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Perspective essay

A simple landscape design framework for biodiversity conservation

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HIGHLIGHTS

- We propose a simple, flexible framework that uses only readily-available data.
- Our framework is more practical and feasible than existing guidelines.
- Such a framework is needed to keep pace with very rapid global land cover change.

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ABSTRACT

Local government planning agencies play an important role in conserving biodiversity in human-altered landscapes. Such agencies frequently have a limited knowledge of wildlife biology and few resources to carry out research, and therefore require simple, practical guidelines for biodiversity conservation. We propose a landscape design framework for biodiversity conservation that is sequential, prescriptive, and supported by current landscape ecological science. Unlike existing guidelines, our framework can be implemented in any given landscape using only land cover data and it explicitly considers constraints on land use planning. The steps of our framework, in the order in which they should be implemented are: (1) select land cover data and decide which land cover classes constitute unaltered or altered land covers; (2) list the constraints on land use planning (e.g., economic, social) that exist for the landscape; (3) maximize the total amount and diversity of unaltered land cover, especially near water; (4) minimize human disturbance within altered land cover, especially near water; and (5) aggregate altered land covers associated with high-intensity land uses, especially away from water. We illustrate the utility of our approach by applying it to a hypothetical landscape and comparing the outcome to those from the application of traditional ecological guidelines to inform land use planning.

1. Introduction

Land cover change has been the most important direct driver of global terrestrial biodiversity loss in the last 60 years, and is projected to have an increasing impact in most ecosystems (Millennium Ecosystem Assessment, 2005). In addition to an enormous amount of primary research on this subject (e.g., Fahrig, 2003; Fahrig & Rytwinski, 2009; McKinney, 2008; Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005), there is a growing literature that attempts to translate our understanding of the effects of land cover change on biodiversity into principles, guidelines, and recommendations to inform land use planning (hereafter, ecological guidelines) (Table 1).

Despite the proliferation of ecological guidelines and the recognition that local planning agencies can make a significant contribution to biodiversity conservation (Ahern, Leduc, & York, 2006; Forman, 2002; Miller et al., 2009), there has been little on-the-ground change in how we plan for use of the land (Ahern, 2013; Berke, 2007; Nassauer & Opdam, 2008; Stein, 2007). Landscape ecological knowledge is not being widely used in landscape decision-making (Ahern, 2013; Nassauer & Opdam, 2008) and

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Table 1
A selection of ecological principles, guidelines or recommendations for land use planning. Checkmarks indicate that one or more items in each source requires species-specific information, is not prescriptive, does not consider socioeconomic constraints, or the presentation of items is not sequential. N/A = not applicable.

Source	Species-specific information required	Not prescriptive	Number of items	Not sequential	Does not consider socioeconomic constraints
Soulé (1991)	√	√	5	√	√
Dramstad, Olson, and Forman (1996)	√	√	55	√	√
Duerksen et al. (1997)	√	√	19	√	√
Bennett (1999)	√	√	5	√	√
Dale et al. (2000)	√	√	8	√	√
Zipperer, Wu, Pouyat, and Pickett (2000)		√	6	√	√
Forman (2002)	√	√	7	√	√
Pulliam and Johnson (2002)		√	4	√	√
Environmental Law Institute (2003)	√	√	16	√	√
Environment Canada (2004)	√	√	18	√	√
Li, Wang, Paulussen, and Liu (2005)	√	√	21	√	√
Fischer, Lindenmayer, and Manning (2006)	√		10	√	√
Lindenmayer et al. (2006)	√	√	31	√	√
Colding (2007)			1	N/A	√
Noss (2007)	√	√	7	√	√
Forman (2008)	√	√	121	√	√
Lindenmayer et al. (2008)	√	√	13	√	
Opdam and Steingröver (2008)	√	√	10	√	√
Lovell and Johnston (2009)	√	√	6		√
Stagoll, Manning, Knight, Fischer, and Lindenmayer (2010)	√	√	16	√	√
Sayer et al. (2013)	√	√	10	√	
The present framework			5		

more broadly, land use planners generally do not incorporate science-based information into plans (Berke, 2007; Stein, 2007). For example, less than five percent of staff time is devoted to biodiversity conservation in the municipalities of three large metropolitan regions in the US (Miller et al., 2009).

Based on a review of ecological guidelines (Table 1), we argue that they are not considered in land use planning because they exhibit one or more characteristics that limit their practicality and feasibility. First, most guidelines require species-specific information, which limits their utility since such information at the spatial scales required for planning is scarce for the majority of species and costly and time-consuming to collect (Ahern et al., 2006; Pullin, Knight, Stone, & Charman, 2004). To exacerbate this, insufficient resources are allocated to the collection of biodiversity data in most planning offices (Ahern et al., 2006; Miller et al., 2009). Second, most ecological guidelines are not prescriptive, in the sense that they do not provide specific, actionable instruction. The majority of planning offices in the US lack the ecological expertise to interpret broad guidelines for their particular context (Beatley, 2000; Stein, 2007), making it difficult for planners to translate general principles into specific planning actions (Theobald et al., 2000). Third, guidelines may include dozens of items, belying planners' need for simple, succinct, and integrative rules (Azzerad & Nilon, 2006). Fourth, with one exception, none of the guidelines we reviewed present their suggestions in a sequential manner (Table 1). This is an impediment to use by planners because of the possibility of mutually-conflicting guidelines in a non-sequential list (which occurred in one-third of the guidelines that we reviewed). Finally, very few ecological guidelines incorporate socioeconomic constraints on biodiversity conservation. This is incompatible with the compromises required of planners to satisfy multiple, often competing objectives and reduces the likelihood of successful implementation of conservation initiatives (Ahern et al., 2006; McShane et al., 2011; Stein, 2007).

Here, we propose a simple landscape design framework intended to maximize native biodiversity, i.e., the "genes, individuals, demes, populations, metapopulations, species, communities, ecosystems, and the interactions between these entities" (Lindenmayer, Franklin, & Fischer, 2006), in a given planning area. Our framework, which is based on current landscape ecological science, is sequential and prescriptive, can be implemented in any given landscape using only GIS-based land cover data, and explicitly considers socioeconomic constraints on land use planning. In the following, we demonstrate that these characteristics make our framework more practical and feasible than existing approaches and consequently more likely to be used by planners.

2. The framework

Our framework is organized into five steps, ordered by the sequence in which they should be implemented:

1. Select land cover data and decide which land cover classes constitute unaltered or altered land covers.
2. List the constraints on land use planning (e.g., economic, social) that exist for the landscape; and, within the constraints identified in Step 2.
3. Maximize the total amount and diversity of unaltered land cover, especially near water.
4. Minimize human disturbance within altered land cover, especially near water; and
5. Aggregate altered land covers associated with high-intensity land uses, especially away from water.

2.1. Step 1: Select land cover data and decide which land cover classes constitute unaltered or altered land covers

The distinction between unaltered and altered land cover classes is central to our approach but we acknowledge that this binary classification is an extreme simplification of a diverse multi-dimensional reality. Since the goal of our framework is to maximize native biodiversity in a broad sense (see above), it is necessary to use a very broad categorization of cover types. The intent of the categorization is to distinguish between cover types that are associated with lower (unaltered) or higher (altered) intensities of human use and thus generally support or do not support native biodiversity, respectively. This binary definition will be subject to differences in interpretation among users of our framework. Indeed, the subjectivity of our categorization of cover types is necessary to allow our framework to be applied to a wide variety of landscapes, each with unique biogeophysical and socioeconomic characteristics. In particular, specific altered and unaltered cover types will differ in different parts of the world and individual cover types, such as shrub cover, might be considered altered, e.g., if it represents an intensively cultivated bioenergy crop, or unaltered, e.g., if it represents regenerating forest, in different landscapes. The classification of cover types will also by necessity depend on the types of land covers present in a particular landscape. For instance, grazed land might be considered altered if it is the only cover type subject to human use in a landscape and unaltered if it is much less altered by human use than are other cover types in the landscape.

2.2. Step 2: List the constraints on land use planning (e.g., economic, social) that exist for the landscape

Our framework explicitly recognizes that biodiversity conservation is not the only goal of land use planning, especially in rapidly changing human-dominated landscapes. For our purposes, we define socioeconomic constraints on biodiversity conservation as broad social and economic norms and activities that limit the formulation of recommendations, i.e., the extent to which land cover can be manipulated at Steps 3 and 5 or human activities altered at Step 4 (see below). Note that we do not consider local norms and activities particular to individual landowners as constraints at this step but rather during the implementation of the recommendations from our framework (see Section 3.6). Typical socioeconomic constraints include the maintenance or projected change in extent or intensity of urban development, major transportation corridors, and agricultural, forestry, and mining operations. For example, it is generally not possible to move existing houses to improve biodiversity conservation, and farmland preservation programs in some areas may preclude any change to the extent of agricultural land. Constraints may also include widespread social norms, such as the use of pesticides on lawns and around homes and the low value attached to public transit, that limit or preclude changes to human activities that might be recommended at Step 4.

