Designing natural heritage systems in southern Ontario using a systematic conservation planning approach

by Danijela Puric-Mladenovic[1] and Silvia Strobl[2]

ABSTRACT

Landscape planning in settled landscapes includes identifying larger areas of natural vegetation to be conserved protected and/or managed for various environmental and public services. These "green backbones" of the landscape, called Natural Heritage Systems (NHS) in the settled landscapes of southern Ontario, Canada, should have appropriate land use planning and natural areas management actions and related policies to protect and enhance biodiversity and ecological functions. As such, an NHS should be derived using a rigorous and defensible methodology while ensuring public involvement and input during this process. This paper describes the methodology for regional NHS design currently being implemented by OMNR in collaboration with numerous conservation partners and municipalities in southern Ontario. The methodology combines the principles and methods of landscape planning, conservation planning, and spatial analysis, while ensuring that the process is adaptable and repeatable over time and different scales. For each landscape, explicit and transparent conservation objectives, features and targets are identified based on stakeholder inputs. Numerous conservation and restoration objectives are translated into explicit quantitative targets for each analysis unit, and a mathematical optimization algorithm is used to represent all the targets at minimal cost (least land area). The methodology is illustrated using examples from a pilot study in Ecodistrict 7E–5 with some references to ongoing NHS implementation projects as well as potential applications of this method.

Key words: biodiversity targets, ecological function targets, ecological restoration, fragmentation, Natural Heritage System, landscape ecology, landscape planning, Marxan, protected areas, simulated annealing algorithm, scenario analysis, southern Ontario, spatial conservation prioritization, systematic conservation planning

RÉSUMÉ

La planification de l'utilisation du territoire dans un environnement habité comporte l'identification de grandes superficies de végétation naturelle à conserver, à protéger ou encore aménager dans le but de produire divers services environnementaux et publics. Ces « charpentes écologiques » du paysage, que l'on nomme systèmes de patrimoine naturel (SPN) dans les zones habitées du sud de l'Ontario, au Canada, devraient pouvoir compter sur une utilisation du territoire bien planifiée ainsi que sur des activités d'aménagement des zones naturelles et une réglementation spécifiques afin de protéger et d'accroître la biodiversité et les fonctions écologiques. Pour créer un SPN il faudrait une méthodologie rigoureuse et crédible, garantissant la participation et l'apport du public tout au long du processus. Cet article décrit la méthodologie qu'utilise présentement MRNO pour la conception d'un SPN régional en collaboration avec différents partenaires de la conservation et des municipalités du sud de l'Ontario. La méthodologie utilise à la fois les principes et méthodes pour planifier l'utilisation du territoire et la conservation et l'analyse spatiale, tout en assurant que le processus permet d'être adapté et répété dans le temps et à différentes échelles. Pour chaque territoire, on convient d'objectifs de conservation explicites et précis ainsi que de caractéristiques et de cibles établies à partir des renseignements fournis par les intervenants. Les nombreux objectifs de conservation et de restauration sont transposés sous forme de cibles quantitatives explicites pour chaque unité analysée et on se sert alors d'un algorithme mathématique d'optimisation pour atteindre tous les objectifs au moindre coût (plus petite unité de superficie). La méthodologie est illustrée au moyen d'exemples tirés d'une étude pilote réalisée dans le district écologique 7E-5 et accompagnée de quelques références aux projets de SPN en cours et aux applications potentielles de cette méthode.

Mots clés : objectifs de biodiversité, objectifs des fonctions écologiques, restauration écologique, fragmentation, système de patrimoine naturel, écologie des paysages, planification des paysages, Marxan, territoires protégés, algorithme SAEM, analyse de scénario, sud de l'Ontario, priorisation de la conservation spatiale, planification systématique de la conservation

[1]Information Management and Spatial Analysis, Southern Science and Information Section, Ministry of Natural Resources, 300 Water St., 4th Floor South Tower, Peterborough, Ontario K9J 8M5. E-mail: danijela.puricmladenovic@ontario.ca
Faculty of Forestry, University of Toronto, 33 Willcocks St., Toronto, Ontario M5S 3B3
[2]Information Management and Spatial Analysis, Southern Science and Information Section, Ministry of Natural Resources, 300 Water St., 4th Floor South Tower, Peterborough, Ontario K9J 8M5. E-mail silvia.strobl@ontario.ca

Danijela Puric-Mladenovic

Silvia Strobl

Introduction

The geometric, rectilinear pattern of the first land surveys provided a blueprint for European settlement and subsequent land development and land use in southern Ontario, and has permanently shaped the remaining natural areas, habitats and biodiversity south and east of the Canadian Shield (Riley and Mohr 1994, Puric-Mladenovic 2003, Moss and Okey 2004). For over a century, conservation and natural resource managers in southern Ontario have tried to mitigate the negative impacts caused by the loss and fragmentation of natural vegetation cover. Initial conservation efforts included the establishment of the first provincial parks. In the early 20th century, the first large-scale tree plantings in southern Ontario were undertaken to mitigate soil erosion, flooding, and land degradation caused by widespread forest clearing for settlement and agriculture (OMNR 1986). In addition to creating parks and restoring areas of highly erodible fine sandy soils to Agreement Forests, other activities were pursued, such as the conservation of additional public and private lands with varying degrees of management and protection. Even though these efforts shared a common vision of conserving, enhancing, and sustaining the use of natural resources, they were often initiated to combat emerging, specific, and localized issues. Although these land protection and restoration activities contributed to critical conservation needs, and in most cases accomplished their intended local objectives, they were rarely considered as part of an integrated, strategic, and long-term planning and management strategy for the region's landscapes. Until recently, there has been no regional approach or strategy to guide continuing site-specific restoration activities towards integrated, regional goals that optimize biodiversity conservation across spatial and temporal scales.

In the last two decades, conservation, landscape planning, landscape ecology, and spatial analysis sciences developed novel methods for addressing and efficiently responding to landscape planning and conservation issues. The idea of regional systems was introduced to bridge the gap between land use planning and the conservation. The concept of regional systems of ecological networks was developed and subsequently implemented across Europe, then in Australia, and finally applied to parts of North America (Jongman *et al.* 2004, Jongman and Pungetti 2004). These systems, depending on their primary function, scale, geographic location, and the methods and concepts used to design them, have been referred to as: ecological networks; greenway systems; ecological greenways; core areas and corridors; natural systems; green infrastructure; green spaces; protected natural areas systems; greenbelts; and in southern Ontario—Natural Heritage Systems (Riley and Mohr 1994, Fábos and Ahern 1995, Fábos 2004, Jongman *et al.* 2004, Jongman and Pungetti 2004, Fábos and Ryan 2006).

By the early 1990s, it became apparent that existing designations and conservation lands (e.g., parks and protected areas, Areas of Natural and Scientific Interest [ANSIs], Provincially Significant Wetlands [PSWs]) alone were not sufficient to sustain ecologically sound and functioning natural areas and ecological process within southern Ontario's landscapes. In response, the first conceptual framework of landscape systems, based on natural networks and natural core areas, corridors, and connecting links, was introduced to southern Ontario by the Ministry of Natural Resources in 1991 (OMNR 1991). A few years later the need for landscape system-based policy and natural heritage and environmental protection was further emphasized (Riley and Mohr 1994). This resulted in the establishment of the Natural Heritage System (NHS) concept through the Provincial Policy Statement (PPS) in 1997 (and amended in 2005) (OMMAH 1997, 2005), and the development of supporting Natural Heritage Reference Manuals in 1999 and 2010 (OMNR 1991, 2010).

Box 1

Policy 2.1.2 of the Provincial Policy Statement

The diversity and connectivity of natural features in an area, and the long-term ecological function and biodiversity of natural heritage systems, should be maintained, restored or, where possible, improved, recognizing linkages between and among natural heritage features and areas, surface water features and ground water features (OMMAH 2005).

The introduction of the NHS concept into the PPS (Box 1), prompted the design of natural heritage systems at the regional, municipal, watershed, and political designation scales. Regional design efforts, including *The Big Picture* (Jalava *et al.* 2002) and *The Conservation Blueprint* (Henson *et al.* 2005, Wichert *et al.* 2005), visually and conceptually demonstrated the need for regional planning. The Oak Ridges Moraine (ORM) Conservation (2002) and Greenbelt (2005) Plans were the first land use policy examples incorporating regional natural heritage systems into the land use planning process of politically designated areas. These provincial NHSs were delineated and protected from development by provincial policy, ensuring their incorporation into municipal official plans.

Since 1997, a number of municipalities and Conservation Authorities, driven by PPS Policy 2.1.2 (Box 1), have produced NHS mapping for their jurisdictions as shown in Fig. 1. Based on a summary of the results of a 2010 survey conducted by OMNR, areas identified in dark gray in Fig. 1 represent those municipalities that have met the PPS definition of having identified core natural areas and linkages. However, the NHSs designed in these municipalities were developed without a strategic and integrated regional context, except for municipalities that had to comply with the ORM and Greenbelt NHS.

