creek watershed (Figure 3). As a result, 15 patches of dense forests are selected as source patches with a total of 810 hectares. These source patches have a maximum size of 190 hectares and an average size of 40 hectares.

The friction to animal movement for a land-use type is associated with factors such as food sources, protective cover, or disturbances that affect survival probability of the species during their daily or seasonal movement (Wegner and Merriam 1979). In this study, the integer scale of 1 – 10 is used to assign a friction value to each of the 12 land-use types (Forman 1995). All forest patches are assigned the lowest friction value of 1 because these patches are areas where wildlife has the richest food sources, cover, and the least disturbances. By contrast, urban areas, where wildlife is easily disturbed or killed, are assigned the

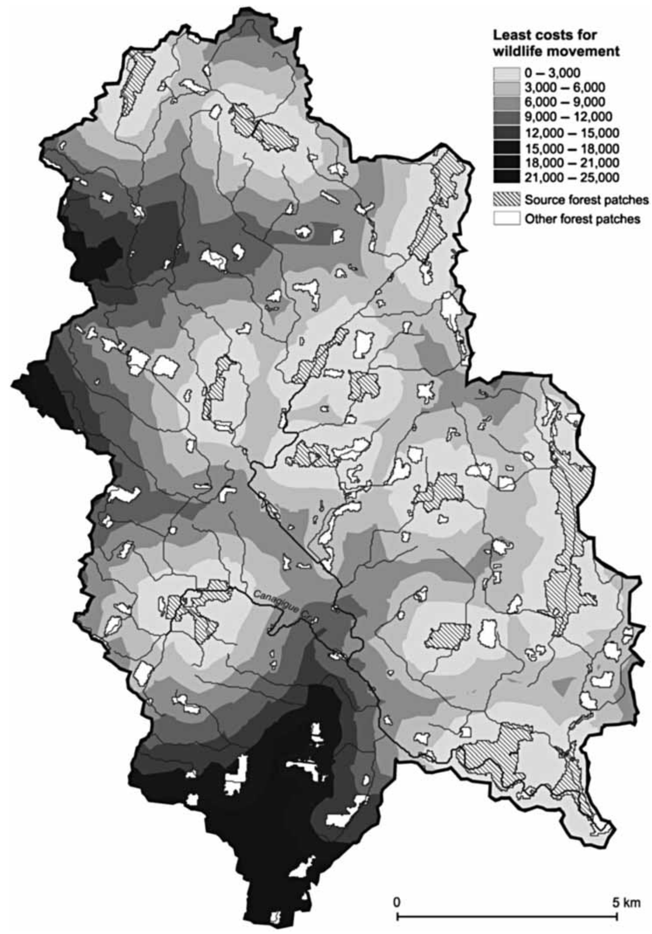

Figure 3 Spatial distribution of habitat source patches and accumulative least costs for wildlife in the Canagagigue Creek watershed.

highest friction value of 10. Open water bodies are assigned the medium friction value of 5 because they are either valued resources, or impedance to wildlife movement. The monoculture forest plantations and pastures have similar friction for wildlife movement but more than marsh land because marsh land provides more food and water resources as well as protective cover. As a result, marsh land is assigned a friction value of 2, while both plantation land and pasture land are assigned a friction value of 4. Both golf courses and forage land are assigned a friction value of 6 because of intensive management and mowing frequency. Since the disturbance on agricultural land, such as chemical use and other farming activities, appears more than that on forage land, agricultural land is assigned a

Table 3 Distribution of habitat improvement by sub-catchments in the Canagagigue Creek watershed with 20-metre riparian buffers

Range for habitat improvement/cost ratio (units/$1000)	Number of sub-catchments	Area (ha)	% of total buffer area	Habitat improvement for area (units)	% of total habitat improvement
0.1–10	49	466.5	53.8	892.7	18.4
10–20	23	187.4	21.7	910.0	18.8
20–30	7	75.0	8.6	700.5	14.5
30–110	13	138.3	15.9	2344.2	48.3
Total	92	867.1	100.0	4847.4	100.0

friction value of 7. The food sources on gravel extraction sites are more than urban areas but less than cropland. Thus, the extraction sites are assigned a friction value of 8. The road corridors are assigned friction values 8 for narrow, low-speed local roads and 9 for wide, high-speed major roads.

