Green and brown infrastructures support a landscape-level implementation of ecological engineering

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ARTICLE INFO

Keywords:
Brown infrastructure
Buffer zones
Constructed wetlands
Ecological network
Ecosystem services
Green infrastructure
Landscape planning
Land-use conflict

ABSTRACT

The green infrastructure (GI) is a network of natural and semi-natural areas with environmental features that is designed and managed to deliver a wide range of ecosystem services. The concept has roots in the former hierarchical system of ecological networks. There are several examples of GIs, but details of their implementation at a landscape level are often missing or they have been used non-systematically. Here, we demonstrate opportunities for landscape-level implementation of GIs based on spatial analysis through the application of ecological engineering or other measures. Using maps and expert evaluations of different land-use types, we created a methodology for national-scale determination of Estonia’s GI. Based on spatially explicit datasets (e.g., land cover, soils, topography, roads), we determined the proportions of greenness and brownness (primarily anthropogenic) landscape indices. Areas with the highest greenness values served as the GI’s core areas, whereas areas with the greatest anthropogenic composition represented the brown infrastructure. Identification and classification of hotspots where the two infrastructures are in conflict (e.g., construction, mining areas, roads, settlements, airports, power lines, wind turbines) revealed locations where ecological engineering and other measures are needed to mitigate or eliminate the conflict. Developing spatially explicit models of the conflicts between the infrastructures represents a new approach in landscape planning and environmental management that links coarse-scale landscape planning and regional landscape plans with more detailed local landscape plans that support the design of site-specific ecological engineering and other measures. We demonstrate that the implementation of GIs is inseparably connected with ecological engineering and landscape-scale planning.

1. Introduction

1.1. Historical background

In recent decades, the concept of a green infrastructure (GI, the network of natural and semi-natural components of a landscape) has become increasingly important in environmental planning and management, both internationally (UNEP, 2014) and at a national level in the development of policy agendas (e.g., in France, Grenelle Environment, 2010; in the UK, DCLG, 2012; in the United States, EPA, 2014). However, the early development of this idea can be traced back to the ecological networks described in the theories of Heinrich von Thünen, Walter Christaller, and Edgar Kant. Von Thünen (1826) proposed the first conceptual scheme for the optimization of land-use patterns in agricultural landscapes. Christaller (1933) introduced the theory of central places, then enlarged the concept to the whole region, and Estonian geographer Edgar Kant (1935) implemented it for the first time at a national level (Tammiksaar et al., 2018). The next major step was by Russian geographer Rodoman (1974), whose theory of polarized landscapes showed the role of the network of natural and semi-natural land uses as a counterbalance to human-engineered infrastructure. In the second half of the last century, landscape planning practices in several European countries incorporated elements of nature conservation and environmental management (Haber, 1973; Olschowy, 1981; Sukopp and Weiler, 1988; Prendergast et al., 1993). Specific and detailed concepts, as well as national ecological network plans based on...
1.2. Current status of green infrastructures

The present environmental policies in Europe and the United States are based on the green infrastructure concept, and integrate the biodiversity targets from the ecological network concept, but also emphasize other ecosystem services. In Europe, green infrastructures are strategically planned networks of natural and semi-natural areas with environmental features that are designed and managed to deliver a wide range of ecosystem services. They incorporate green spaces (or “blue” spaces if aquatic ecosystems are also present) and other physical features in both terrestrial areas (including coastal, urban, and rural settings) and marine areas (EC, 2012; Davies and Lafortezza, 2017). The infrastructure is an interconnected network of green spaces that conserves natural ecosystem values and functions to provide associated benefits to human populations (Benedict and MacMahon, 2002, 2006). Maintaining the provision of ecosystem services through the development of green infrastructures is therefore increasingly recognized as a strategy to cope with changing future conditions. Thus, this represents a tool for providing ecological, economic, and social benefits through natural solutions, while also helping us to understand the benefits that nature offers to human society and helping to mobilize investments that sustain and enhance these benefits (EC, 2013; EEA, 2014). In the United States, green infrastructures include a strong component of stormwater management, especially in urban areas (EPA, 2010, 2014; Copeland, 2016). Often, the extensive man-made infrastructure (sometimes called “grey infrastructure”) only fulfills single functions such as drainage or transportation, whereas nature often provides multiple solutions that are also cheaper, more robust, and economically and socially more sustainable (EEA, 2014).