Those areas identified in light gray in Fig. 1 were judged to only have identified feature-based natural core areas (e.g.,

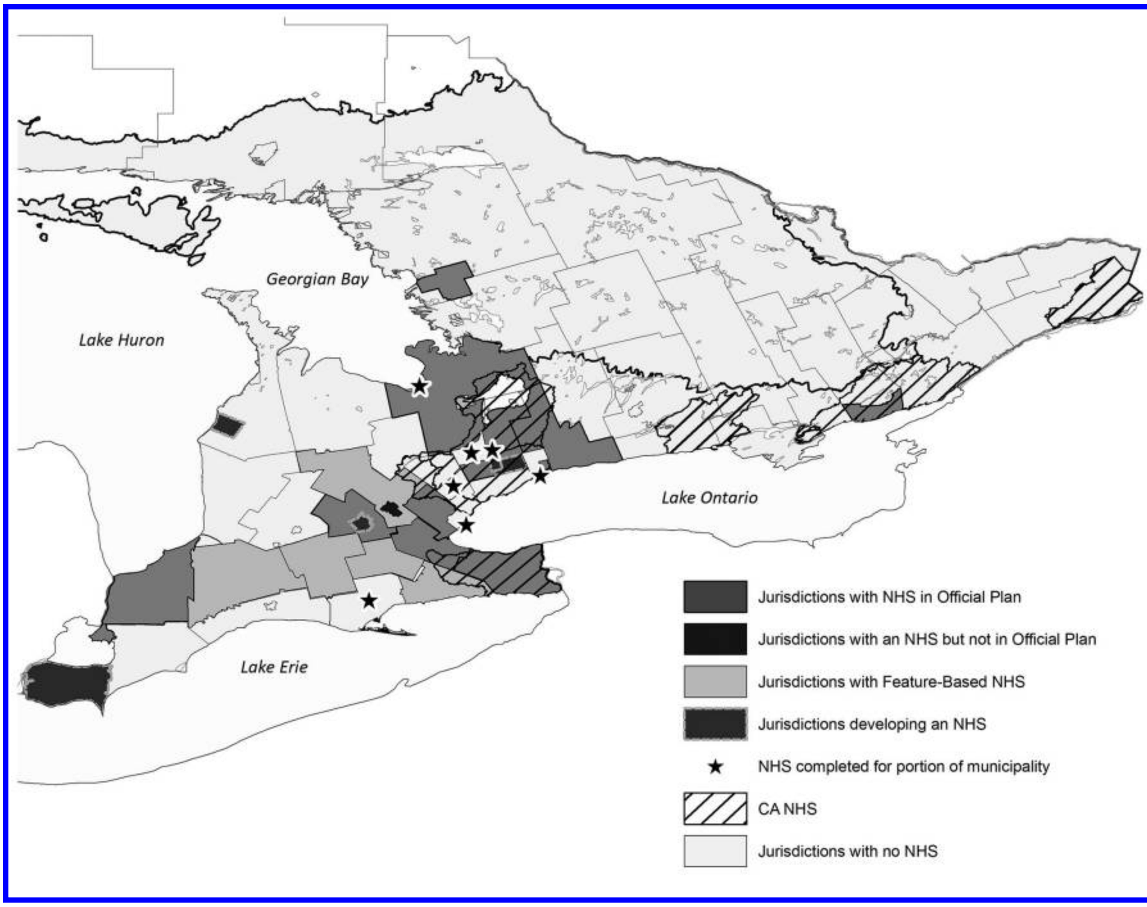


Fig. 1. Status of Natural Heritage Systems delineation by municipalities and Conservation Authorities in southern Ontario jurisdictions.

ANSIs and PSWs). For more than half of southern Ontario, however, municipalities (legend–jurisdictions with no NHS) have yet to design an NHS and implement Policy 2.1.2.

While the ORM Conservation and Greenbelt Plans as well as municipal and Conservation Authority efforts in identifying NHSs represent progress towards designing and conserving systems of natural areas and linkages, the methods and approaches used to delineate NHSs do not consider the regional context, explicit conservation targets, stakeholder engagement and scenario planning. For example, many NHSs, though referred to as systems, are in effect based on a feature approach that lacks integration across spatial and ecological scales. On the other hand, some NHSs are conceptually sound and are accompanied by policy implications, but the methodology used to delineate natural heritage systems lacks explicitness and transparency, making it both difficult to quantify what the system represents and to defend it when applied to planning decisions.

NHS Design Based on Landscape Planning and Systematic Conservation Planning Principles

To support NHS design as one component of landscape planning, we used ecological boundaries (bio-physical regions, watersheds, land forms, river valleys) rather than political ones (e.g., municipal). In addition, we used and adapted principles and tools from systematic conservation planning and spatial conservation prioritization (Pressey *et al.* 1993, Margules and Pressey 2000, Margules and Sarkar 2007, Moilanen *et al.* 2009, Wilson *et al.* 2009) that have been traditionally used to inform the design of systems of reserves and protected areas. Systematic conservation planning has been applied to numerous conservation efforts in both terrestrial and marine environments (Margules and Pressey 2000), but can be readily applied to settled landscapes (Puric-Mladenovic and Strobl 2006, ORMF 2005) and NHS design with some adaptations. The major steps in systematic conservation planning (Pressey *et al.* 1993, Margules and Pressey 2000, Margules and Sarkar 2007, Moilanen *et al.* 2009) with some adaptations to southern Ontario NHS design include:

1) Determine the ecological scale of analysis and, hence, the study area.
2) Identify the spatial conservation prioritization tool to support the analysis.
3) Identify and engage stakeholders in the planning process.
4) Identify the vision and high-level goals and specific conservation objectives for the planning region.
5) Gather, compile data and maps, and complete a gap analysis to measure the specific conservation objectives (e.g., biodiversity representation) that existing natural areas in the planning region achieve.
6) Define a set of targets for specific conservation objectives and conservation features.
7) Review and include socio-political inputs.

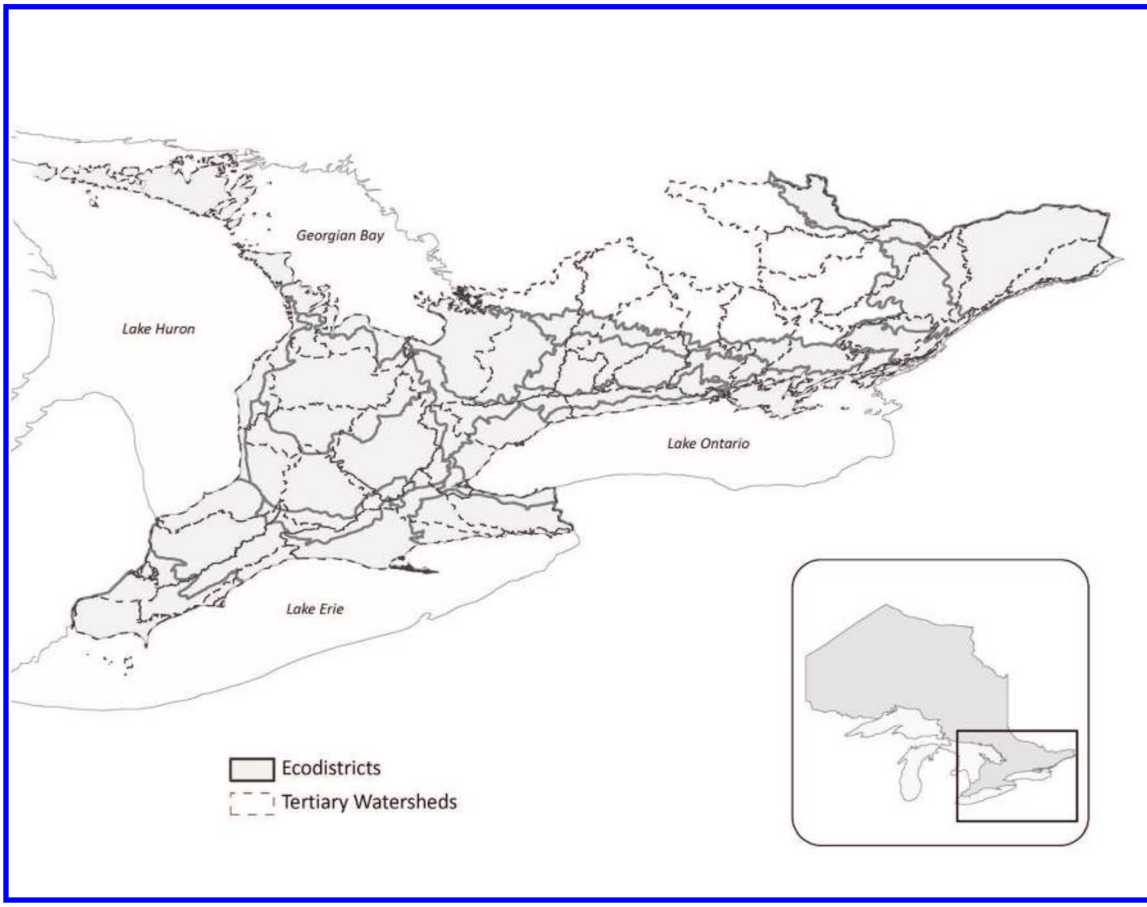


Fig. 2. Ecodistricts and watersheds in southern Ontario's settled landscape.