2.3. Step 3: Maximize the total amount and diversity of unaltered land cover, especially near water

Our focus in Step 3 on the amount of unaltered land cover derives from the fact that habitat amount is the most important determinant of biodiversity. This assertion is based on three lines of evidence. First, habitat loss by means of land cover change was the most important direct driver of global terrestrial biodiversity loss in the last 60 years (Millennium Ecosystem Assessment, 2005), a trend that will continue in this century (Sala et al., 2000). Second, the positive relationship between species number and area is a ubiquitous pattern in ecology (Rosenzweig, 1995). Large areas have many species because they: contain many individuals, thus sampling the potential species pool to a greater extent; have low population extinction rates due to large population sizes; contain many different habitat types; are often subject to less frequent and less intense disturbances (McGuinness, 1984). Third, theoretical and experimental landscape ecological work has shown that habitat amount is a more important determinant of biodiversity than other components of landscape structure, such as matrix quality and habitat configuration (i.e., fragmentation *per se* (*sensu* Fahrig, 2003) or the spatial arrangement of habitat in a landscape, controlling for changes in habitat amount) (Andrén, 1994; Fahrig, 1997, 2001, 2003; Radford & Bennett, 2007; Radford, Bennett, & Cheers, 2005; Smith, Fahrig, & Francis, 2011).

The diversity of unaltered land covers is also an important determinant of biodiversity (Cramer & Willig, 2005; Fahrig et al., 2011; Ricklefs & Lovette, 1999). Different cover types sustain different elements of biodiversity (MacArthur & MacArthur, 1961) and serve to fulfill the complementary life history needs of some species (Dunning, Danielson, & Pulliam, 1992). In our framework, the total amount of unaltered land cover, i.e., the combined area of all unaltered cover types, can be maximized by avoiding or minimizing the loss of any unaltered land cover. For a given amount of total unaltered land cover, its diversity can be maximized by maximizing the representation of rare unaltered land cover types, which increases the evenness of the representation of unaltered cover types in a landscape.

To the greatest degree possible, these actions should be undertaken at the land-water interface. Land adjacent to lotic, lentic, and marine systems harbors different species than upland areas, thereby increasing regional biodiversity, and is generally considered to be more biodiverse than uplands (Calvão, Pessoa, & Lidon, 2013; McLachlan, 1991; Naiman, Décamps, & Pollock, 1993; Sabo et al., 2005; Smith-Ramirez, 2004; Strayer & Findlay, 2010). In addition, an increase in unaltered land cover near water has a positive effect on water quality (Tran, Bode, Smith, & Kleppel, 2010), to the benefit of aquatic and semi-aquatic species (e.g., Moore & Palmer, 2005). Finally, land adjacent to water is generally rare in comparison to uplands (e.g., Goebel, Palik, & Pregitzer, 2003) so its prioritization will contribute to an increase in unaltered land cover diversity in landscapes.

2.4. Step 4: Minimize human disturbance within altered land cover, especially near water

For a given amount and diversity of unaltered land cover in a landscape, the second most important step to conserve biodiversity is to minimize human disturbance within altered land cover, i.e., the matrix. Matrix quality, or the degree to which human activities in the matrix disturb natural processes, has been shown to influence biodiversity in numerous ways in a wide variety of systems (Friesen, Eagles, & Mackay, 1995; Kupfer, Malanson, & Franklin, 2006). Of the components of landscape structure, matrix quality is second only to habitat amount in terms of the magnitude of its effects on biodiversity (Fahrig, 2001; Quesnelle, Fahrig, & Lindsay, 2013; Radford & Bennett, 2007). The effects of matrix quality on biodiversity are also larger than those of habitat configuration (Diekötter, Haynes, Mazeffa, & Crist, 2007; Fahrig, 2001; Guadagnin & Maltchik, 2007; Haynes, Diekötter, & Crist, 2007; Quesnelle et al., 2013; Radford & Bennett, 2007).

Minimizing human disturbance within altered land cover can be accomplished by minimizing the intensity of land use activities. Reductions in the intensity of agricultural practices (Reidsma, Tekelenburg, van den Berg, & Alkemade, 2006), urbanization (Gagné & Fahrig, 2011), and resource extraction activities (Laliberté et al., 2010; Niemelä, 1997) lead to benefits to biodiversity. The same can be said of a reduction in traffic volume (Fahrig & Rytwinski, 2009). As for Step 3, such measures should be carried out especially near water (e.g., Eigenbrod, Hecnar, & Fahrig, 2008).

2.5. Step 5: Aggregate altered land covers associated with high-intensity land uses, especially away from water

For a given amount and diversity of unaltered land cover and a given level of human disturbance within altered land cover in a landscape, benefits to biodiversity may still be accrued by aggregating altered land covers associated with high-intensity land uses. Gagné and Fahrig (2010a,b) found that compact residential development minimized the negative impacts of a given human population on forest biodiversity compared to dispersed residential development. Similarly, road and traffic bundling has been shown to minimize the detrimental effects of a road network on simulated wildlife populations compared to a dispersed pattern of roads and traffic (Jaeger, Fahrig, & Ewald, 2005).

This final step is the only one in our framework that refers to the spatial configuration of land cover. The ordering of Step 5 with respect to Steps 3 and 4 reflects the generally weaker effect of habitat configuration on biodiversity in relation to the effects of habitat amount and matrix quality. In their reviews, Andrén (1994) and Fahrig (2003) concluded that habitat amount is a more important determinant of biodiversity than habitat configuration. Compared to the consistently strong positive effects of habitat amount, habitat configuration's effects on biodiversity are generally weak and conflict across species and spatial scales (Fahrig, 2003; Smith et al., 2011). Simulation studies have indicated that habitat configuration has weaker effects on population extinction than habitat amount (Fahrig, 1997) that manifest only under a relatively narrow set of conditions (Fahrig, 1998) and that habitat configuration is less important than reproductive rate, emigration rate, and matrix quality in influencing the extinction threshold (Fahrig, 2001). Radford et al.'s (2005) and Radford and Bennett's (2007) field studies of forest-dependent birds in agricultural landscapes produced similar results: configuration variables were less important to bird species richness and bird occurrences than variables describing habitat amount and matrix quality, among others.

These lines of evidence supporting the lower priority of Step 5 relative to the other steps deal with the configuration of habitat rather than the configuration of altered land cover. This is because, to our knowledge, there is currently no study that has directly compared the relative importance of matrix area and matrix configuration. However, since we use a binary classification of land cover in our framework, the research comparing the effects of amount and configuration of habitat can be interpreted to support a greater importance of the amount of altered area over its spatial contagion, supporting the lower priority of Step 5. Note also that we present Step 5 in terms of the configuration of altered (rather than unaltered) land cover mainly to address the accommodation of new altered land cover in a landscape (e.g., due to human population growth).

The instruction in this last step to create areas of high-intensity human use may appear contrary to the prescription in Step 4 of minimizing human disturbance within altered land cover. The ordering of Steps 4 and 5 reflects the fact that, for a given amount and diversity of unaltered land cover and a given level of human disturbance within altered land cover in a landscape, an overall reduction in disturbance should have a greater positive effect on biodiversity than a change in the spatial distribution of that disturbance. If new altered land cover associated with high-intensity human uses must be accommodated in a landscape to satisfy constraints elaborated at Step 2, its aggregation into one or a few areas with existing altered land cover will result in a smaller increase in overall disturbance than its dispersal throughout the landscape. In sum, Step 5 is intended to prescribe (1) a change in the spatial arrangement of existing altered land cover that further reduces the overall level of human disturbance in a landscape, i.e., in addition to the reduction resulting from actions undertaken to accomplish Step 4, and (2) the spatial arrangement of new altered land cover in order to minimize the unavoidable increase in overall disturbance level brought about by its accommodation in a landscape.

Building compact development and road and traffic bundling are examples of measures that would address Step 5 in our framework. Areas containing different types of high-intensity land uses, such as intensively-managed cropland and high-density residential development, could also be aggregated. Aggregation should occur away from water as much as possible to minimize the negative effects of adjacent high-intensity land uses on water resources (Young & Collier, 2009).