The friction values for riparian buffers are determined based on a comparison with other land cover types. Vegetative cover on riparian buffers is considered similar to forest patches or plantation land based on the food and water sources. For example, the 20-metre riparian buffer with a total width of 40-metre on both side of streams is complex and as good as forest land for wildlife in terms of food abundances and the shelter role, while the 5-metre stream buffer with a total width of 10 metre is less complex and plays a similar role for wildlife as plantation land does. Therefore, the 20-metre stream buffer is assigned a friction value of 1, while 4 is assigned to the 5-metre buffer. Friction values for the 10- and 15-metre buffers can be assigned between 1 and 4, with 2 for 10-metre buffer and 3 for 15-metre buffer.

After the source patch and friction grids are determined, the LCD model is run for the base scenario and the four riparian buffer options in each of the 92 agricultural sub-catchments to estimate wildlife habitat improvement in terms of reduction in the least costs for wildlife movement on the landscape. In all the model runs the source grid is the same. Following the methodology suggested by Feather *et al*. (1999), the friction grid is updated by putting only one riparian buffer in the base grid at a time while keeping the rest of the land cover unchanged. In this way, the wildlife habitat improvement is estimated for each of the buffer options in a specific agricultural sub-catchment.

The least costs for wildlife movement quantified by the LCD model are a relative measure of wildlife habitat quality on the landscape. In the Canagagigue Creek watershed, the base level of least costs for wildlife movement is 6530.9 (unitless). The closer the location from source patches, the lower the least costs (Figure 3). The habitat quality improvement after establishing 5-, 10-, 15-, and 20-metre buffers along the drainage network in terms of reduction in least costs for wildlife movement are 368.2, 1096.5, 2578.9, and 4847.4, respectively, which represent 5.6%, 16.8%, 39.5%, and 74.2% improvement, respectively, in wildlife habitat quality when comparing to base conditions. The habitat improvements from 5- to 20-metre are increasing because wider buffers contribute more to habitat quality from decreased friction, and increased connectivity and habitat amount.

For individual riparian buffers, the habitat improvement is also spatially variable across sub-catchments. For example, for 20-metre riparian buffers, the habitat improvement cost ratios are in the range of 0.1 to 110/$1000. Among the 92 riparian buffers, 72 of them have habitat improvement cost ratio below 20/$1000. These buffers accounts for 75.5% of the total buffer area but contribute only 37.2% of the total habitat improvement. The other 20 buffers comprise only 24.5% of the buffer area and contribute 62.8% to the habitat improvement (Table 3). The pattern clearly shows that only a small portion of the riparian buffers contribute to effective habitat improvement in the study watershed.

4 Empirical results

In the empirical application section, data are prepared for economic costs, water quality, and wildlife habitat benefits from establishing 5-, 10-, 15, and 20-metre riparian buffers in each of the 92 agricultural sub-catchments in the Canagagigue Creek watershed. The data are input into the integrated modelling framework to identify riparian buffers cost-effectively for achieving three environmental and ecological goals: sediment abatement only, habitat improvement only, and riparian buffer acreage only.

4.1 *Empirical results for the sediment abatement goals*

Agricultural stewardship programmes for establishing riparian buffers typically have a priority in improving water quality. In this study, a range of sediment abatement goals from 20% to 50% have been specified to examine not only the targeting of riparian buffers for a specific goal but also the difference in cost-effectiveness between these goals. As shown in Table 4, achieving 20% sediment abatement only needs 66 hectares of riparian buffers with a yearly economic cost of about $16,000. For additional 10% sediment abatement, 67 more hectares of riparian buffers are targeted with an additional cost of $20,000. For 40% sediment abatement, the incremental acreage from 30% level is 102 more hectares with $34,000 additional costs.

Table 4 Environmental and ecological benefits achieved by targeting riparian buffers to achieve sediment abatement goals in the Canagagigue Creek watershed

Sediment abatement goal (%)	Sediment abatement (tonnes)	Land in buffers (ha)	Habitat improvement (units, percentages in parenthesis)	Crop return losses ($1000)	Avrg. costs ($/ha)	Marginal costs[a] ($/acre)	Marginal cost ($/tonne)
20	105.5	66.3	140.0 (2.1)	16.1	242.2	449.3	282.4
30	157.8	133.1	377.3 (5.8)	36.2	272.0	550.7	464.5
40	210.2	234.9	878.8 (13.5)	70.9	301.8	789.9	882.6
50	262.3	440.9	1812.8 (27.8)	146.3	331.9	1425.5	2394.2

[a]Equals (sediment abatement * marginal cost in $/tonne)/land in buffers.