8) Run the analysis to select areas for inclusion in the NHS design. This includes the preparation of data inputs specific to the spatial conservation prioritization tool being used.
9) Develop NHS scenarios by evaluating and mapping the analysis results.
10) Select a preferred scenario for the NHS design by stakeholder consensus.

Each of the steps in the approach will now be discussed in detail.

1. Determine the ecological scale of analysis and, hence, the study area

Decision-making that is constrained within the geometric boundaries of municipalities and individual land parcels can lead to cumulative environmental impacts that may be observed as regional-scale impacts over time. The loss of biodiversity, environmental changes caused by climate change, and the loss of specific and representative habitat types have regional impacts and logically require conservation, planning and management actions to be developed at this level, but integrated and applied at the local (e.g., municipal) scale.

Canada and Ontario have a long history of applying ecological regionalization in resource management (Hills 1959, Rowe 1972, Hills 1976, Ecological Stratification Working Group 1996, Wiken *et al*. 1996). In Ontario, ecoregions and ecodistricts have been applied to parks and protected area programs, ecodistrict reporting, and the confirmation of Areas of Natural and Scientific Interest (ANSIs) (Crins *et al.* 2009).

In addition to ecoregions and ecodistricts, watershed regions are also used in Ontario, particularly for resource management and planning activities delivered by Conservation Authorities (Fig. 2). Following the introduction of the Clean Water Act, watershed boundaries (hydrological landscapes) have been used as a framework for source water protection planning. However, many biodiversity and ecological functions cross watershed boundaries and are therefore best addressed within biophysical regions. Similarly, hydrological functions and processes are best addressed within watersheds.

Competing land uses and numerous environmental issues (from single species, habitat, or biodiversity loss to the provision of water quality and quantity) are common in settled landscapes. To avoid duplication and maximize the ecological benefits and returns from subsequent implementation, planning and management must include strategic integration across biophysical and/or hydrological regional scales (Omernik and Bailey 1997).

Southern Ontario, located within the Mixedwood Plains Ecozone, is made up of two climatically distinctive units, the Lake Simcoe–Rideau Ecoregion and the Lake Erie–Lake Ontario Ecoregion. The 22 ecodistricts or landscape units within these two ecoregions are used to support NHS design and planning in southern Ontario. Each ecodistrict has specific climate, soil, topography, natural vegetation characteristics and human footprint (Jalava *et al.* 1997, Crins 2002, Crins *et al.* 2009). Ecodistricts characterized by a milder climate and productive soils experience the greatest impacts of settlement, including the highest levels of habitat fragmentation and biodiversity loss. For example, Ecodistrict 7E–7 is entirely within the Greater Toronto Area and almost completely urbanized. Many ecodistricts within ecoregion 7E, with more productive soils and milder climate, currently have less than 15% natural cover due to their suitability for agriculture.

While an integrated regional approach to landscape and spatial planning is supported by policies in other jurisdictions around the world, the adoption of this concept in Ontario is still in the early stages. The biophysical scale, ecodistrict-based approach to NHS design and planning was successfully piloted within Ecodistricts 6E–6 and 7E–5, and subsequently applied by the Integrated Landscape Management project within Ecodistricts 6E–10 and 6E–11 (comprising Leeds and Grenville County) and by the NHS design and planning project in Ecodistrict 6E–15 (comprising Prince Edward County and environs). One of the primary advantages of applying a consistent, ecodistrict-based approach for NHS design and planning is the ability to cross municipal boundaries, and integrate ("puzzle together") individual natural heritage systems across southern Ontario to produce a comprehensive NHS at the ecoregion scale.

2. Identify the spatial conservation prioritization tool to support the analysis

A number of different site selection planning and mathematical optimization programs are available to assess conservation priority areas, solve spatial conservation problems, and provide spatial outputs (Moilanen *et al.* 2009). Some of the best known include C-plan, SPEXAN, SITES, ResNet, and Zonation (Moilanen *et al.* 2009). Of all of the conservation planning software, Marxan, has been the most widely used and has been applied to different conservation problems at various spatial scales. The technical and computational advantages of Marxan have led to its use by over 600 government, non-government, conservation, and academia organizations in about 95 countries in the world (Ardron *et al.* 2010). The program can: help solve spatially complex conservation problems; address multiple conservation objectives; be easily linked to Geographic Information Systems (GIS) either indirectly or through program interfaces (MarZone, CLUZ, or Panda); and produce outcomes that are readily quantifiable and mapped. Finally, free access, support from the developers, and a wide group of users have also played a role in the widespread adoption of Marxan. Marxan is a site selection program that uses a mathematical optimization algorithm, simulated annealing, to find near-optimal solutions that meet conservation objectives and their specific targets. The program finds a spatial solution that represents all targets at minimal cost, while ensuring compactness of the system (Ball *et al.* 2009).

To facilitate rapid computation, the site selection algorithms require dividing the landscape (area) of interest (e.g., ecodistrict or watershed) into a number of smaller planning or analysis units. Each unit acts as a container that carries relevant conservation and land use information and enables the site-selection algorithm to define the most efficient configurations of planning units. Our NHS design methodology uses a relatively fine 5-ha analysis unit that corresponds to the level of landscape fragmentation, patch size and patch separation distance in southern Ontario.

3. Identify and engage stakeholders in the planning process

When using spatial prioritization tools such as Marxan, it is still critical to define the conservation problem correctly, ask the right questions, and set meaningful conservation objectives and sound conservation targets. In a complex, settled landscape like southern Ontario where many organizations and agencies have a role in land use planning, conservation and natural resource management, these decisions are best made by multiple stakeholders that represent the numerous interests in the landscape. The stakeholder engagement process is fully described in the companion paper (Spang *et al.* 2012). In southern Ontario, regional, integrated NHS planning is largely dependant on influencing local planning authorities (municipalities) to adopt this approach. The stakeholder engagement process has numerous benefits as identified by Spang *et al.* (2012), but primarily it enables participating organizations to buy into the design and planning process and subsequently implement the final NHS.

4. Identify the vision and high-level goals and specific conservation objectives for the planning region

High-level goals and vision give an NHS a long-term purpose that is independent of the data, information and spatial prioritization tools. They are fundamental and guiding components of NHS design and should be shaped primarily by societal or cultural values and stakeholder input. High-level goals inform the identification of specific conservation objectives. For example, a high-level goal can be the maintenance of species' habitats, while one possible specific objective to support this may be interior forest habitat for area-sensitive bird species. For the two pilot projects, Ecodistricts 6E–6 and 7E–5, high-level goals were not defined by a stakeholder group; rather, they were developed by an internal working group of OMNR staff (Table 1).

The stakeholder team that was involved in design of the NHS for Ecodistricts 6E–10 and 6E–11 identified the vision and high-level goals shown in Table 1. Interestingly, many of the high-level goals and visions identified by these stakeholders are also articulated in Ontario's Biodiversity Strategy (OMNR 2005), which was developed by bringing together a broad spectrum of contributors including industry, environmental groups, government agencies, and members of the public. Thus, the NHS approach and method we describe in this paper can be used as a means of implementing the recommendations in Ontario's Biodiversity Strategy and bringing a range of stakeholders towards a common long-term landscape vision.

5. Gather, compile information and maps, and complete gap analysis

To use a decision support tool like Marxan these high-level goals and specific objectives need to be translated into specific mapped conservation features and their conservation targets based on available spatial data. Two types of information

Table 1. The vision and high-level goals developed for the NHS design projects in Ecodistricts 7E–5 and 6E–6 (by OMNR staff) and Ecodistricts 6E–10 and 6E–11 (by the stakeholder team).

	Ecodistrict 7E–5 and 6E–6 NHS projects (identified by OMNR staff)	Ecodistricts 6E–10 and 6E–11 NHS project (identified by the stakeholder team)
Vision	None identified	A sustainable quality of life for the communities within and adjacent to the study area is supported by a balance of environmental, economic, cultural, and social land uses that includes a system of connected natural areas capable of conserving indigenous biodiversity, ecological functions and species habitats.
High-level goals	The NHS should include: a) the diversity of ecological communities and native species; b) areas for restoration and recovery including representative and threatened natural areas; c) significant natural heritage features as defined in the PPS; d) known occurrences of species at risk and their habitats; e) protected areas and public lands, and f) sensitive surface water and groundwater features, and other aquatic habitats.	To identify, through engagement and agreement of local communities, a healthy natural heritage system (NHS) for the study area that will: • Provide a focus for strategic land restoration to improve land sustainability, land securement, stewardship, and the conservation of biodiversity. • Inform and support sustainable land use planning and resource management decision-making. • Support sustainable economic opportunities. • Support social well-being. • Maintain cultural heritage.

inputs, ecological and socio-political, were developed using spatial information readily available from OMNR's Land Information Ontario Warehouse. A few spatial information layers for socio-political inputs were obtained from conservation and non-governmental organizations. Some data sets were derived from existing spatial layers to represent specific objectives and conservation targets (e.g., forest interior habitat was derived from forest cover mapping).