3. Hypothetical example

We now describe the application of our framework to an example landscape by outlining the decisions and recommendations of a hypothetical planner following the steps (Fig. 1). We also compare the outcome of our approach to those from a selection of existing guidelines.

For our example we selected a 50 × 50 km landscape located west of Ottawa, ON, Canada that encompasses some of the inner and outer suburbs of the city as well as adjoining rural towns and townships (Fig. 2). The landscape is of a similar size to the planning area of the City of Ottawa (2778 km^2) but includes a more heterogeneous mix of land cover types and amounts that better serves to illustrate the types of recommendations produced by the steps in our framework. Uplands (maximum elevation in the landscape is 223 m) are dominated by sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), and eastern hemlock (*Tsuga canadensis*). Lowlands (minimum elevation in the landscape is 52 m) consist primarily of marshes and fens and wet forests dominated by eastern white cedar (*Thuja occidentalis*), silver maple (*Acer saccharinum*), and ash (*Fraxinus* spp.). Red pine (*Pinus resinosa*) and balsam fir (*Abies balsamea*) plantations dot the landscape. Agricultural activities include mainly corn, soybean, and grain cultivation and the rearing of livestock. Maple sugar production and gravel quarry operations also occur in the area.

3.1. Step 1: Select land cover data and decide which land cover classes constitute unaltered or altered land covers

Our hypothetical planner has access to land cover data that includes 11 aggregated classes that occur in the example landscape as well as road data (National Road Network, Edition 2.0, Natural Resources Canada) and hydrological data (Ontario Hydrographic Network, Version 1, Ontario Ministry of Natural Resources) (Fig. 2, Appendix A). (We have provided our planner with data on roads and streams for illustrative purposes only. Our framework could still be applied even if our planner had access to solely the land cover data.)

Our planner decides to consider the Shrubland, Wetland, Coniferous Forest, Deciduous Forest, and Mixed Forest classes as unaltered land cover, as all these represent areas dominated by vegetation with no human influence according to class definitions (Appendix A). The Built and Annual Cropland classes and roads she considers as altered land cover because they represent areas heavily modified by humans. Our planner chooses to include Pasture in the unaltered land cover category because it represents areas dominated by vegetation (Appendix A) and she considers the human uses of these areas in the example landscape, i.e., predominantly for grazing and hay production, as of low intensity, especially relative to the intensity of human uses represented by the Built and Annual Cropland classes.

Our planner decides not to consider the Barren/Non-vegetated and Exposed Land classes in subsequent steps (see Appendix A). Also, she does not categorize the Water class or watercourses as unaltered or altered because this distinction refers to the terrestrial elements in a landscape.

3.2. Step 2: List the constraints on land use planning (e.g., economic, social) that exist for the landscape

Our planner infers from population projections for the City of Ottawa and the surrounding region that, over a 30-year period, the number of commuters in the example landscape will increase by 55% and the extent of Built land cover will increase by 71%. She also surmises that agricultural land cover, defined as the combined area of Annual Cropland and Pasture, can decrease by ≤10%. This is based

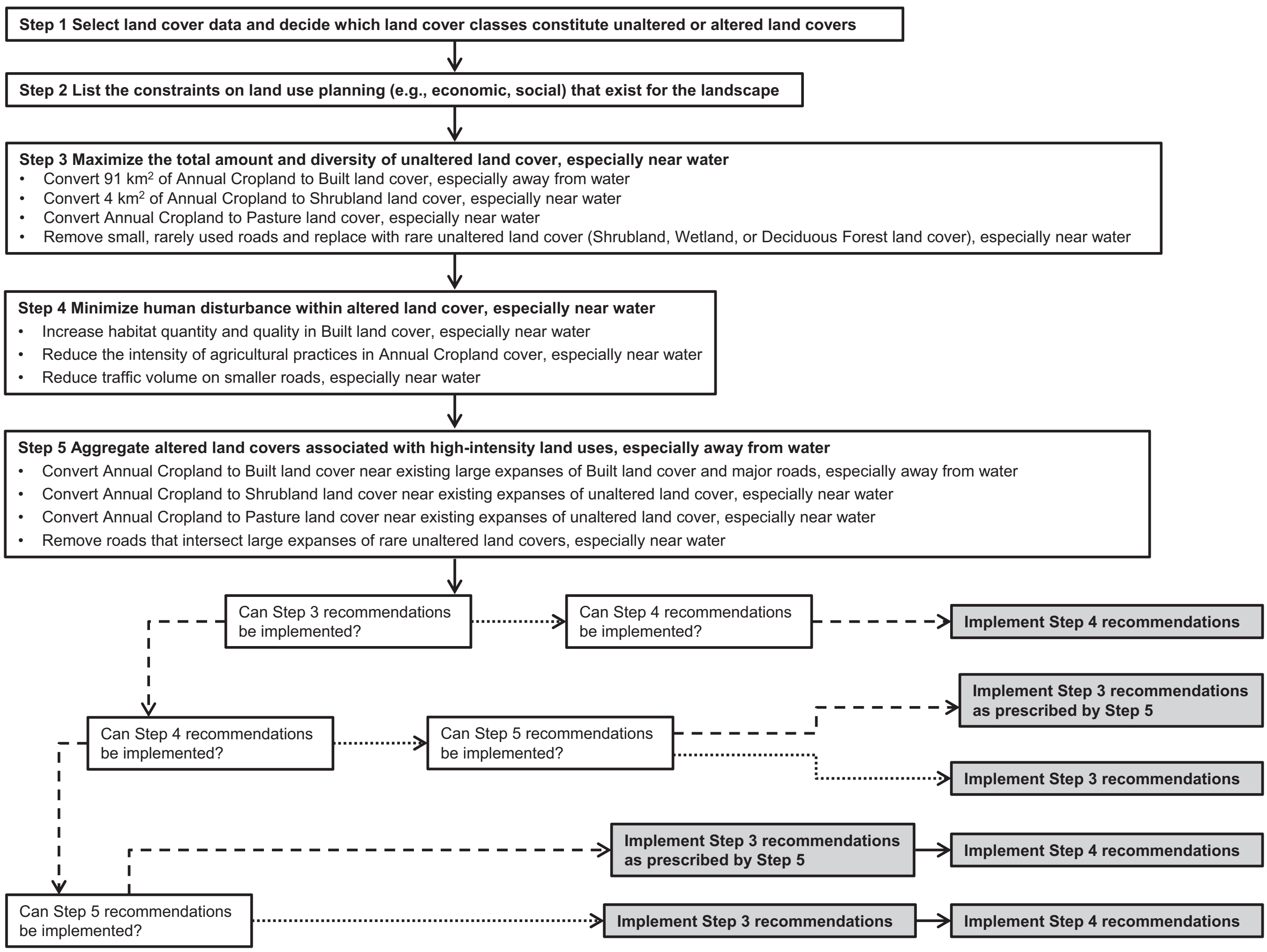

Fig. 1. The use **of the** landscape design framework for biodiversity conservation. Open boxes include the steps and questions a user should answer after formulating recommendations for Steps 3–5. Recommendations pertinent to the hypothetical example described in the text are shown. Dashed arrows represent a "yes" answer and dotted arrows represent a "no" answer to questions. The shaded boxes describe the implementation of the recommendations from the steps.

on estimated past net losses of agricultural land area (cropland and pasture) in US counties in the same ecoregion as the example landscape (between 4.1% and more than 15% per county between 1949 and 1997, Brown, Johnson, Loveland, & Theobald, 2005). Finally, she is aware that the current levels of forestry, maple sugar production, and quarry operations are to be maintained into the future.

3.3. *Step 3: Maximize the total amount and diversity of unaltered land cover, especially near water*

To accomplish Step 3, our planner calculates the present and planned extents of each land cover class in the landscape (Table 2). She calculates planned extents with reference to the constraints elaborated at Step 2. To avoid the loss of unaltered land cover in the landscape, our planner recommends that the 71% increase (91 km^2) in Built land cover be situated on Annual Cropland, the only other altered cover type in the landscape with the exception of roads (Fig. 1). Given that agricultural land cover can be reduced by 95 km^2, she recommends increasing the amount of unaltered land cover in the landscape by converting an additional 4 km^2 of Annual Cropland to Shrubland cover through regeneration (Fig. 1). She selects Shrubland cover, rather than the similarly rare Wetland or Deciduous Forest covers (with respect to their proportion of the total amount of unaltered land cover (Table 2)), because the recommended increase in its extent results in greater land cover diversity in the landscape, as indicated by the Shannon evenness measure (Magurran, 2004), compared to alternative allocations (e.g., evenly allocating 4 km^2 among the three rarest unaltered land cover types). Our planner also recommends the conversion of Annual Cropland to Pasture land cover, an unaltered land cover type (Fig. 1). This latter recommendation results in no net loss of agricultural land cover since agricultural land cover was defined as the combined area of Annual Cropland and Pasture. Finally, our planner recommends removing some small, rarely used roads or sections of roads in the landscape and replacing them with rare unaltered land cover, i.e., Shrubland, Wetland, or Deciduous Forest (Fig. 1).