For 50% sediment abatement, an additional 206 hectares of riparian buffers from the 40% goal are targeted and lead to additional $75,000 yearly costs. The pattern indicates that the additional acreage and costs for establishing riparian buffers at higher levels of sediment abatement increase rapidly. The pattern is also signalled by the marginal costs of sediment abatement, which are $449.3/hectare, $550.7/hectare, $789.9/hectare, and $1425.5/hectare, respectively, for the 20%, 30%, 40%, and 50% sediment abatement goals. The pattern can be explained by the fact that the riparian buffers with higher benefit to cost ratios have been targeted first and the additional sediment abatement needs to be achieved by riparian buffers with lower benefit to cost ratios.

Another noticeable pattern is that the wildlife habitat benefits in terms of per cent reduction in the least costs for wildlife movement are considerably lower than the corresponding sediment abatement goals. The habitat improvement for 20%, 30%, 40%, and 50% sediment abatement goals are only 2.1%, 5.8%, 13.5%, and 27.8%, respectively. This pattern reveals the trade-offs between the sediment abatement and habitat improvement. For sediment abatement goals, riparian buffers with 5-metre widths dominate the targeted buffers. While the narrow buffers have higher benefit to cost ratios for sediment abatement, these buffers have relatively lower contribution to habitat improvement because narrow buffers are less valuable in providing wildlife habitats than those of wide buffers. In addition, most of the targeted riparian buffers are further away from source patches and therefore ineffective in improving wildlife habitat benefits (Figure 4).

4.2 *Empirical results for the habitat improvement goals*

For consistency, the habitat improvement goals are set at the levels of least cost reduction for wildlife movement achieved by 20%, 30%, 40%, and 50% sediment abatement goals, which are 2.1%, 5.8%, 13.5%, and 27.8%, respectively. The actual habitat improvement achieved from model runs are 4.1%, 4.1%, 15.0%, and 27.7%, respectively, which are slightly different from the pre-defined goals. The reason is that the riparian buffers are not dividable and they can only be

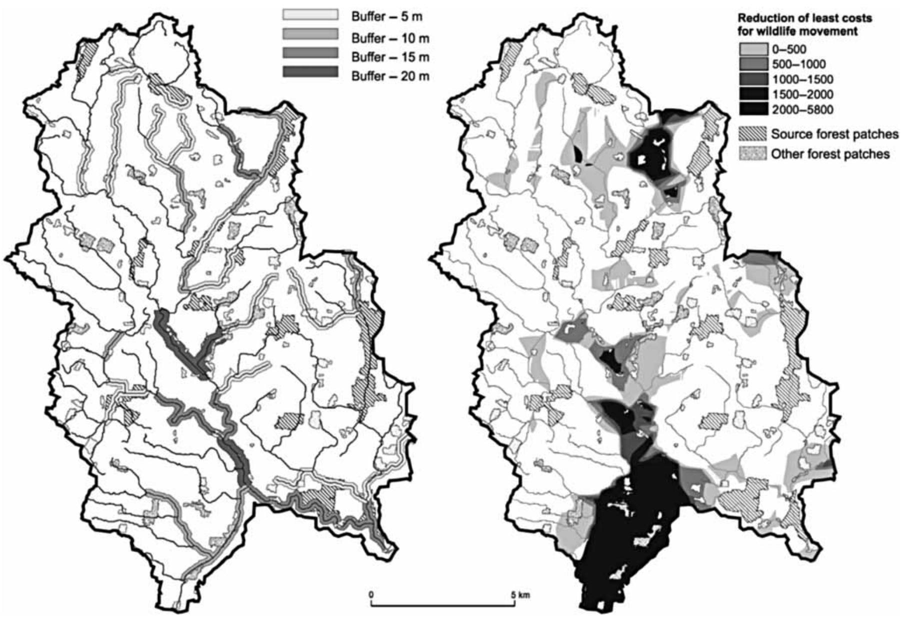

Figure 4 Spatial distribution of targeted riparian buffers for achieving 30% sediment abatement goal in the Canagagigue Creek watershed.

identified to achieve the habitat improvement goals in the approximate range.