Green infrastructure can be also considered as a kind of counter-balance against the anthropogenic infrastructure – the human-engineered structures such as settlements, paved surfaces, roads, power lines, and mining areas. Because of their conceptual distance from natural systems, intensively managed agricultural fields can be...
considered to be part of the anthropogenic infrastructure. To provide a clear contrast with green infrastructures, we propose the term “brown infrastructure” to describe the anthropogenic infrastructure. Because brown infrastructure often damages or eliminates the biophysical processes necessary to sustain people, ecosystems, habitats, and livelihoods, it was traditionally considered to be in conflict with green infrastructures, which can compensate for the negative impacts of human activities in rural and urban areas (Ignatieva et al., 2011; Rolf et al., 2017). Intersection of the two infrastructures creates hotspots of environmental problems, where solutions such as the implementation of ecological engineering or other measures (e.g., hedgerows, buffer zones, constructed wetlands, wildlife corridors such as ecoducts) are needed (van Bohemen, 1998). However, there are increasing opportunities to combine the two infrastructures synergistically to achieve better results than either infrastructure could accomplish on its own. For instance, in water management, supplementing or integrating green infrastructure with biophysical systems is critical to meet current and future water needs (Palmer et al., 2015).

Green infrastructures play an important complementary role in the implementation of the EU’s biodiversity strategy, and have been influential in shaping the wider policy context of nature conservation in Europe. However, as shown by Garmendia et al. (2016),
implementation of a green infrastructure strategy without specific measures to account for biodiversity and environmental issues will not have a satisfactory result. Thus, a comprehensive concept for the implementation of green infrastructure strategies in combination with environmental management, landscape-scale (regional) planning, and ecological economics is needed.

Several studies have demonstrated the benefits of including ecological engineering principles in green infrastructures (Mitsch and Jørgensen, 2004; Jørgensen, 2009; Brüll et al., 2011), and vice versa, by using landscape ecology concepts for proper implementation of eco-technological or other measures (Forman and Godron, 1986; Jongman et al., 2004; Vymazal, 2011). However, a general integration of ecological engineering with green infrastructures has not yet been proposed.

Based on spatially explicit data from Estonia, we propose a new approach to the implementation of green infrastructures at a national scale based on an analysis of the conflicts between the green and brown infrastructures. In so doing, we highlight several conflict types that must be solved through ecological engineering or other measures. Here, we will focus on ecological engineering.

In the present study, our objectives were to:

- Create a methodology for determining the greenness and brownness of landscapes at a national level.
- Develop a methodology for creating maps of Estonia’s green and brown infrastructures based on the proportions of natural areas (green) and human-altered areas (brown) in the landscape.
- Identify and classify hotspots where conflicts occur between the green and brown infrastructures and where ecological engineering or other measures are needed.
- Provide a new concept for the relationships between green and brown infrastructures to support the implementation of ecological engineering or other measures at a landscape level.

2. Materials and methods

2.1. Initial datasets and preprocessing

Land use and land cover (LULC) data were obtained from the Estonian National Topographic Database (ENTD; 1:10,000; Estonian Land Board, 2006) in vector format. ENTD is the most detailed and accurate map for all of Estonia. It contains > 120 different feature classes. We used data from the Semi-Natural Habitats inventory (1:10,000) from 2014 to identify managed semi-natural habitats (e.g., wooded meadows, coastal grasslands). Each LULC was represented as polygonal features using version 10.4 of ArcMap (ESRI, 2018). In addition, we used the CORINE Land Cover 2012 database (CLC, 2012) to specify the land cover classification (Fig. 2). We used the Estonian Soil Map (1:10,000; Estonian Land Board, 2009) to specify forest types (Table 1). All final LULC types were assigned scores using expert knowledge. Table 1 summarizes the classification. The experts then assigned scores to each category based on its ecological value, which represented their assessment of the values for habitat diversity and for the ability to regulate nutrient (nitrogen and phosphorus) and carbon cycles. For each LULC, we multiplied its area by the score in Table 1 to define its net ecological value.

Nature conservation data was derived from the Database of Protected Areas of Estonia in the Estonian Nature Information System (Estonian Land Board, 2010). All types of protected areas defined by national legislation (Nature Conservation Act, 2004) and designated according to international conventions (e.g., Important Bird Areas identified by BirdLife International, Ramsar Convention sites, and Helsinki Commission (HELCOM) sites identified by the Baltic Marine Environment Protection Commission) or protected at a local administrative level were assigned scores according to their conservation status and protection goal (Table 2). Expert scores were again used to simultaneously amplify the effects of the spatial extent and conservation strictness of the conservation areas; in this case, the calculated value was the area raised to the power of the expert score (i.e., the score was used as an exponent).