With the exception of the conversion of Annual Cropland to Built land cover, these recommendations should be implemented near water to the extent this is possible. For example, Annual Cropland located near water should be converted to Shrubland land cover (Fig. 3A). Conversely, Annual Cropland should be converted to Built land cover especially away from water. In our binary landscape description, the addition of new altered land cover in locations far from water indirectly results in the preservation of unaltered land cover near water, thereby accomplishing Step 3.

3.4. *Step 4: Minimize human disturbance within altered land cover, especially near water*

There are three major ways that our planner can minimize human disturbance within altered land cover (Fig. 1). First, she

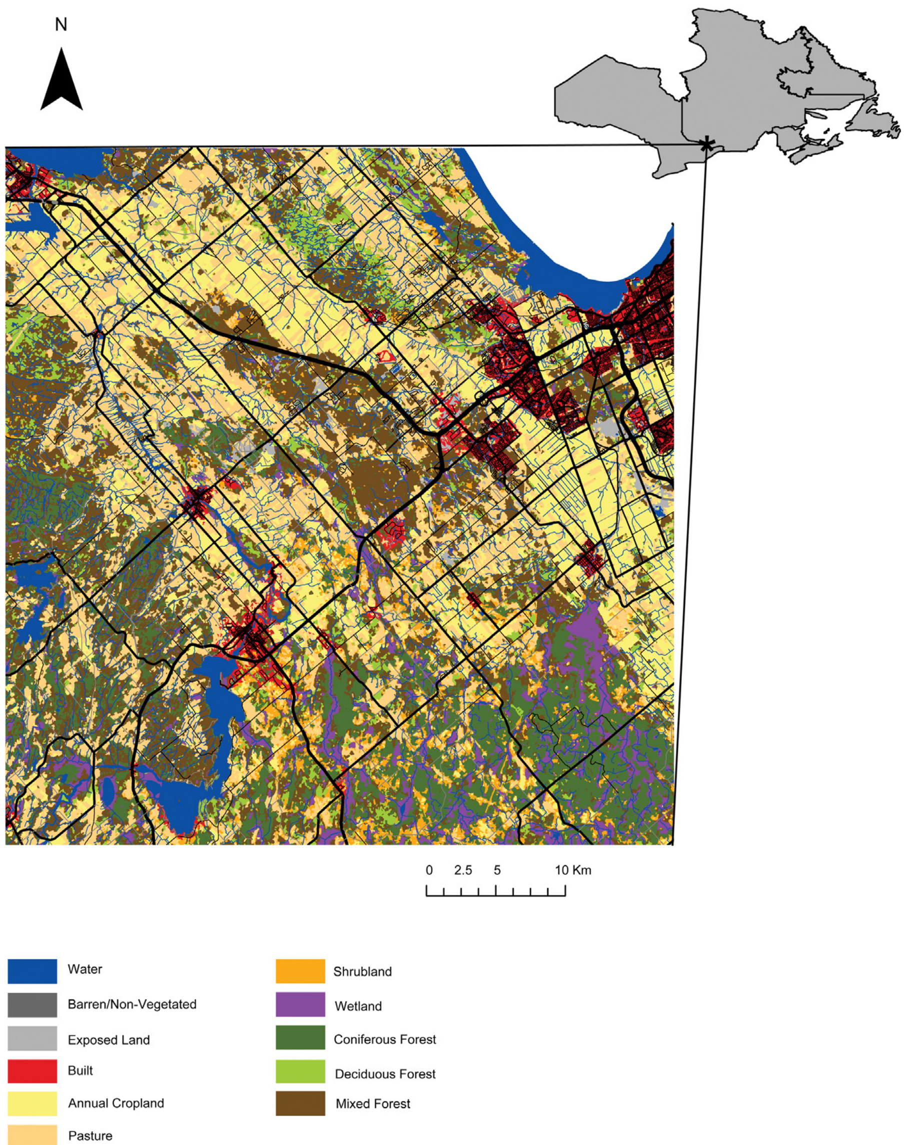

Fig. 2. The example landscape west of Ottawa, Ontario in eastern Canada. Black and gray lines represent paved and unpaved roads, respectively, and blue lines represent watercourses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
The present and planned extents of land cover classes in the example landscape. Unaltered land cover includes the Pasture, Shrubland, Wetland, Coniferous Forest, Deciduous Forest, and Mixed Forest classes. Altered land cover includes the Built and Annual Cropland classes and roads (not shown). Agricultural land cover includes the Annual Cropland and Pasture classes. The Water, Barren/Non-vegetated, and Exposed Land classes were not categorized (see Appendix A). Planned extents are calculated with reference to the constraints and recommendations described in the text, which refer to a selection of land cover classes.

Land cover class	Present extent (km^2)	Planned extent (km^2)	Change in extent (km^2)	Present proportion of total (%)	Present proportion of unaltered land cover (%)	Planned proportion of total (%)	Change in proportion of total (%)
Water	98.68			4.10			
Barren/Non-vegetated	0.68			0.03			
Exposed Land	38.23			1.59			
Built	128.30	219.40	91.1	5.33		9.11	3.78
Annual Cropland	343.65	248.60	−95.05	14.28		10.33	−3.95
Pasture	606.86			25.21	33.76		
Shrubland	116.45	120.40	3.95	4.84	6.48	5.00	0.16
Wetland	122.98			5.11	6.84		
Coniferous Forest	288.59			11.99	16.05		
Deciduous Forest	123.83			5.14	6.89		
Mixed Forest	538.94			22.39	29.98		
Unaltered land cover	1797.65	1801.60	3.95	74.68	100.00	74.84	0.16
Altered land cover	471.95	468.00	−3.95	19.61		19.44	−0.17
Agricultural land cover	950.51	855.46	−95.05	39.49		35.54	−3.95
Total	2407.19			100.00			