Similar to the pattern under the sediment abatement goal, the targeted riparian buffers under habitat improvement goals achieve less percentage sediment abatement (Table 5). For example, riparian buffers for achieving 4.1%, 15.0%, and 27.7% of habitat improvement can only achieve 3.1%, 5.5%, and 9.9% of sediment abatement, respectively. Most of the riparian buffers targeted for habitat improvement have 20-metre width. The wide buffers contribute more to wildlife habitat improvement. However, these buffers have lower benefit to cost ratios in terms of sediment abatement.

For achieving 4.1% habitat improvement, only 12 hectares of riparian buffers need to be targeted with an economic cost of \$2500 per year. For 15.0% habitat improvement, the acreage of targeted riparian buffers is 44 hectares with a yearly cost of \$13,000. For 28% habitat improvement, 102 hectares of riparian buffers need to be targeted with a cost of \$31,000 per year. The pattern of increasing incremental acreages and costs for higher habitat improvement goals is similar to that of sediment abatement goal. The pattern can also be explained by the sequence of targeted riparian buffers starting from those with higher benefit to cost ratios.

The scenario for habitat improvement tends to target riparian buffers that are closer to source habitat patches and the areas with higher least costs for wildlife movement on the base landscape. For example, setting the habitat improvement goal at 2.1% identifies only one riparian buffer that links the two largest source patches and is near the urban area that has the highest least costs on the base landscape. Similarly, the 5 and the 10 buffers targeted for achieving 15% and 28% habitat improvement goals are also located near the source patches and the areas that have higher least costs for wildlife movement on the base landscape (Figure 5).

Table 5 Environmental and ecological benefits achieved by targeting riparian buffers to achieve habitat improvement goals in the Canagagigue Creek watershed

Habitat improvement (units, percentages in parenthesis)	Sediment abatement (tonnes, percentages in parenthesis)	Land in buffers (ha)	Cropping return losses (\$1000)	Average cost (\$/ha)
267.9 (4.1)	16.4 (3.1)	12.3	2.5	205.6
977.3 (15.0)	28.8 (5.5)	44.1	13.0	294.7
1811.6 (27.7)	52.1 (9.9)	102.3	31.2	304.7

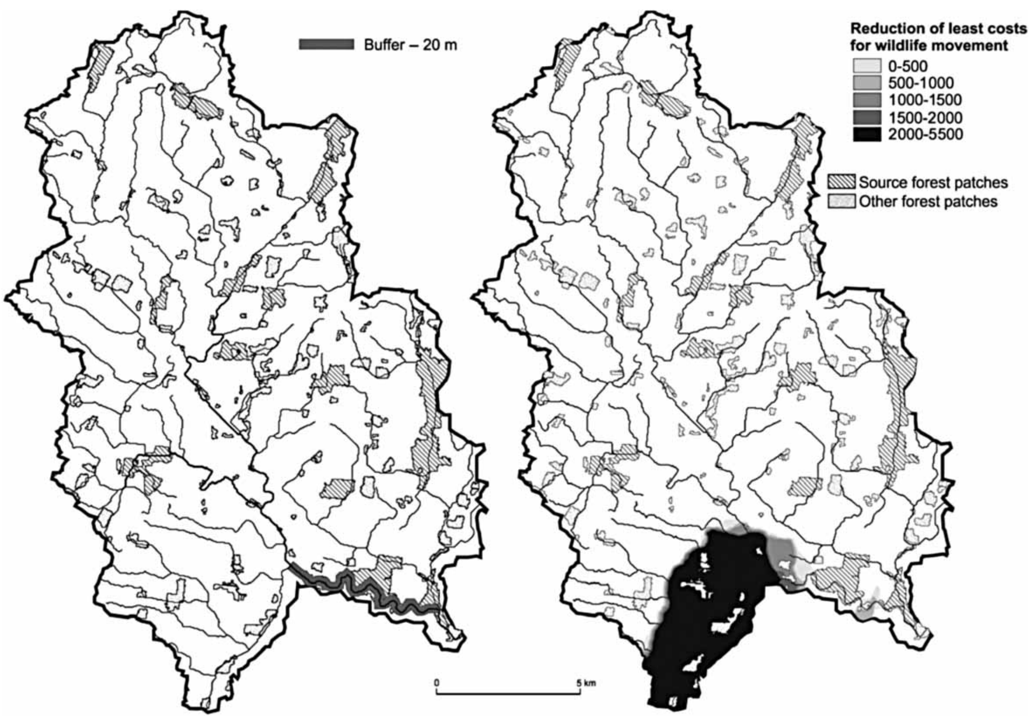

Figure 5 Spatial distribution of targeted riparian buffers for achieving 4.1% habitat improvement goal in the Canagagigue Creek watershed.