The quality and defensibility of the final NHS is dependent on how conservation features are defined as well as the quality of the information inputs used to map and measure the specific conservation features. A key requirement of spatial prioritization is the availability of standardized spatial datasets for the entire extent of the area of interest. For Ecodistricts 6E–6 and 7E–5 existing spatial data were assessed to determine the spatial extent of the data, the context and type of information and data quality. Where existing data did not provide enough detail, surrogate information was used. For example, due to the absence of relevant vegetation mapping, soil types were used as surrogates to represent vegetation biodiversity. Setting targets for conservation features mapped only for a portion of the study area would have introduced bias towards those areas, and hence were excluded. However, where applicable these localized data sets can be used to support development of an NHS at a finer, local scale that is still consistent with the NHS defined at the regional scale.

Gap analysis

Prior to setting desired conservation targets, a gap analysis is conducted to measure the extent of the existing conservation features and compare it to a reference or desired condition (e.g., historical or potential vegetation, potential or historical species habitat and range) (Puric-Mladenovic 2003). This quantitative comparison measures the degree of departure between current and desired conditions and informs target setting. The results of the gap analysis and science-based ecological thresholds, if available, inform decisions on appropriate conservation targets. A gap analysis may also identify biodiversity elements that are not adequately represented in existing protected areas. The gap analysis for Ecodistrict 7E–5, located in Niagara region in southern Ontario (Fig. 3) showed that the dominant land cover class in this area is agriculture, with 36% of the landbase consisting of either monoculture or mixed crops and another 34% in hay, pasture, or idle/marginal lands. Eighteen percent of existing land cover is wooded, which includes swamps (3%). Nine percent of the landbase consists of built-up, settled areas (e.g., towns and cities), and approximately only 1% is wetlands. The results of the gap analysis showed that forest cover on uplands and productive soils, favouring upland forests types and associ-

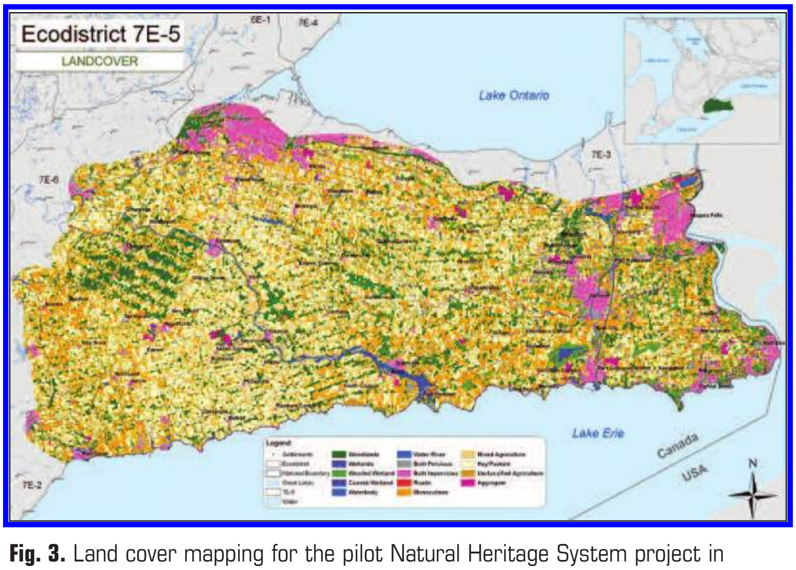


Fig. 3. Land cover mapping for the pilot Natural Heritage System project in Ecodistrict 7E–5.

ated species, is unrepresented, while remaining forest cover disproportionately occurs on less productive soils (e.g., on poorly drained soils).

6. Define a set of targets for specific conservation objectives and conservation features

Each conservation objective is spatially represented and mapped based on the available data. Once mapped, specific conservation objectives are referred to as conservation features for which specific conservation targets can be set. Conservation targets enable achieving both the specific conservation objectives as well as broad ecological goals. A single conservation objective can be expressed and mapped as numerous conservation features. For example, the conservation objective of forest diversity representation includes representation of diverse forest types. Each forest type (e.g., maple-beech, early successional poplar, white pine, or hemlock forest type) represents conservation features that collectively correspond to and address forest biodiversity conservation objective. For each conservation feature, explicit conservation targets, ideally based on a gap analysis and science-based thresholds, are set to designate how much of it should be represented within the system.

Conservation targets can be expressed as percentages, the amount of area to be captured, or the number of species or habitat occurrences (e.g., 70% of existing hemlock forest; five viable species habitats). Using explicit targets ensures transparency, defensibility and adaptability in the NHS design and planning process.

While explicit target setting gives the NHS transparency and measurability, it also creates uncertainty about "how much is enough"? To address this challenge and set targets to ensure biodiversity and ecological functions are protected in the NHS, we used four approaches:

a) set targets based on the existing science and known thresholds,
b) set targets based on expert opinions,
c) set targets based on consensus of the stakeholder team, and
d) a combination of these.

Conservation targets need to be scientifically sound and defensible. They need to be set based on scientific evidence and ideally above known thresholds. Environment Canada's *How Much Habitat is Enough?* (Environment Canada 2004) provided a starting point for setting a number of the conservation targets, supplemented by other scientific literature. However, some conservation features had to be set based on consensus decision because scientific evidence to identify a threshold or target was unavailable. Such targets can be defended as "ethical" and "collective" if they are established through stakeholder engagement with reference to local knowledge and expert opinion.

While Marxan can accommodate large numbers of conservation features and integrate multiple objectives, to ease communication and minimize confusion among stakeholders, we grouped specific conservation objectives and corresponding conservation features into the following categories:

a) overall landscape biodiversity and landscape representation (Margules and Pressey 2000),
b) species and habitats, and
c) ecological functions and processes.

Additional categories of targets could be considered, for example, for restoration of underrepresented biodiversity values such as prairie and savannah communities. Over 60 different conservation features and targets were set for the Ecodistrict 7E–5 pilot project. However, in study areas with rich fine-scale vegetation and species maps the number of conservation features and targets can exceed several hundred. Thus, conservation objectives and features differ from project to project depending on local stakeholder and societal values and goals, but are mostly reliant on available spatial information.

Overall landscape biodiversity and landscape representation targets

Overall landscape diversity is usually expressed as representation of a mosaic of vegetation communities. Some studies suggest that about 80% of indicator species could be captured by landscape-vegetation diversity conservation features and targets derived from adequate and comprehensive vegetation inventory (Howard *et al.* 1999). For Ecodistrict 7E–5, coarse-scale land cover mapping was used to set five vegetation conservation feature targets (i.e., for deciduous, mixed and coniferous forest, and marsh and swamp wetlands). Since coniferous and mixed forests are not naturally abundant in Ecodistrict 7E–5, higher targets for these features were set to ensure that they were captured within the NHS and contribute to biodiversity. Examples of some of the biodiversity features and targets set for Ecodistrict 7E–5 are shown in Table 2. For the Ecodistrict 6E–10 and 6E–11 project, more detailed vegetation mapping was available which enabled setting targets for 47 forest and five wetland fine-scale biodiver-

Table 2. Example of biodiversity and landscape representation feature and targets set in the Ecodistrict 7E–5 pilot (% represents the percentage of the total area of the specific types of features to be protected).

Conservation feature	Target 1 scenario (%)	Target 2 scenario (%)	Target 3 scenario (%)	Target 4 scenario (%)	Target 5 scenario (%)
Wetland	100	100	100	100	100
Swamp	100	100	100	100	100
Deciduous forest	30	30	30	0	0
Mixed forest	30	30	30	0	0
Coniferous forest	30	30	30	0	0
Forest on clay soils, imperfectly drained	30	30	30	30	100
Forest on sandy soils, rapidly drained	30	30	30	30	100
Riparian forest	75	75	75	0	0
Riparian wetland	75	75	75	0	0

sity conservation features in addition to six overall landscape-vegetation diversity targets. Examples of the fine-scale, conservation features included Dry–Fresh Sugar Maple–Beech Deciduous Forest Type, Fresh–Moist Sugar Maple–Lowland Ash Deciduous Forest Type, Dry–Fresh Oak–Maple–White Pine Mixed Forest Type, and Dry–Fresh Pine–Oak–Maple Mixed Woodland Type (Lee *et al*. 1998).