We used soil taxonomic diversity map developed by Kikas et al. (2017). It is based on the Estonian Soil Map (1:10,000), which distinguishes 109 soil taxonomic units. Soil diversity was calculated using Simpson’s diversity index based on the number of soil taxonomic units and associations between taxonomic units within 1 km² (Kikas et al., 2017). Higher diversity was preferred at a landscape level, and received the highest score. Soil taxonomic diversity is an integral indicator of the potential natural biological and landscape diversity, but also partly reflects the LULC type and complexity of the topography, and shows additional potential for “greening” in human-influenced areas.

The total length of the elevation contour lines (at 2.5-m intervals) was derived from ENTD. The ENTD contour lines are generated by Estonian Land Board and are based on LiDAR data. The raw LiDAR data comprises approximately 550,000 points per 1 km², with about half of them being ground points (Estonian Land Board, 2013). We defined the relief complexity as the total length of the contour lines per km².

Linear patches of woody vegetation (hereafter, “hedgerows”) were identified from the ENTD database. We used spatial queries to identify all the hedges that were located next to or separated from water bodies. The lengths of these vegetation patches were calculated separately. Hedgerows can function as corridors for wildlife, locations for biodiversity, and as buffers that prevent material flows. Because of their importance for protecting water bodies against soil erosion, hedgerows beside bodies of water received a higher weight (6 points out of 10) than other hedgerows (4 points out of 10). These weights were then multiplied by the length of the hedgerows.

Water courses were also derived from the ENTD database. Rivers, streams, and ditches were identified as separate features, and their lengths per km² were calculated and used for the water course dataset. Water courses serve a regulation function for material flows and a corridor function at local and regional levels for the spread of species, protection of biological diversity, and maintenance of habitat heterogeneity. Different weights were used for watercourses based on their type: considering the habitat quality they provide, rivers and streams received a higher weight (7 points out of 10) than channels and ditches (3 points out of 10).

Road network data was derived from the ENTD database and the length of roads was calculated. This was expressed as the length (km) per 1 km².

Traffic intensity was obtained from the Estonian Road Administration (2017). The Estonian Road Administration collects data on the number of vehicles, their classes, and the traffic volumes using stationary and portable traffic counters. We used the number of vehicles per year to calculate the weight for each road.

Wind turbines with a rated capacity ≥ 100 kW or a maximum height ≥ 30 m were also identified. Wind turbine data was derived from the database of wind turbines of Estonia. Because the installed generating capacity per hectare in wind farms is nearly constant, we used the presence or absence of wind turbines per km² to represent their anthropogenic pressure.

High-voltage power lines (∼ 35 kV) were derived from the ENTD. We generated a 25-m-wide buffer around lines ranging from 35 to 110 kV and a 40-m-wide buffer around lines ranging from 220 to 330 kV, and calculated the area within these buffers.

We used the vector layer representing a regular grid of 1 × 1 km (1 km²) cell size (Remm, 2000) for intersecting all the datasets. When the vector layers are intersected with the grid, no data is lost, so it is not necessary to determine how to deal with mixed or partial pixels. All indicators were expressed per 1 km² to enable comparisons across the study area (Fig. 2).
Table 1

<table>
<thead>
<tr>
<th>CORINE land cover code</th>
<th>CORINE land cover type</th>
<th>Estonian National Topographic Database type</th>
<th>Estonian Soil Map</th>
<th>Score for the ecological value</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>Continuous urban fabric</td>
<td>Continuous urban fabric</td>
<td></td>
<td>-4</td>
</tr>
<tr>
<td>112</td>
<td>Discontinuous urban fabric</td>
<td>Yards</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>113</td>
<td>Industrial or commercial units</td>
<td>Industrial or commercial units</td>
<td></td>
<td>-5</td>
</tr>
<tr>
<td>114</td>
<td>Road and rail networks and associated land</td>
<td>Road and rail networks and associated land</td>
<td></td>
<td>-5</td>
</tr>
<tr>
<td>123</td>
<td>Port areas</td>
<td>Port areas</td>
<td></td>
<td>-5</td>
</tr>
<tr>
<td>124</td>
<td>Airports</td>
<td>Airports</td>
<td></td>
<td>-4</td>
</tr>
<tr>
<td>131</td>
<td>Mineral extraction sites</td>
<td>Peat extraction fields</td>
<td></td>
<td>-4</td>
</tr>
<tr>
<td>132</td>
<td>Dump sites</td>
<td>Dump sites</td>
<td></td>
<td>-3</td>
</tr>
<tr>
<td>133</td>
<td>Construction sites</td>
<td>Construction sites</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>141</td>
<td>Green urban areas</td>
<td>Green urban areas</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>142</td>
<td>Sport and leisure facilities</td>
<td>Urban forests, cemeteries</td>
<td></td>
<td>-2</td>
</tr>
</tbody>
</table>