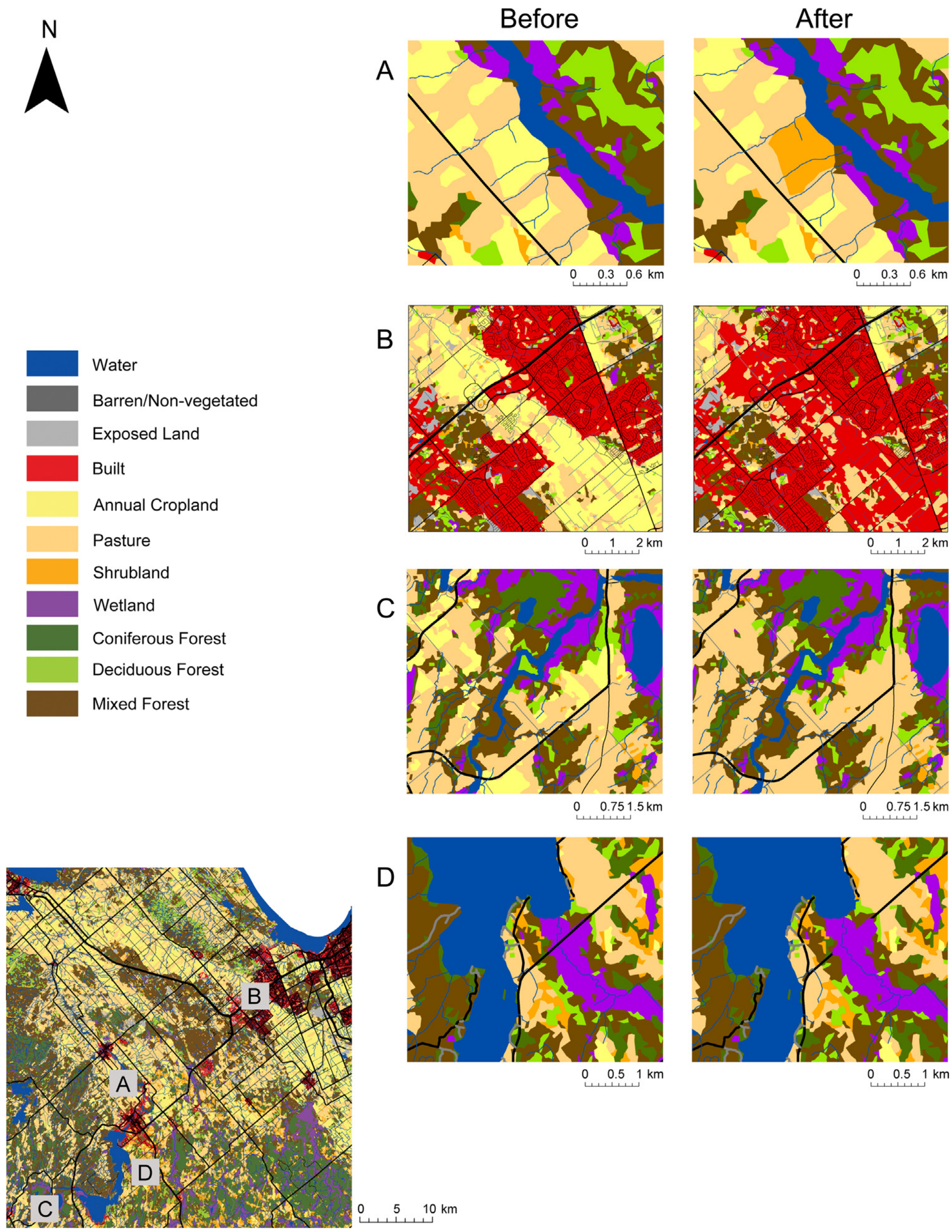

Fig. 3. Insets depicting the implementation of some of the recommendations from the hypothetical example described in the text (the reader is referred to the color version of this figure in the web version of the article). (A) Annual Cropland near water is converted to Shrubland cover. (B) Annual Cropland is converted to Built land cover near existing large areas of Built land cover and major roads and far from a major body of water. (C) Annual Cropland is converted to Pasture land cover near existing expanses of unaltered land cover that are located near water. (D) A road that intersects a large expanse of Wetland cover near water is removed. The locations of insets in the example landscape are indicated by their respective letters.

recommends increasing habitat quantity and quality in Built land cover. To do this, she suggests policies for developed areas that: (i) reduce impervious surface area by creating vegetated medians and parking lot islands (Fig. 4) and green roofs, façades, and walls (Oberndorfer et al., 2007); (ii) increase tree cover along city streets (Fernández-Juricic, 2000) and replace lawns with trees and shrubs (Daniels & Kirkpatrick, 2006); (iii) restore wetlands and riparian areas and improve the ecological quality and performance of stormwater management systems (Kazemi, Beecham, & Gibbs, 2009); and (iv) eliminate pesticide use (Bertoncini, Machon, Pavoine, & Muratet, 2012). Second, she recommends reducing the intensity of agricultural practices in Annual Cropland cover. This can be accomplished by offering incentives to farmers who reduce ploughing frequency and pesticide and fertilizer use, and who diversify the types of crop they grow (Reidsma et al., 2006). Third, our planner recommends reducing traffic volume on smaller roads by downgrading smaller paved roads to unpaved roads and by installing traffic-calming structures. She also notes that investment in the public transit system would significantly reduce overall traffic volume in the landscape. Our planner attempts to implement all of these recommendations, i.e., she does not preferentially select some recommendations over others. The implementation of recommendations should occur near water to the greatest degree possible.

3.5. Step 5: Aggregate altered land covers associated with high-intensity land uses, especially away from water

In Step 5, our hypothetical planner chooses locations for the measures recommended in Step 3 that will maximize the

Fig. 4. A parking lot island on the University of North Carolina at Charlotte campus.

aggregation of altered land covers associated with high-intensity land uses, especially away from water. First, she recommends converting Annual Cropland to Built land cover near existing large areas of Built land cover and major roads (Fig. 1). For example, approximately 20% of the planned increase in Built land cover can be accommodated in an existing area of Annual Cropland located on either side of a major freeway between two large outer suburban areas (Fig. 3B). Our planner chooses this area in part because it is far from a major body of water. However, the area is intersected with smaller watercourses and thus, our planner recommends that the measures identified in Step 4 to minimize human disturbance within altered land cover be incorporated into the new development.

Second, our planner recommends converting 4 km^2 of Annual Cropland to Shrubland cover and converting Annual Cropland to Pasture near existing expanses of unaltered land cover, especially if these are located near water (Figs. 1 and 3C). Third, she recommends removing small, rarely used roads or sections of roads that intersect large expanses of rare unaltered land covers, such as Wetland cover, especially if these are located near water (Figs. 1 and 3D). This and the measures our planner undertakes to reduce traffic volume on smaller roads (Step 4) should be accompanied by improvements to major roads so they may accommodate higher traffic volumes. In this way, traffic impacts in the landscape can be transformed from widely distributed on many small roads to concentrated or bundled on a few major roads. Traffic bundling and an improved public transit system should effectively manage the 55% increase in the number of commuters projected for the landscape.

3.6. Implementation of the recommendations from Steps 3–5

In order for the sequence of the steps of our framework to be preserved during implementation, our planner proceeds to determine whether the recommendations from Steps 3, 4, and 5, in that order, can be implemented (Fig. 1). Constraints in addition to those identified at Step 2, such as lack of personnel, landowner consent, or political will, may limit the implementation of the recommendations from our framework. In the case where the recommendations from an earlier step cannot be carried out, our planner should still proceed with the implementation of the recommendations from the later step, if possible. For example, if the amounts of land covers in the example landscape cannot be changed as recommended in Step 3, our planner should still proceed with the implementation of the recommendations from Step 4 (Fig. 1). The reverse is also true. For example, if the only place where Annual Cropland can be converted to Pasture happens to be next to a housing development, this conversion should still be implemented even though it would not satisfy the recommendation from Step 5 (but still satisfies the recommendation from Step 3) (Fig. 1). By making it clear that the recommendations from Steps 3 and 4 take priority (in that order) over those from Step 5, our planner explicitly takes into account the fact that the largest impacts on biodiversity will occur through increasing unaltered areas and (secondarily) reducing human impacts in altered areas, and that changing the specific locations of these activities, while of some benefit, will have a much smaller effect on biodiversity.

3.7. Application of existing ecological guidelines to the example landscape and comparison of the outcomes to that of our approach

We applied 14 sets of existing ecological guidelines to the example landscape as a hypothetical planner would in order to compare the outcomes with that from our framework. In so doing, we assumed that the planner had no ecological expertise, that the planner's knowledge of the example landscape was limited to the context we described at the beginning of the hypothetical example, that the planner had access to the data described at Step 1, and that no limitations on land cover change existed unless a framework considered socioeconomic constraints (if such was the case, we used the constraints described at Step 2).

On average, two-thirds of the items in any given set of guidelines could not be implemented in the example landscape (Table 3). The hypothetical planner could not implement the items in a set if she could not formulate recommendations for the example landscape because of the requirement for species-specific information or a lack of prescription or if formulated recommendations were not feasible because they mutually conflicted or involved the removal of Built land cover. With the rare exception of the requirement for detailed information that wasn't species-specific, such as the concentration of total suspended sediment in stream water, no other characteristics impeded the implementation of items.

Of the characteristics just listed, the requirement for species-specific information and a lack of prescription were the most common impediments to implementation (Table 3). All frameworks included at least one item that exhibited one of these characteristics and in one case, all of the items did so (Opdam & Steingröver, 2008). The two best performing frameworks (Lovell & Johnston, 2009; Sayer et al., 2013), which were the only ones to base their guidelines on a multifunctional landscape approach, were highly prescriptive and required little species-specific information.

Items that were not prescriptive were also often complex in nature. In many cases, rather than include a prescription for action, items would describe the highly context-specific nature of the issue under consideration or the lack of scientific consensus pertaining to the issue, using technical terminology and reference to additional scientific literature in doing so. For example, Fischer, Lindenmayer, & Manning's (2006) instruction for their strategy, "Maintain and create large, structurally complex patches of native vegetation", is "Some structural elements are particularly important . . . What constitutes such "keystone structures" varies between ecosystems, and can include a wide range of structural features, ranging from ephemeral water bodies . . . (Tews et al., 2004) to tree hollows . . . (Gibbons and Lindenmayer, 2002)". Complex descriptions such as this may be less likely to be used by planners, as evidenced by the rare use of primary scientific literature by nature reserve management planners in the UK in part because it is too technical and difficult to interpret (Pullin et al., 2004).

Nine of the 14 frameworks included items that produced recommendations that mutually conflicted or called for the removal of Built land cover (Table 3). For example, the recommendation to favor simple patch shapes rather than convoluted ones conflicted with the recommendation to prioritize edges with coves

Table 3
The outcomes of the application of existing ecological principles, guidelines, or recommendations to the landscape in the hypothetical example. The total number of items that could not be implemented is the sum of items that require species-specific information, lack prescription, mutually conflict, and/or recommend the removal of Built land cover. Some items exhibited more than one of these characteristics.