4.3 *Empirical results for the riparian buffer acreage goals*

From previous scenarios, we can see that there exist trade-offs between water quality and wildlife habitat improvement from establishing riparian buffers. The targeted buffers for achieving sediment abatement lead to lower benefits in wildlife habitat improvement. Conversely, the targeted buffers for improving wildlife habitat benefits achieve less sediment abatement benefits. The pattern is clearly shown in the Lorenz curves that show the relationship between 20-metre riparian buffer acreage and related sediment abatement and wildlife improvement benefits (Figure 6). For example, 19% of the 20-metre riparian buffer acreage can achieve 50% of sediment abatement benefits. But for the same riparian buffer acreage, it can only achieve 17% of habitat improvement benefits. The wavy and irregular 'habitat' line indicates importance of critical habitat sizes. Habitat improvement may have moderate increase within an acreage threshold but significant increase when reaching an acreage threshold. In contrast, the 'sediment abatement' line is relatively smooth and concave, indicating a gradual increase but at a decreasing rate as riparian buffer acreage increases.

The trade-offs between sediment abatement and habitat improvement suggest that it is not likely to achieve the comparable levels of both benefits from the same sets of riparian buffers.

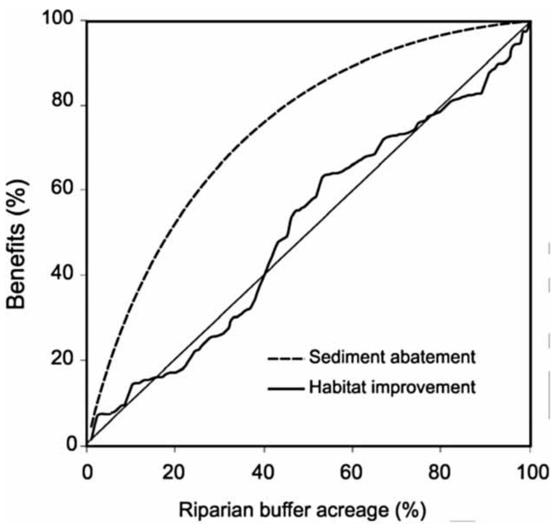

Figure 6 Lorenz curves that show the relationship between riparian buffer acreage and related sediment abatement and habitat improvement benefits.

In practice, land acreage in stewardship is typically used as a programme goal or an indicator for measuring programme performance. For this reason, the third scenario in this study is to specify an acreage goal that is comparable with the riparian buffer acreages identified for the 20%, 30%, 40%, and 50% sediment abatement goals, which are 66.3, 133.1, 234.9, and 440.9 hectares, respectively (Table 6).

For the four acreage goals, the achieved habitat improvements are 1.9%, 11.1%, 19.9%, and 33.4%, respectively, which are similar or higher than the habitat improvement achieved under the scenario with habitat improvement only constraint. The higher wildlife habitat benefits are mainly contributed by the additional riparian buffer acreages compared to the acreages identified in the habitat improvement only scenario. The sediment abatement achieved for the four acreage goals are 7.4%, 17.0%, 25.3%, and 34.7%, respectively. The achieved percentages of sediment abatement are below the levels under the scenarios with sediment abatement constraint only. Therefore, the targeting of riparian buffers under the acreage goal represents a compromise between the scenarios with sediment abatement goal only and the habitat improvement goal only (Figure 7).

The economic costs in corresponding to the four acreage goals also show a similar pattern to those of the sediment abatement or habitat improvement goals. The second acreage goal is 67 hectares more than the first acreage goal of 66 hectares and the additional cost is about $15,000 per year. The average cost of the additional acreage is $227/hectare. The third acreage goal is about 105 hectares more than the second acreage goal with an additional yearly cost of $26,000. The average cost of additional acreage is $247/hectare. The fourth acreage goal is about 200 hectares more than the third acreage goal with an additional cost of $70,000 per year. The average cost is $350/hectare. Again, the pattern can be explained by the targeting sequence that starts from riparian buffers with lower economic costs.