Species habitat targets

Ideally, conservation targets would also be set for conservation features such as species with different habitat requirements and varying ranges to ensure that umbrella, keystone, indicator, ecologically significant species habitats, and viable populations are part of the NHS. However, the lack of comprehensive vegetation inventory (e.g., vegetation maps with information about plant species composition, vegetation structure, and age) in the pilot area precluded use of available wildlife models and significant wildlife habitat guidelines (OMNR 2000) to create specific wildlife habitat mapping.

Nevertheless, ovenbird (*Seiurus aurocapilla* [Linnaeus, 1766]) habitat was used as a conservation feature. This conservation feature was mapped based on findings from Burke and Nol (2000) suggesting that only the very largest forest patches acted as sources for Ovenbird reproduction (i.e., >23 ha in forest interior and 225 ha in total forest area).

Based on the stakeholders' recommendation, important migratory bird stopover areas were mapped and targeted in the NHS design for Ecodistrict 7E–5. Migratory bird stopover area mapping was developed based on the extent of natural areas derived from several land cover types (e.g., woodlands and wetlands) and a methodology developed by Ewert *et al*. (2006). Finally, data on occurrences of rare and species at risk were used to model species hotspots. The targets set for these species conservation features in the Ecodistrict 7E–5 pilot are shown in Table 3.

Ecological function and processes targets

An NHS should also account for important ecological functions and processes within defined landscapes. Natural areas that support biodiversity often support other ecological functions and process. For example, natural vegetation has indirect impacts on many hydrological functions such as water quality and aquatic habitat. In addition, vegetation cover within headwater areas not only supports hydrological functions, but also specific biodiversity values (e.g., shading cold water ephemeral streams). The spatial conservation prioritization tool (Marxan) enables optimizing all the targets for biodiversity and ecological functions in the least amount of area, so one feature on the landscape may contribute to several conservation targets. Ecological functions and processes mapped in spatial format (e.g., patch size, wetland functional zones, and coastal wetlands) were included in this category and examples of some of the targets are shown in Table 4.

In addition, stakeholders expressed that natural vegetation in headwater areas should be part of the NHS due to its importance for water quality. A target of 50% of existing vegetation in headwater areas was set to ensure that the NHS captures at least half of the existing forest and wetland in headwater areas. The set target was based on the stakeholders' consensus since there was no specific evidence in the scientific literature.

7. Review and include socio-political inputs

The term *socio-political inputs* refers to the set of inputs and information that are the result of political, social, and land use activities. In general, there are three groups of socio-political inputs: conservation lands, other existing land uses that represent either an obstacle or opportunity for the NHS, and cost of the NHS. The Marxan algorithm is able to account for these different socio-political inputs by assigning one of four possible values to planning unit status: conserved, excluded, available, and earmarked.

Table 3. Example species habitat targets from the Ecodistrict 7E–5 pilot. (% represents the percentage of the total area of the specific types of features to be protected.)

Conservation feature	Target 1 scenario (%)	Target 2 scenario (%)	Target 3 scenario (%)	Target 4 scenario (%)	Target 5 scenario (%)
Species at risk hotspot areas	100	100	100	0	0
Migratory bird stop over areas	100	100	0	0	0
Ovenbird habitat	100	100	100	0	30

Table 4. Example of ecological function features and targets from the Ecodistrict 7E–5 pilot. (% represents the percentage of the total area of the specific types of features to be protected.)

Conservation feature	Target 1 scenario (%)	Target 2 scenario (%)	Target 3 scenario (%)	Target 4 scenario (%)	Target 5 scenario (%)
Interior forest (100 m from edge)	50	50	50	0	0
Interior forest (200 m from edge)	100	100	100	0	0
Patch size (5 ha – 100 ha)	25	25	25	0	0
Patch size (100 ha – 200 ha)	50	50	50	0	0
Patch size (>200 ha)	100	100	100	0	0
Vegetated wetland functional zone	75	75	75	0	0

Conserved units are "locked in" and are considered to be part of the initial reserve as well as in the final solution regardless of their contribution to conservation targets. As a result they have to be part of the final solution. Planning units with excluded status will not be considered for inclusion in the NHS. The rest of the landscape is given the status "available", which represents land that has neither an imposed conservation status nor physically restricting conditions (e.g., impervious cover). These areas are assessed and selected only based on their contribution to conservation targets while minimizing cost. Similarly, planning units that have lands with some conservation status, but lack full protection were given earmarked status so that they will be given preference at the start of the annealing process over available units. Earmarked planning units are included in the "seed" reserve or the initial reserve; however, depending on their contribution and cost they may or may not be in the final NHS. Different levels of conservation status, associated policy land use and socio-political values, sometimes result in different options for what should be conserved or available, and thus require exploration of different alternative scenarios to determine how they affect the NHS design.

Conservation lands

Conservation lands are an important part of NHS design, as they can serve as building blocks and are used as an opportunity for developing a regional NHS. Building an NHS around parks and protected areas and other conservation lands managed for long-term protection is necessary in southern Ontario where more than 90% of the land is privately owned. Conservation lands are protected "islands" and their functions and biodiversity are dependent on processes in the surrounding areas, and as such they will also benefit from stewardship and management activities focus on adjacent lands.

Over 40 different types of conservation lands occur in southern Ontario. Provincial and federal parks supported by legislation comprise about 1.1% of the landscape. An equivalent percentage of the landscape comprises either public or privately owned lands that have some degree of protection, designation and/or management for conservation purposes (Gray *et al.* 2008). To communicate this complexity of conservation lands to stakeholders and formulate the problem properly, we group conservation lands into two broad categories:

i) lands that are protected and that are pre-conditioned to be included in the final NHS solution; and
ii) all other lands that are managed or designated for some conservation purpose, but have no legally binding or firm legal guaranties to support their long-term persistence.

Assessing the status of the second category of conservation lands is not as straightforward, and was accomplished differently by stakeholders in Ecodistrict 6E–6, who felt that provincially significant wetlands (PSWs) needed to be assigned conserved status, and those in Ecodistrict 7E–5, who felt that these wetlands do not have the same level of protection as protected areas, and thus should not be locked in the system.

Other land use categories

The remaining landscape needs to be designated as either suitable or not for the NHS. In southern Ontario, many areas are already developed or degraded, do not support natural habitats, and often represent barriers for species movement. Such areas include urban impervious areas, major highways and paved roads, road intersections, irreversibly hardened shorelines, and airports. However, this does not mean that some of these areas have no conservation or societal values at a local scale. For example, data on the urban tree canopy could support analysis at the local planning scale and identify urban NHSs. For the pilot areas, planning units were designated as excluded if they had more than 50% impervious cover (urban development) or more than 0.5 ha of area in roads.

Cost

The term *cost* comes from the mathematical optimization and it is the value that Marxan tries to minimize. It can be any relative, social, economic, or ecological measure, or combination thereof. Examples include opportunity cost, land market value, restoration cost, and total land area. Similar to other data inputs, data for costs needs to be sound, spatial, and available for the entire region. For the pilot areas we used the amount of productive agricultural land (in hectares) within the planning unit as a cost, requiring the algorithm to achieve the conservation targets while minimizing inclusion of productive agricultural land. The application of cost in this way also addresses stakeholder values to accommodate local food production and rural agricultural landscapes.

8. Run the analysis to select areas for inclusion in the NHS design

Running the analysis using Marxan to select areas for inclusion in the NHS requires preparation of input data for each (5 ha) planning unit. In addition, several parameters in the Marxan software must also be calibrated before running scenarios. These steps are briefly described in this section.

Prepare data inputs and Marxan program specifics

Planning units

The site selection algorithm uses thousands of smaller planning (analysis) units within an ecodistrict as building blocks to design the NHS. Each of the analysis units contains explicit information about each of the conservation features (i.e., the number of hectares of key species habitat or forest type, the total amount and status of land managed for conservation, hectares of developed land, etc.). The analysis units also allow for data flow and communication between GIS applications and the Marxan software, which enables mapping and comparison of NHS scenarios.

Typically, analysis units are polygons of either regular or irregular shape, depending on the application, objectives, and scale of the analysis (e.g., sub-catchments, watersheds, land parcels). After testing the application of different analysis units (polygon shape) with the software, we chose regularly shaped units. Some of the advantages of using regularly shaped units include:

- size and shape of the units do not change over time,
- units are not directly related to any land holdings,
- units are randomly derived,
- units support rerunning of Marxan when new information and data become available, and
- units facilitate "stitching together" of NHS plans across ecodistricts as well as accommodating "cookie-cutting" out specific units by local municipalities within an ecodistrict.