Source	Number of items	Number of items that require species-specific information	Number of items that lack prescription	Number of items that produced recommendations that mutually conflicted	Number of items that recommended the removal of Built land cover	Total number of items that could not be implemented
Soulé (1991)	5	4	3	2	0	4 (80%)
Dramstad et al. (1996)	55	15	20	15	3	41 (75%)
Duerksen et al. (1997)	19	7	4	2	0	9 (47%)
Dale et al. (2000)	8	2	5	2	0	5 (63%)
Environmental Law Institute (2003)	16	10	5	0	4	14 (88%)
Environment Canada (2004)	18	3	2	0	2	5 (28%)
Fischer et al. (2006)	10	5	6	0	0	8 (80%)
Lindenmayer et al. (2006)	31	12	15	2	0	25 (81%)
Noss (2007)	7	1	3	3	0	6 (86%)
Lindenmayer et al. (2008)	13	5	11	0	0	11 (85%)
Opdam and Steingröver (2008)	10	9	4	0	0	10 (100%)
Lovell and Johnston (2009)	6	2	2	0	0	2 (33%)
Stagoll et al. (2010)	16	5	2	0	1	7 (44%)
Sayer et al. (2013)	10	2	2	0	0	2 (20%)
The present framework	5	0	0	0	0	0

and lobes over straight edges from Dramstad, Olson, and Forman's (1996) principles, and two of Environment Canada's (2004) guidelines collectively recommended the removal of 11 km^2 of Built land cover. Recommendations to remove Built land cover resulted from guidelines that called for continuous or near continuous riparian buffers or buffers surrounding all remnant patches. Frameworks that consider socioeconomic constraints are less likely to include these types of guidelines because such guidelines produce recommendations that are clearly unfeasible in many human-modified landscapes.

This highlights a major advantage of considering socioeconomic constraints in the formulation of ecological guidelines, namely that doing so produces a more realistic conservation outcome. The 4 km^2 increase in Shrubland cover that is the result of our approach represents a net increase in unaltered land, i.e., one that takes changes to Annual Cropland, Built land cover, and roads into account. In contrast, the real-world outcome of frameworks that do not consider socioeconomic constraints is unknown. For example, Environment Canada's (2004) guidelines collectively recommend an increase in 166 km^2 of unaltered land cover in the example landscape. If the constraints used in our framework existed during the implementation of these recommendations, then at best 4 km^2 of unaltered land cover would be gained. Thus, the face value result of Environment Canada's (2004) guidelines is misleading because in reality, socioeconomic constraints of some degree are very likely to exist in most landscapes.

In sum, many characteristics of existing ecological guidelines severely restricted their implementation potential to the example landscape, in contrast to our approach. Consequently, we posit that our framework will be more useful to the many planners who work in conditions similar to those described in the hypothetical example, i.e., with very limited ecological expertise and little or no access to species-specific information.

4. Integration of our framework with existing planning practice

Even though the example we used to illustrate the utility of our approach is hypothetical, we believe it is representative of the real circumstances encountered by planners. We used a landscape of the approximate size of a real planning jurisdiction, real land cover data, and realistic socioeconomic constraints. The landscape we selected represents areas at the urban fringe, where land use and land cover change are typically high and biodiversity conservation is a concern (Brown et al., 2005). Also, the recommendations from our framework have precedent in the real world. For instance, cropland is routinely converted to development or pasture (e.g., 27% of new development and 75% of new pasture replaced cropland between 1982 and 2007 in the US, US Department of Agriculter, 2009). However, we note that the implementation of recommendations such as those in our example will unavoidably depend on the particular cultural, political, and economic circumstances of a planning region.

In the hypothetical example, our planner was able to unilaterally direct the planning process. In reality, the planning process may be influenced to varying degrees by the community. In fact, collaboration with a diversity of stakeholders at all planning stages is recommended to effectively tackle the complex problem of meeting the multiple and often competing goals of land use planning (Botequilha Leitão & Ahern, 2002; Duerksen, Elliott, Hobbs, Johnson, & Miller, 1997), in part because implementation success is more likely when stakeholder perspectives and values are considered (Bohnet & Smith, 2007; Botequilha Leitão & Ahern, 2002; Innes & Booher, 1999). Community values may play a particularly important role in planning for biodiversity conservation by providing the broad support needed for conservation initiatives (Stokes, Hanson, Oaks, Straub, & Ponio, 2010). Our framework can be a useful tool in a community-driven planning process. Because the steps of our framework address conservation and socioeconomic goals (those listed as constraints at Step 2), their recommendations are likely to provide a productive basis for discussion among people with differing values. Also, stakeholders may be more willing to accept the recommendations of our framework because it is simple and prescriptive and thus likely to be understood by all parties (Duerksen et al., 1997; Innes & Booher, 1999). Our approach can also be used to inform broad community-based initiatives, such as land suitability assessments that seek to identify and minimize conflicts among competing land uses, including biodiversity conservation (Collins, Steiner, & Rushman, 2001; Malczewski, 2004). For instance, the prescriptions in Steps 3–5 and their sequence could be used as an expert basis for stakeholder discussions of suitability criteria, such as distance to existing altered land cover, and their relative importance (e.g., Bojórquez-Tapia, Diaz-Mondragó, & Ezcurra, 2001). Finally, our framework may be useful in building broad community support for biodiversity conservation in a planning region if rare land covers are presented as conservation flagships and the human benefits of recommendations from Step 4, such as cleaner drinking water, are emphasized (Stokes et al., 2010).

Spatial scale is a significant consideration in planning for biodiversity conservation. We illustrated the use of our approach at the approximate scale at which planning occurs in the City of Ottawa. This scale is embedded within the wide range of scales across which ecological patterns and processes and their biophysical and socioeconomic drivers occur. The mismatch between the scale of planning and the scales of target ecological variables and their drivers is a significant problem because it can result in a lack of effectiveness of planning interventions and/or unintended negative consequences (Borgström, Elmqvist, Angelstam, & Alfsen-Norodom, 2006; Cumming, Cumming, & Redman, 2006). A few examples from our framework illustrate this issue. At Step 3, maximizing diversity of unaltered land cover at the expense of the common unaltered land cover type could result in too little of the common unaltered land cover over the region, for species that need large areas of this land cover for population persistence. Similarly, at Step 4, the creation of parking lot islands over a limited planning extent may have little impact on species that use significantly larger areas. And, at Step 5, the benefits to biodiversity of aggregating altered land cover may be less in small planning areas than in large ones for a given amount of altered land cover. A solution to scale mismatches such as these is to plan and manage at multiple scales (Bruce Jones et al., 2013; Cumming, Olsson, Chapin, & Holling, 2013; Goddard, Dougill, & Benton, 2010). In practical terms and with reference to our approach, this means that planners should coordinate the implementation of the recommendations from the steps across scales within and among jurisdictions. How best to facilitate this process is a topic of current investigation (e.g., Borgström et al., 2006; Carmona-Torres, Parra-López, Groot, & Rossing, 2011; Cumming et al., 2006, 2013; Goddard et al., 2010).

Our framework complements approaches to biodiversity conservation that focus on species protection. If protected areas exist in a planning unit, they should not be considered in the steps. For example, in the tabulation of the present and planned extents of land cover classes at Step 3, a planner should omit the habitat of a species whose protection is mandated under an instrument such as the Ontario Endangered Species Act (2007) (see Appendix B for an example). The exclusion of protected areas from consideration in our framework avoids any conflict between legislative requirements and the recommendations produced by the steps, which may include the loss of unaltered land cover if socioeconomic constraints are very limiting. If the protection of a species is not legislated but is nevertheless a priority, then its habitat should be considered as an individual unaltered land cover type at Step 1 and the specific measures deemed necessary to conserve the species should be implemented in conjunction with the recommendations of our framework (Appendix B).

5. Conclusions

In this paper, we proposed a landscape design framework for biodiversity conservation that is more practical and produces a more feasible outcome than existing approaches, while still being based on current landscape ecological science. We believe these characteristics make our framework more likely to be used by planners. Because our framework was designed for situations where no species-specific information and only GIS-based land cover data are available, it can be viewed as a starting point for conservation that can be elaborated if detailed biodiversity data exist. We think that an approach such as ours that is simple, widely-accessible, and flexible is needed to keep pace with the very rapid rates of land use and land cover change occurring around the world (Gaston, 2010).