The scenario with acreage constraint is essentially targeting riparian buffers with lower costs without considering their environmental and ecological attributes. For this reason, the average costs of riparian buffers for the four acreage goals are the lowest among the three scenarios, which are $169/hectare, $195/hectare, $224/hectare, and $282/hectare, respectively. The scenario with sediment abatement constraint only has the highest average costs for the targeted riparian buffers, which are $242/hectare, $272/hectare, $302/hectare, and $332/hectare,

Table 6 Environmental and ecological benefits achieved by targeting riparian buffers to achieve acreage goals in the Canagagigue Creek watershed

Riparian acreage goal (ha)	Sediment abatement (tonnes, percentages in parenthesis)	Habitat improvement (units, percentages in parenthesis)	Cropping return losses ($1000)	Average cost ($/ha)
65.7	39.0 (7.4)	125.3 (1.9)	11.1	168.7
132.3	88.9 (17.0)	726.6 (11.1)	25.8	195.4
237.8	132.4 (25.3)	1301.1 (19.9)	53.2	223.6
439.0	181.8 (34.7)	2181.4 (33.4)	123.8	282.0

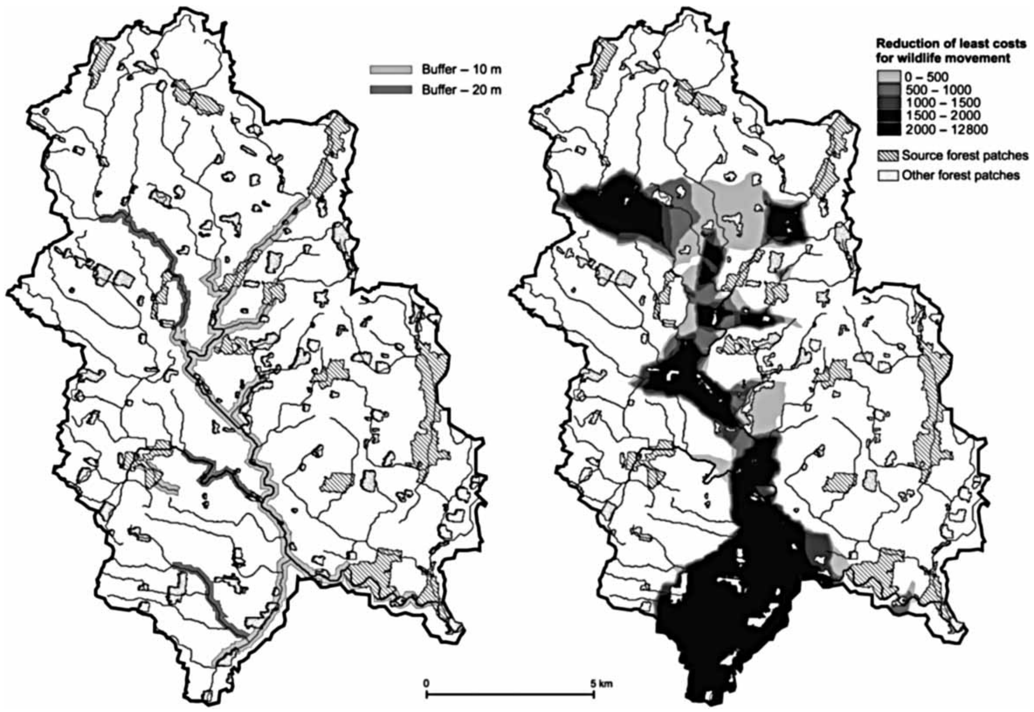

Figure 7 Spatial distribution of targeted riparian buffers for achieving 132-hectare acreage goal in the Canagagigue Creek watershed.

respectively, for the four sediment abatement goals. The scenario with habitat improvement only constraint has average costs for targeted riparian buffers between the previous two scenarios, which are \$206/hectare, \$206/hectare, \$294/hectare, and \$305/hectare for the four habitat improvement goals. The patterns clearly show that the spatial distributions of economic costs, sediment abatement, and wildlife habitat improvement from establishing riparian buffers are very different across agricultural subcatchments.

5 Discussions and conclusions

Establishing riparian buffers in agricultural stewardship programmes typically have a priority in improving water quality. The riparian buffers also have additional benefits in improving habitat quality on the landscape. Because of the heterogeneity of agricultural land in the watershed, the spatial distributions of economic costs, water quality, and habitat improvement benefits from establishing riparian buffers could be very different. An important policy question that arises is how to target and design riparian buffers for achieving both water quality and habitat improvement benefits at least costs.