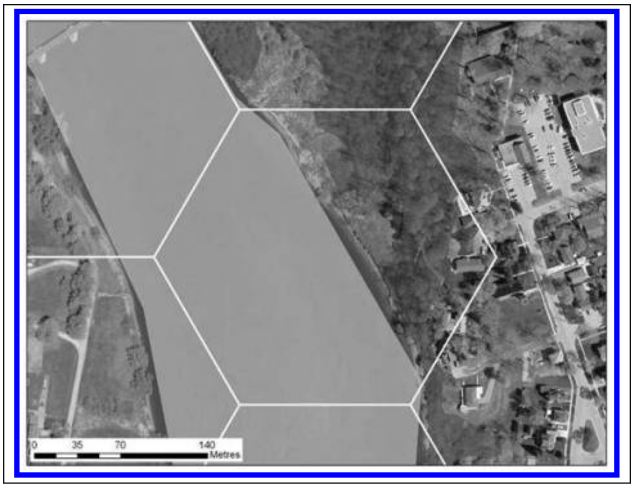


Fig. 4. Five-ha hexagon planning units used to conduct the Marxan alogrithm's analysis and select units for inclusion in the NHS.

We used the Landscape Scripting Language or LSL developed by Kushneriuk and Rempel (2004) to divide the landscape of southern Ontario (Ecoregions 6E and 7E) into equal sized 5-ha seed hexagons (Fig. 4). About 80 000 planning units for Ecodistrict 7E–5 were extracted from the planning unit net for southern Ontario. The southern Ontario net has about 2 million 5-ha hexagons that can be aggregated into larger (35 ha) units and support design of an NHS for all of southern Ontario in one analysis.

Calibration parameters
A number of calibration parameters need to be set by knowledgeable technical staff running the analysis (Ball and Possingham 2000, Game and Grantham 2008, Ball *et al*. 2009, Ardron *et al*. 2010). The calibration process is unique to each project and needs be conducted before running the analysis. Once parameters are selected, however, they must remain constant for each scenario run.

Boundary length modifier (BLM) is a parameter that facilitates design of a more compact NHS that is easier to manage and implement. The higher the BLM, the more Marxan tries to cluster the units and produce compact final solutions, selecting planning units to achieve conservation targets, while considering the cost of planning units as well as preferring connected neighboring planning units.

Species penalty factor (SPF) is a multiplier that determines the size of the penalty that will be incurred if the target for a conservation feature is not met. If the targets for one or two features are consistently being missed, it may be appropriate to set an SPF for these features. Otherwise, all features should start with the same SPF (Game and Grantham 2008). Different SPF values should be explored, tested and calibrated for each conservation problem, with associated BLM values and planning unit costs. These calibration parameters are part of the objective function that Marxan minimizes (Box 2).

A final calibration step includes defining the number of iterations and the number of runs. In general, the number of iterations determines how close the outcome comes to an optimal solution. To set the number of iterations, a number of test runs are done at different iterations per run to set the optimal number necessary to achieve consistent results and ensure that where possible targets can be achieved. In each

Box 2
Objective function (from Game and Grantham 2008)

$$\overbrace{\sum_{PUs} Cost}^{①} + \underbrace{BLM \sum_{PUs} Boundary}_{③} + \overbrace{\sum_{CnValue} SPF \times Penalty}^{②}$$

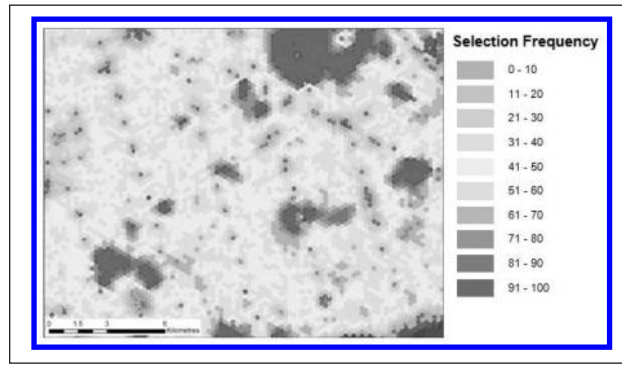


Fig. 5. Example of Marxan selection frequency map based on 100 runs for the Ecodistrict 7E–5 area. The legend identifies the number of times in 100 runs that each hexagon was chosen for inclusion in the solution.

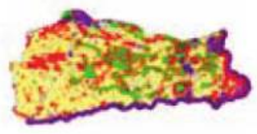
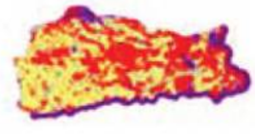
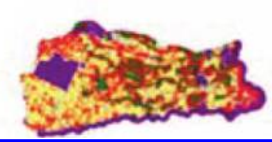
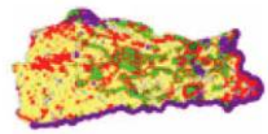
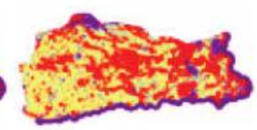
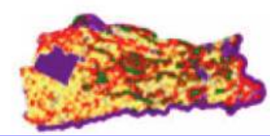
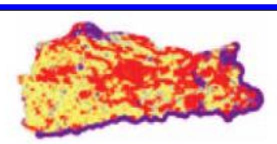
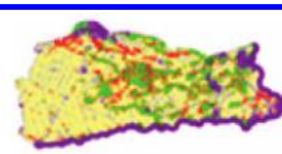
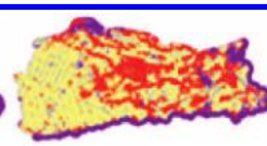
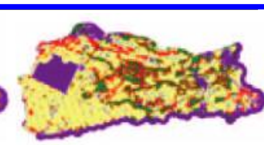
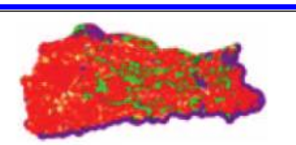
run, the simulated annealing algorithm starts at a random planning unit, so slight differences in output may be observed with each run.

For each scenario in the pilot projects, 100 runs were used to obtain a selection frequency map. The higher the selection frequency of a specific planning unit, the greater its conservation value since its inclusion contributes to an efficient reserve system. An example of the selection frequency output from Marxan is shown in Fig. 5. For the pilot areas, we assumed that planning units selected more than 60% of the time provide an efficient solution for each scenario, and this output was used to compare scenarios and evaluate how well each scenario met the targets. However, we could also have used the output from the most efficient run (i.e., one individual selected "best" run of 100 runs) or any of the individual 100 runs to compare among scenarios. Alternatively, a combination of Marxan selection frequency output, selected best run and any of the individual runs could be used to define the final selections.

9. Develop NHS scenarios by evaluating and mapping analysis results with varying sets of both targets for conservation objectives and socio-political inputs
Five sets of targets for a number of conservation features and three sets of socio-political inputs were considered and assessed in the pilot Ecodistrict 7E–5 project. Eleven different NHS scenarios for Ecodistrict 7E–5 were created by combining a set of ecological targets with a set of planning unit treatments or socio-political inputs (Table 5).

The T1 scenarios had targets for biodiversity representation and ecological function set according to thresholds rec-

Table 5. Natural Heritage System scenarios for Ecodistrict 7E-5. Red hexagons were those selected in the final solution.

Planning Unit Treatments			S1	S2	S3
Set of targets	**Scenario Description**		All provincial and national parks are *conserved*	All but built-up areas are *available*	All conservation lands are *conserved;* First Nations lands are *excluded*
T1	Conservation targets based on scientific literature	**Output**			
		Area (ha)	170 125	170 675	200 035
		Landbase	39%	39%	46%
T2	Same as T1 with additional species at risk targets	**Output**			
		Area (ha)	170 060	167 720	200 985
		Landbase	39%	39%	46%
T3	Same as T1, with the exception of a 0% target for Important Bird Areas	**Output**			
		Area (ha)		165 095	
		Landbase		38%	
T4	Forest biodiversity representation targets only, set at 30% and 100% of wetlands	**Output**			
		Area (ha)	121 265	119 770	127 190
		Landbase	28%	28%	29%
T5	Forest biodiversity representation targets only, set at 100% and 100% of wetlands	**Output**			
		Area (ha)	342 500		
		Landbase	79%		

ommended in the scientific literature (Environment Canada 2004). When the First Nations lands (i.e., the large purple square that represents Six Nations lands) was excluded in the T1 S3 scenario the output revealed that many of the ecological function targets (e.g., interior forest, forest patch size) could not be met.

The T2 scenarios had the same conservation targets as T1 plus several additional targets for species at risk element occurrences including, hot spots (100% or all mapped hot spot areas), endangered (100%), threatened (100%), and special concern species (50%). In this study area, these additional targets provided no additional area to the NHS design, demonstrating that the biodiversity representation and ecological function targets adequately captured known species at risk habitats. As a result, the NHS can be designed without these targets and the conservation feature input and output data can be distributed without compromising sensitive data about species at risk.

The T3 scenarios had the same conservation targets as T1, with the exception of a target for important bird areas (IBA). Adding a target based on coarse-scale IBA data did not substantially affect the design of the NHS, and highlights the importance of data quality for landscape-level projects.