Future work should test our approach and compare it to other approaches using biodiversity data. Although the evidence we present, i.e., empirical and simulation studies of various systems using various measures of habitat amount, matrix quality, and habitat configuration, lends support to the generality of our framework, it is necessary to test this generality using data on other taxa in other landscapes. Comparisons with other approaches will be most easily accomplished by simulating projected changes to species distributions in scenarios. In conjunction, we advocate that our and other frameworks be compared in the real-world using an adaptive design approach (*sensu* Ahern, 2013), in which planning interventions are considered experiments. Planners and the governance structures in which they are embedded that learn from the comparison of the outcomes of alternative planning strategies will be most effective at managing for future landscape change (Cumming et al., 2013).

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Appendix A.

The aggregated and original land cover classes that occur in the example landscape. Land cover class definitions are from the feature catalogue accompanying the Land Cover, Circa 2000, Edition 1.0 (Natural Resources Canada) data. Aggregated land cover classes were derived by combining original land cover classes that likely represent the same use or cover. For example, the Herb, Grassland, and Perennial Cropland and Pasture classes were aggregated into one class denoted Pasture because all three original classes represent areas that are likely used for grazing and hay production. Similarly, all the classes that include shrub cover were aggregated because the original Shrubland, Shrub Low, and Shrub Tall classes include areas that are probably similar in cover. The Water, Barren/Non-vegetated, and Exposed Land classes were not categorized as unaltered or altered land covers in the hypothetical example in the text because this distinction refers to the terrestrial elements in a landscape or these classes represent a potentially large number of cover types, including unaltered (e.g., beaches, bare rock, and moraines) and altered (e.g., tailings and gravel pits) land covers (Barren/Non-vegetated and Exposed Land classes). In the latter case, there is no way of knowing which cover types are included in each class in the example landscape.

Aggregated land cover class	Original land cover class	Definition
Water	Water	Lakes, reservoirs, rivers, streams, or salt water
Barren/Non-vegetated	Barren/Non-vegetated	Predominately non-vegetated and non-developed. Includes: exposed lands, snow, glacier, rock, sediments, burned areas, rubble, mines, or other naturally occurring non-vegetated surfaces. Comments: Mines or similar human activity may be mapped by this class, or may be mapped by the developed class. Excludes fallow agriculture
Exposed Land	Exposed Land	River sediments, exposed soils, pond or lake sediments, reservoir margins, beaches, landings, burned areas, road surfaces, mudflat sediments, cutbanks, moraines, gravel pits, tailings, railway surfaces, buildings and parking, or other non-vegetated surfaces
Altered land covers:		
Built	Built	Land that is predominantly built-up or developed and vegetation associated with these land covers. This includes road surfaces, railway surfaces, buildings and paved surfaces, urban areas, industrial sites, mine structures, and farmsteads
Annual Cropland	Annual Cropland	Annually cultivated cropland and woody perennial crops. Includes annual field crops, vegetables, summer fallow, orchards, and vineyards. Comments: Classification process primarily detects and delineates lands that change from bare cover to green/vegetated cover during the growing season
Unaltered land covers:		
Pasture	Herb	Vascular plant without woody stem (grasses, crops, forbs, graminoids); minimum of 20% ground cover or one-third of total vegetation must be herb
Pasture	Grassland	Native grass: Predominantly native grasses and other herbaceous vegetation; may include some shrubland cover. Land used for range or native unimproved pasture may appear in this class. Comments: Alpine meadows fall into this class
Pasture	Perennial Cropland and Pasture	Periodically cultivated cropland. Includes tame grasses and other perennial crops such as alfalfa and clover grown alone or as mixtures for hay, pasture or seed. Comments: Fall seeded crops such as winter wheat may be erroneously identified in this class. Grassland and shrubland may be delineated within this class
Shrubland	Shrubland	Predominantly woody vegetation of relatively low height (generally $\pm$ 2 m). Comments: May include grass or grassland, wetlands with woody vegetation, or regenerating forest
Shrubland	Shrub low	At least 20% ground cover which is at least one-third shrub; average shrub height <2 m. In the North, moist erect low shrub <40 cm forming more than 25% of the vegetated cover, consisting mainly of dwarf birch (*Betula* spp.) and/or willow (*Salix* spp.). Remaining cover consists of graminoids and/or lichen and may contain prostrate dwarf shrubs and bare soil
Shrubland	Shrub tall	At least 20% ground cover which is at least one-third shrub; average shrub height $\geq$2 m. In the North, moist to wet erect tall shrub >40 cm forming more than 25% of the vegetated cover, consisting mainly of dwarf birch (*Betula* spp.), willow (*Salix* spp.), and/or alder (*Alnus* spp.). Remaining cover consists of graminoids and/or lichen and may contain <10% prostrate dwarf shrubs and bare soil
Wetland	Wetland	Land with a water table near/at/above the soil surface for enough time to promote wetland or aquatic processes (semi-permanent or permanent wetland vegetation, including fens, bogs, swamps, sloughs, marshes, etc.). Comments: This class is mapped based on cover properties corresponding with image date(s) conditions
Wetland	Wetland-Herb	Land with a water table near/at/above the soil surface for enough time to promote wetland or aquatic processes; the majority of vegetation is herb
Wetland	Wetland-Shrub	Land with a water table near/at/above the soil surface for enough time to promote wetland or aquatic processes; the majority of vegetation is tall, low, or a mixture of tall and low shrub
Wetland	Wetland-Treed	Land with a water table near/at/above the soil surface for enough time to promote wetland or aquatic processes; the majority of vegetation is coniferous, broadleaf, or mixed wood
Coniferous Forest	Coniferous Forest	Predominantly coniferous forests or treed areas. May include mixed forests and shrubland areas
Coniferous Forest	Coniferous Open	26–60% crown closure; coniferous trees are 75% or more of total basal area
Coniferous Forest	Coniferous Dense	>60% crown closure; coniferous trees are 75% or more of total basal area
Deciduous Forest	Deciduous Forest	Predominantly broadleaf/deciduous forests or treed areas. May include mixed forests and shrubland areas
Deciduous Forest	Broadleaf Open	26–60% crown closure; broadleaf trees are 75% or more of total basal area
Deciduous Forest	Broadleaf Dense	>60% crown closure; broadleaf trees are 75% or more of total basal area
Mixed Forest	Mixed Forest	Mixed coniferous and broadleaf/deciduous forests or treed areas
Mixed Forest	Mixedwood Sparse	10–25% crown closure; neither coniferous nor broadleaf trees account for 75% or more of total basal area
Mixed Forest	Mixedwood Open	26–60% crown closure; neither coniferous nor broadleaf trees account for 75% or more of total basal area
Mixed Forest	Mixedwood Dense	>60% crown closure; neither coniferous nor broadleaf trees account for 75% or more of total basal area

Appendix B. An example of how the landscape design framework complements approaches to biodiversity conservation that focus on species protection.

We illustrate how our framework complements approaches to biodiversity conservation that focus on species protection using the bogbean buckmoth (*Hemileuca* sp.), a species listed as endangered under the Ontario Endangered Species Act (2007) and that occurs in the example landscape. The habitat protection recommendations we use here are identical to those listed in the Act's habitat regulation for the species with the exception that the bogbean buckmoth's distribution is more widespread than in reality (the species is actually limited to a single location in the example landscape). Under the Act, it is prohibited to kill, harm, or harass the bogbean buckmoth in its fen habitat and in buffer areas within 120 m of habitat patches (Fig. B1). Human activities in buffer areas that are generally compatible with the protection of the species are non-intensive pasturing or agricultural practices, spot treatments with herbicides or pesticides, and the pruning of shrubs or trees for maintenance purposes. In addition, non-motorized vehicle use of existing recreational trails may take place within fens and buffers. Activities that are to be avoided in fens and buffers include the broad-scale application of road salt, fertilizers, herbicides, or pesticides, the alteration of wetland vegetation or water levels, the removal of peat, the construction of houses, other structures, or roads, and the use of all-terrain vehicles or snowmobiles.