One of the research directions on conservation buffers is to include an array of benefits characterizing improvements on multiple ecosystem functions. For example, Qiu and Dosskey (2012) examined cost-effectiveness of six different planning strategies (two riparian focused, two soil survey based, and two topography based) in achieving multiple benefits including water quality improvement, erosion control, wildlife habitat improvement, and storm water mitigation based on aggregate scores. Complementary to previous research, this study develops an integrated economic, hydrologic, and ecological modelling framework to examine the spatial trade-offs between economic costs, water quality improvement and wildlife habitat improvement benefits from establishing riparian buffers and cost-effective targeting of riparian buffers in agricultural watersheds. The framework is empirically applied to the Canagagigue Creek watershed in Southern Ontario, Canada. Our results reveal that the riparian buffers targeted for achieving sediment abatement goal only are not effective in providing meaningful habitat improvement benefits. Conversely, riparian buffers targeted for substantially improving habitat quality achieve less sediment abatement benefits. The riparian buffer acreage goal as typically practised in agricultural stewardship programmes represents a compromise between the sediment abatement and habitat improvement goals. In addition, as the levels of water quality or habitat improvement increase, additional acreages of riparian buffers and associated economic costs increase rapidly because riparian buffers with lower benefit to cost ratios need to be identified for the programme to achieve higher environmental or ecological goals.

The modelling results have important policy implications for the design of agricultural stewardship programmes. The trade-offs between sediment abatement and habitat improvement suggest that it is not likely that comparable levels of joint benefits can be achieved simultaneously. In particular, targeting riparian buffers with the primary goal of water quality improvement may have limited contribution in improving wildlife habitat benefits. The acreage goal as practised in agricultural conservation programmes may also have limited effectiveness in improving the joint water quality and wildlife habitat benefits. Therefore, a possible solution could be to take the trade-offs between water quality and wildlife habitat benefits into consideration and allocate funds independently for targeting two pools of riparian buffers: for improving water quality only or for improving habitat only. The proportion of the allocation will depend on the weights of the two programme objectives in terms of water quality and wildlife improvement benefits (Qiu and Dosskey 2012).

Another solution is to enhance the design of riparian buffers to improve water quality and wildlife habitat for at-risk species. Site-specific design of riparian buffers with fine-scale terrain modifications and diverse vegetation could improve filtering and infiltration of surface runoff while providing food and protective cover for wildlife. As a result, the function of riparian buffers – even buffers as narrow as 5 metre – is enhanced through reducing trade-offs between water quality and wildlife habitat (Bentrup *et al*. 2004).

The pattern of benefit to cost ratios in corresponding to increasing water quality and wildlife improvement levels could also be used as references for the design of stewardship programme goals. An appropriate goal should be set at the turning point between the gentle and steep slope of the marginal costs of environmental or ecological benefits. This setting will help policy-makers to save programme costs and move additional funds to other watersheds with higher benefit to cost ratios in order to achieve environmental and ecological goals cost-effectively in a large policy region.

This study examined the targeting of riparian buffers to achieve two distinct types of environmental and ecological benefits. However, conservation measures involved in agricultural stewardship programmes are various and the environmental and ecological benefits are also multi-faceted. How to incorporate the trade-offs between different conservation measures and the multiple benefits is a challenging task that needs to be addressed further (Qiu and Dosskey 2012). This study has the potential to be extended to examine the complexities involved in cost-effective targeting of agricultural stewardship programmes. For example, in addition to riparian buffer, other conservation buffers such as filet strip, grass waterway, and upland cover need to be included in the examination (Qui *et al.* 2009, Qiu and Dosskey 2012). Conservation tillage can be combined with riparian buffers to address water quality problems. On the other hand, agricultural land with conservation tillage also has the potential to improve wildlife habitat quality because less disturbed cropland may provide better cover and food for wildlife while mitigating soil and nutrient deposition (Boutin and Jobin 1998, Ribic *et al.* 1998). The spatial distribution of economic costs, water quality, and wildlife improvements for conservation tillage and conservation buffers are likely very different across agricultural landscapes. An understanding of the complex trade-offs and associated targeting of multiple conservation measures for cost-effectiveness will contribute to better design of agricultural stewardship programmes.

Acknowledgments

This research is jointly supported by the Social Sciences and Humanities Research Council, Ontario Ministry of Agriculture, Food, and Rural Affairs, and the Canadian Water Network. We thank the Grand River Conservation Authority and AGRICORP for providing data, Saleh Sebti for research assistance, and Marie Puddister for designing figures.

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