The T4 and T5 scenarios were generated to evaluate the

NHS design that would result if only biodiversity representation targets were included. Only 14% natural cover remains in this ecodistrict, and setting biodiversity representation targets at 100% as in T5 results in 100% of all remaining natural features being included in an NHS design that comprises 79% of the landbase. Every remaining natural area patch is required to meet the targets. In contrast, the T4 scenario with biodiversity representation targets set at 30% results in an NHS design that resembles the T1 S3 scenario, described previously, which does not meet the ecological function targets (e.g., large forest patches).

Investigating scenarios permits examination of how sensitive the NHS design is to specific conservation features and targets and socio-political inputs. Comparing and contrasting scenarios with drastically different target levels provides stakeholders with a better understanding of the landscape, how much natural area is required to meet the targets, and the contributions of specific natural area patches. In general, differences among most of the Ecodistrict 7E–5 scenarios were small. This is indicative of the fact that in landscapes where little natural cover is left, there are fewer options available for system design. In contrast, the pilot project in Ecodistrict 6E–6 that had 36% natural cover resulted in outputs that were considerably more sensitive to changes in socio-political inputs and target levels.

10. Select a preferred scenario for the NHS design by stakeholder consensus

Based on feedback from a stakeholder workshop in February 2007 in Vineland, Ontario adjustments were made to socio-political inputs and conservation features and targets for the Ecodistrict 7E–5 pilot and a final preferred scenario was run with the following socio-political inputs and conservation targets. The preferred NHS scenario is shown in Fig. 6.

Socio-political inputs to the preferred NHS scenario:

a) PSWs were *conserved*, or locked-in to the system.
b) First Nations lands were *available* to contribute to targets.
c) Where PSWs and impervious cover or roads and road intersections overlapped, the PSWs *conserved* status took precedence.

Ecological targets for the preferred NHS scenario included all T3 targets, plus all coastal wetlands, headwater wetlands, and Niagara Escarpment woodlands, each treated as separate variables (target = 100%). In addition, new conservation feature mapping was created for Lake Erie shoreline migratory bird stopover sites based on Ewert *et al.* (2006) treated as two variables (target = 100% for very high and target = 80% for high importance sites, respectively).

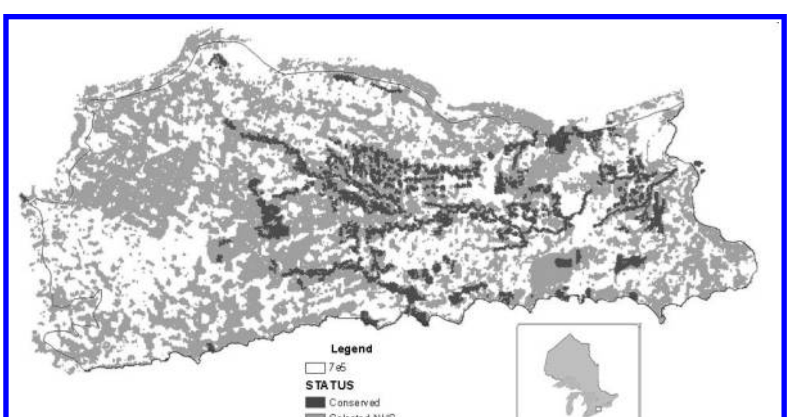


Fig. 6. Preferred Natural Heritage System scenario for Ecodistrict 7E–5 based on stakeholder feedback. This represents the selected planning units output which can easily be mapped back to the underlying natural features to support subsequent planning or analyses.

Next Steps in NHS Planning

Overall, the use of landscape planning principles in combination with systematic conservation planning approach supported by site-selection algorithm was effective for establishing sound objectives and conservation features. The process was also efficient in identifying landscape configurations that meet multiple objectives and targets, and hence can contribute to development of an integrative natural heritage system that meets diverse objectives. The pilot projects also demonstrated just how important it is to engage local stakeholders and partners in any strategic planning for natural heritage and having an option to explore and select different solutions and scenarios. Subsequent projects, such as the *Sustaining What We Value Project* in Ecodistricts 6E–10 and 11, have further refined the stakeholder engagement aspect of the approach (Spang *et al.* 2012).

Other Applications of the Approach

Once an ecodistrict-scale NHS is completed, local municipalities can easily "cookie-cut" out the portion of the NHS within their jurisdiction and use it to inform land use planning and policy decisions, priorities for stewardship projects, priorities for conservation land acquisitions, priorities for inventory programs, and assessment of development proposals. An example of the application of the NHS output for impact assessment is provided in the following case study of two development proposals, a commercial heliport (Eurocopter) and golf course (Baker Creek) in the Town of Fort Erie within Ecodistrict 7E–5 (Fig. 7).

Each hexagon has information on how much it contributes to each of the targets, and many contribute to more than one target. This means that the impact of a development removing those areas of natural cover can be easily quantified to provide information on whether the loss is acceptable, or alternatively, how much restored value elsewhere is needed to compensate for the loss. Table 6 shows that although the Eurocopter development only has 70 ha within the NHS, that 70 ha is contributing 161 ha worth of natural heritage values to the NHS. This means that every hectare that might be lost to the development is really worth 2.29 ha in value to the NHS. The results are similar for the proposed Baker Creek golf course development. The NHS output also facilitates quantifying the cumulative impacts of both developments. If both developments proceed, 356 ha worth of natural heritage values would be lost. This tool, accompanied with adequate spatial information, has major benefits for objectively quantifying cumulative impacts of local developments to regional scales.

Since each planning unit in the final NHS output is attributed with information on how much it contributes to each of the targets, there

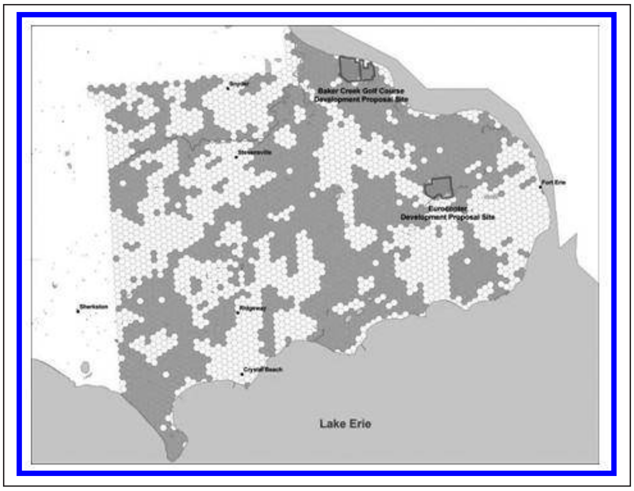


Fig. 7. Portion of the final Ecodistrict 7E-5 NHS (shown in gray) within the Town of Fort Erie and locations of two development proposals.

Table 6. Cumulative impacts of two development proposals in the Town of Fort Erie.

Proposed development	Proposal 1	Proposal 2	Both
Proposal area (ha)	66	91	157
Hexagon adjusted proposal area (ha)	80	100	180
NHS area within development proposal (ha)	70	90	160
Percent of proposal area within NHS	88%	90%	89%
Cumulative impact across all NHS features (ha)	161	195	356
Proposal impact multiplier	2.29	2.17	2.22

is no uncertainty about why a particular area was included in the NHS. This results in a much more transparent and defendable NHS. In addition, documenting all the data inputs, goals, objectives, and targets means that this method of NHS design is quickly and easily repeated when new or improved information is available.

Acknowledgements

Danijela Puric-Mladenovic benefited from the opportunity to meet Hugh Possingham, one of the developers of Marxan, at the US-International Association for Landscape Ecology conference in San Diego, CA in April 2006. We thank the Marxan support team at the University of Queensland for adapting the software for the Ontario Ministry of Natural Resources to accommodate a larger number of planning units. Without the support of MNR's Natural Spaces program during the period 2005–07, we would not have had the opportunity to test and develop the approach described in this paper. We also acknowledge the technical support provided by Will Johnson, Nayna Khalatkar, Ryan Large, and Geoff Clark, and the planning and implementation support of Kazia Milian, Steve Voros, David Tellier, Elizabeth Spang, and the partners and stakeholders that were engaged in both the Ecodistricts 6E–10/6E–11 and Ecodistrict 6E–15 NHS planning processes. Elizabeth Spang, Chris Lemieux and Lyn Thompson provided improvements to earlier versions of this manuscript.

Glossary of Acronyms

ANSI = Areas of Natural and Scientific Interest
CA = Conservation Authority
NHS = Natural Heritage System(s)
OMNR = Ontario Ministry of Natural Resources
ORM = Oak Ridges Moraine
PPS = Provincial Policy Statement
PSW = Provincially Significant Wetlands

References

Ardron, J.A., H.P. Possingham and C.J. Klein (eds.). 2010. Marxan good practices handbook, Version 2. Pacific Marine Analysis and Research Association, Victoria, BC. 165 p.

Ball, I.R. and H.P. Possingham. 2000. (V1.8.2): Marine Reserve Design Using Spatially Explicit Annealing, a Manual.