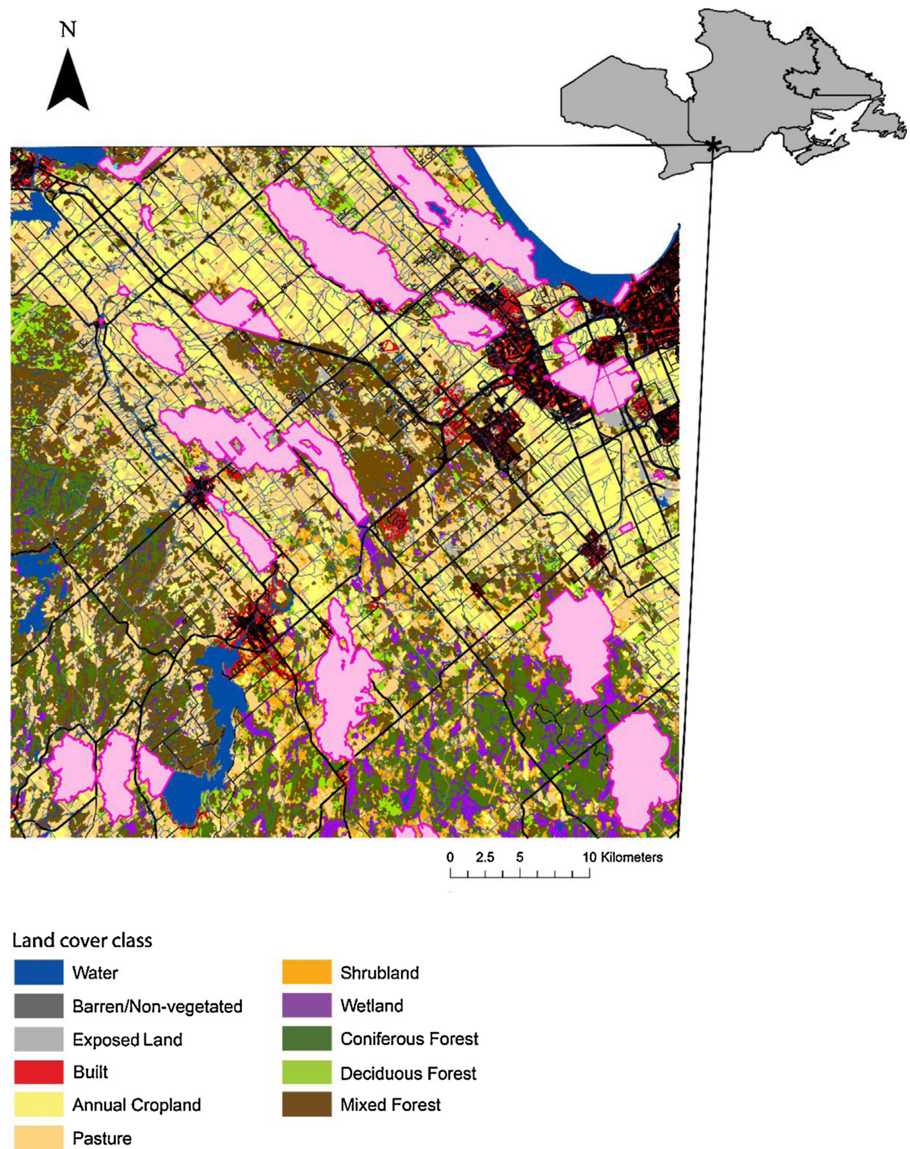

Fig. B1. The hypothetical habitat of the bogbean buckmoth (*Hemileuca* sp.) (light pink areas) surrounded by 120 m radius buffers (dark pink areas). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Since the protection of the bogbean buckmoth is mandated by law, we recommend that its regulated habitat (fens and buffers) be omitted from the tabulation of the present and planned extents of land cover classes at Step 3 (Table B1). This is because, if constraints are very limiting, a possible outcome of the application of our framework is the loss of unaltered land cover. The exclusion of protected areas from consideration in our framework thus avoids any conflict between legislative requirements and the recommendations produced by the steps. Steps 3–5 should then be carried out as described in the hypothetical example in the main text. The implementation of the resulting recommendations should take place in areas outside of the bogbean buckmoth's regulated habitat.

If the protection of the bogbean buckmoth was not mandated by law but was nevertheless a high priority, then we recommend that its fen habitat and surrounding buffers be considered as an individual unaltered land cover type at Step 1 (Table B2). The remaining four steps should then be carried out as usual. The implementation of the resulting recommendations should take into account any particular measures deemed necessary to ensure bogbean buckmoth protection. For example, the conversion of Annual Cropland to Built land cover (see Fig. 1 in the main text) should not occur in or within 120 m of fen habitat.

In the present example, bogbean buckmoth habitat was the third most common unaltered land cover type in the example landscape (with respect to its proportion of the total amount of unaltered land cover) (Table B2). If bogbean buckmoth protection was not legislated and socioeconomic constraints were so limiting that unaltered land cover had to be converted to altered land cover, e.g., because no loss of agricultural land cover could occur to accommodate new Built land, the habitat of the species would be unlikely to be sacrificed. Rather, the most common unaltered land cover other than Pasture, Mixed Forest, would be converted to development to maximize the diversity of unaltered land cover as prescribed at Step 3. In the case where the habitat of a species is the most widespread unaltered land cover in a planning unit and its preservation, although not mandated by law, is considered essential – perhaps because it represents a globally-rare resource – it should be considered to fall outside of the purview of our framework. This is because the habitat may be converted to altered land cover to satisfy constraints in our framework. In all other cases, the species should be considered as one of many components of biodiversity

Table B1
The present and planned extents of land cover classes in the example landscape excluding the fens inhabited by the bogbean buckmoth (*Hemileuca* sp.) and their surrounding buffers. Unaltered land cover includes the Pasture, Shrubland, Wetland, Coniferous Forest, Deciduous Forest, and Mixed Forest classes. Altered land cover includes the Built and Annual Cropland classes and roads (not shown). Agricultural land cover includes the Annual Cropland and Pasture classes. The Water, Barren/Non-vegetated, and Exposed Land classes were not categorized (see Appendix A). Planned extents are calculated with reference to the constraints and recommendations described in the main text, which refer to a selection of land cover classes.

Land cover class	Present extent (km^2)	Planned extent (km^2)	Change in extent (km^2)	Present proportion of total (%)	Present proportion of unaltered land cover (%)	Planned proportion of total (%)	Change in proportion of total (%)
Water	84.96			4.07			
Barren/Non-vegetated	0.65			0.03			
Exposed Land	32.05			1.53			
Built	123.07	210.45	87.38	5.89		10.07	4.18
Annual Cropland	336.42	245.00	−91.42	16.10		11.73	−4.37
Pasture	577.76			27.65	38.20		
Shrubland	105.67			5.06	6.99		
Wetland	83.76	87.80	4.04	4.01	5.54	4.20	0.19
Coniferous Forest	226.75			10.85	14.99		
Deciduous Forest	83.90			4.02	5.55		
Mixed Forest	434.51			20.79	28.73		
Unaltered land cover	1512.35	1516.39	4.04	72.38	100.00	72.57	0.19
Altered land cover	459.49	455.45	−4.04	21.99		21.80	−0.19
Agricultural land cover	914.18	822.76	−91.42	43.75		39.38	−4.37
Total	2089.50			100.00			

Table B2
The present and planned extents of land cover classes in the example landscape. The fens inhabited by the bogbean buckmoth (*Hemileuca* sp.) and their surrounding buffers are listed as an individual land cover class as they would be if the protection of the species was not mandated by law. Unaltered land cover includes the Pasture, Shrubland, Wetland, Coniferous Forest, Deciduous Forest, Mixed Forest, and Buckmoth Habitat classes. Altered land cover includes the Built and Annual Cropland classes and roads (not shown). Agricultural land cover includes the Annual Cropland and Pasture classes. Planned extents are calculated with reference to the constraints and recommendations described in the main text, which refer to a selection of land cover classes.

Land cover class	Present extent (km^2)	Planned extent (km^2)	Change in extent (km^2)	Present proportion of total (%)	Present proportion of unaltered land cover (%)	Planned proportion of total (%)	Change in proportion of total (%)
Water	87.89			3.65			
Barren/Non-vegetated	0.68			0.03			
Exposed Land	34.40			1.43			
Built	126.63	216.54	89.91	5.26		9.00	3.74
Annual Cropland	340.87	247.32	−93.55	14.16		10.27	−3.89
Pasture	594.68			24.70	32.73		
Shrubland	109.70			4.56	6.04		
Wetland	85.79	89.43	3.64	3.56	4.72	3.72	0.16
Coniferous Forest	231.70			9.63	12.75		
Deciduous Forest	87.10			3.62	4.79		
Mixed Forest	445.54			18.51	24.52		
Buckmoth Habitat	262.21			10.89	14.43		
Unaltered land cover	1816.72	1820.36	3.64	75.47	100.00	75.62	0.15
Altered land cover	467.50	463.86	−3.64	19.42		19.27	−0.15
Agricultural land cover	935.55	842.00	−93.55	38.86		34.98	−3.88
Total	2407.19			100.00			

in the planning unit and its particular protection should therefore depend on the rarity of its habitat relative to other unaltered land cover types.

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