Ball, I.R., H.P. Possingham and M.E. Watts. 2009. Marxan and relatives: Software for spatial conservation prioritization. *In* A. Moilanen, K.A. Wilson and H.P. Possingham (eds.). Spatial conservation prioritization. Quantitative methods and computational tools. pp. 185–195. Oxford University Press, UK. 320 p.

Burke, D.M. and E. Nol. 2000. Landscape and fragment size effects on reproductive success of forest-breeding birds in Ontario. Ecological Applications 10(6): 1749–1761.

Crins, W.J. 2002. The Ecozones, Ecoregions, and Ecodistricts of Ontario. (Map) Prepared for the Ecological Land Classification Working Group.

Crins, W.J., P.A. Gray, W.C. Uhlig and M.C. Wester. 2009. The ecosystems of Ontario, Part 1: Ecozones and Ecoregions. Inventory, Monitoring and Assessment Section, Ontario Ministry of Natural Resources, Peterborough, ON. Technical Report SIB TER IMA TR–01.

Ecological Stratification Working Group. 1996. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research, and Environment Canada, State of the Environment.

Environment Canada. 2004. How Much Habitat is Enough? A Framework for Guiding Rehabilitation in Great Lakes Areas of Concern. 2nd Edition. 80 p.

Ewert, D.N., G.J. Soulliere, R.D. MacLeod, M.C. Shieldcastle, P.G. Rodewald, E. Fujimura, J. Shieldcastle and R.J. Gates. 2006. Migratory Bird Stopover Site Attributes in the Western Lake Erie Basin. Final report to The George Gund Foundation.

Fábos, J.G. 2004. Greenway planning in the United States: its origins and recent case studies. Landscape and Urban Planning 68 (2–3): 321–342.

Fábos, J.G. and J. Ahern (eds.). 1995. Greenways: the Beginning of an International Movement. Elsevier Publications, Amsterdam. 491 p.

Fábos, J.G. and R.L. Ryan. 2006. An introduction to greenway planning around the world. Landscape and Urban Planning 76 (1–4): 1–6.

Game, E.T. and H.S. Grantham. 2008. Marxan User Manual: For Marxan version 1.8.10. University of Queensland, St. Lucia, Queensland, Australia, and Pacific Marine Analysis and Research Association, Vancouver, BC.

Gray, P., D. Paleczny, R.J. Davidson, T. Beechey, B. King, S. Janetos, S.B. Feilders, M. Wester and R.G. Davis. 2008. Ontario's Natural Heritage Areas: Their Description and Relationship to the IUCN Protected Areas Classification System. OMNR. 383 p.

Henson, B.L., K.E. Brodribb and J.L. Riley. 2005. Great Lakes Conservation Blueprint for Terrestrial Biodiversity, Vol. 1. Nature Conservancy of Canada and Ontario Ministry of Natural Resources. 157 p.

Hills, G.A. 1959. A Ready Reference to the Description of the Land of Ontario and its Productivity. Preliminary Report. Division of Research, Ontario Department of Lands and Forests, Maple, ON. 142 p.

Hills, G.A. 1976. An Integrated Iterative Holistic Approach to Ecosystem Classification. *In* J. Thie and G. Ironside (eds.). Ecological (Biophysical) Land Classification in Canada: Proceedings of the First Meeting of the Canada Committee on Ecological (Biophysical) Land Classification, Petawawa, Ontario, 25–28 May 1976. pp. 73–97.
Howard, P.C., P. Viskanic and F.W. Kigenyi. 1999. Biodiversity assessment for conservation planning in Uganda's forests. Journal of East African Natural History 88(1): 59–67.
Jalava, J.V., J.L. Riley, D.G. Cuddy and W.J. Crins. 1997. Natural heritage resources of Ontario: revised site districts in ecological site regions 6E and 7E. Draft. Natural Heritage Information Centre, Ontario Ministry of Natural Resources, Peterborough, ON. 17 p.
Jalava, J.V., P.J. Sorrill, J. Henson and K. Brodribb. 2002. The Big Picture Project: Developing a Natural Heritage Vision for Canada's Southernmost Ecological Region. Available at http://www.carolinian.org/ConservationPrograms_BigPictureMethodology2.htm.
Jongman, R.H.G., M. Külvik and I. Kristiansen, 2004. European ecological networks and greenway. Landscape and Urban Planning 68 (2–3): 305–319.
Jongman, R.H.G. and G. Pungetti (eds.). 2004. Ecological Networks and Greenways: Concept, design, implementation. Cambridge University Press. 344 p.
Kushneriuk, R.S. and R.S. Rempel. 2004. Landscape scripting language. Centre for Northern Forest Ecosystem Research, Ontario Ministry of Natural Resources, Thunder Bay, ON.
Lee, H.T., W.D. Bakowsky, J. Riley, J. Bowles, M. Puddister, P. Uhlig and S. McMurray. 1998. Ecological Land Classification for Southern Ontario: First Approximation and Its Application. South Central Science Section, Science Development and Transfer Branch, Ontario Ministry of Natural Resources. SCSS Field Guide FG-02.
Margules, C.R. and R. Pressey. 2000. Systematic conservation planning. Nature 405: 243–253.
Margules, C.R. and S. Sarkar. 2007. Systematic Conservation Planning. Cambridge University Press, New York.
Moilanen, A., K.A. Wilson and H. Possingham. 2009. Spatial Conservation Prioritization: Quantitative Methods and Computational Tools. 320 p.
Moss, M.R. and B.W. Okey. 2004. A landscape-ecological appraisal of the diversity and relevance of cultural landscapes. *In* R.H.G. Jongman (ed.). Volume 4: The New Dimensions of the European Landscapes . pp. 219–235. Springer, Dordrecht, Netherlands.
Omernik, J.M. and R.G. Bailey. 1997. Distinguishing between watersheds and ecoregions. Journal of the American Water Resources Association 33(5): 935–949.
[OMMAH] Ontario Ministry of Municipal Affairs and Housing. 1997. Provincial Policy Statement. Revised February 1, 1997. Queen's Printer. Toronto, ON. 18 p.
_____. 2005. Provincial Policy Statement. March 1, 2005, Queen's Printer for Ontario. 42 p.
[OMNR] Ontario Ministry of Natural Resources. 1986. Evergreen Challenge: The Agreement Forest Story. Toronto, ON. 60 p.
_____. 1991. A Natural Heritage Framework: A Strategy for the Protection and Management of Natural Heritage in the Greater Toronto Area. November 1991. Greater Toronto Area Branch, Discussion Paper 1. 45 p.
_____. 2000. Significant wildlife habitat technical guide. 151 p.
_____. 2005. Protecting what sustains us – Ontario's Biodiversity Strategy. Queen's Printer, Toronto, ON. 44 p.
_____. 2010. Natural Heritage Reference Manual for Natural Heritage Policies of the Provincial Policy Statement, 2005 Second Edition. 227 p.
[ORMF] Oak Ridges Moraine Foundation. 2005. Oak Ridges Moraine Foundation Stewardship Strategy. 6 p. Available at http://www.moraineforlife.org/about/documents/ORMFStwardship.pdf.
Pressey, R.L., C.J. Humphries, C.R. Margules, R.I. Vane-Wright and P.H. Williams. 1993. Beyond Opportunism: Key Principles for Systematic Reserve Selection. Trends in Ecology & Evolution 8(4): 124–128.
Puric-Mladenovic, D. 2003. Predictive vegetation modeling for forest conservation and management in settled landscapes. Ph.D. Thesis. Faculty of Forestry, University of Toronto. 281 + 112.
Puric-Mladenovic, D. and S. Strobl. 2006. Delineating conservation areas on the Oak Ridges Moraine using a systematic conservation planning approach. The Forestry Chronicle 82(3): 395–402.
Riley, J.L. and P. Mohr. 1994. The natural heritage of southern Ontario's settled landscapes. Ontario Ministry of Natural Resources, Southern Region. 78 p.
Rowe, J.S. 1972. Forest Regions of Canada. Canadian Forestry Service Publication No. 1300, Dep. Environ Department of Environment, Ottawa. 172 p.
Spang, L., C. Lemieux, and S. Strobl. 2012. Stakeholder Engagement: A foundation for natural heritage systems (NHS) identification and conservation in southern Ontario. The Forestry Chronicle 88(6): 686–696.
Wichert, G.A., K.E. Brodribb, B.L. Henson and C. Phair. 2005. Great Lakes Conservation blueprint for Aquatic Biodiverstiy, Volume 1. Nature Conservancy of Canada. 86 p.
Wiken, E.B., D. Gauthier, I. Marshall, K. Lawton and H. Hirvonen. 1996. A Perspective on Canada's Ecosystems: An Overview of the Terrestrial and Marine Ecozones.
Wilson, K.A., M. Cabeza and C.J. Klein. 2009. Fundamental Concepts of Spatial Conservation Prioritization. *In* A. Moilanen, K. A. Wilson and H. P. Possingham (eds.). Spatial conservation prioritization. Quantitative methods & computational tools. pp. 16–26. Oxford University Press, UK. 320 p.