Green infrastructure

- 211: Non-irrigated arable land
- 221: Fruit trees and berry plantations
- 231: Pastures
- 243: Land principally occupied by agriculture, with significant areas of natural vegetation
- 311: Broad-leaved forest
- 312: Coniferous forest
- 313: Mixed forest
- 321: Natural grasslands
- 322: Moors and heathland
- 324: Transitional woodland-shrub
- 333: Sparsely vegetated areas
- 411: Inland marshes
- 412: Peat bogs
- 421: Salt marshes
- 511: Water courses (streams and rivers)
- 512: Water bodies (ponds and lakes)
- 521: Coastal lagoons

Brown infrastructure

- 111: Continuous urban fabric
- 112: Discontinuous urban fabric
- 113: Industrial or commercial units
- 114: Road and rail networks and associated land
- 123: Port areas
- 124: Airports
- 131: Mineral extraction sites
- 132: Dump sites
- 133: Construction sites
- 141: Green urban areas
- 142: Sport and leisure facilities

To calculate the greenness index we combined the green LULC type \((\text{LULC}_g)\), nature conservation areas \((N)\), soil taxonomic diversity \((S)\), relief complexity \((R)\), hedgerow density \((H)\), and water course density \((W)\) map layers (Fig. 2, Eq. (1)). To calculate the brownness index we combined the brown LULC type \((\text{LULC}_b)\), road density \((RD)\), traffic intensity \((T)\), power line density \((PW)\), and wind turbine density \((WT)\) (Fig. 2, Eq. (2)). We used the Python Pandas software library (https://pandas.pydata.org/) to process the data tables and calculate the final greenness index and brownness index values.

\[
\text{Greenness index} = \text{LULC}_g + N + S + R + H + W \quad (1)
\]

\[
\text{Brownness index} = \text{LULC}_b + RD + T + PW + WT \quad (2)
\]

We created the conflict intensity map by subtracting the brownness index value for each cell in the grid from the corresponding greenness index value (Eq. (3)):

\[
\text{Conflict intensity} = \text{greenness index} - \text{brownness index} \quad (3)
\]

The conflict intensity has been divided into three classes: if the value of the conflict intensity is higher than the upper quartile, this represents intense conflict, whereas values between the median and the upper quartile represent moderate conflict and values below the median represent no significant conflict. We superimposed the conflict map on the GI map to reveal the most critical areas.

2.2. Calculation of greenness and brownness indices and conflict hotspots

Before combining all the input layers into maps of the two infrastructures, we normalized all the variables by splitting them into quantiles based on expert ratings of their relative importance (Table 3).
2.3. Creating the green infrastructure and brown infrastructure

We used the greenness and brownness indices to define the GI and BI. Areas with a greenness index higher than the upper quartile were defined as suitable for use as core areas. Areas with greenness index values between the median and the upper quartile were defined as suitable for buffer zones, and areas with values of the greenness index lower than the median were defined as not suitable for the GI. BI suitability was defined similarly. Areas with values of the brownness index higher than the upper quartile were defined as having a high human influence, whereas areas with a value between the median and the upper quartile had moderate human influence and areas with a value lower than the median had no significant human influence.

3. Results

3.1. Greenness index of Estonian landscapes

Based on our integration of the enhanced maps for CORINE land cover (forests, wetlands, coastal and riparian areas), soil taxonomic diversity, relief complexity, hedgerow density, and water course density, we created a map of the distribution of the greenness index throughout Estonia. The greenness index values, on a 100-point scale, were presented for each 1-km² cell in the gridded map (Fig. 3). The dark-green areas in this map represent core areas within the ecosystem network map. The lighter green areas represent various buffer zones and corridors between the core areas.

3.2. Brownness index of Estonian landscapes

Integration of the enhanced maps for CORINE land cover, road network density, traffic intensity, power line density, and the presence of wind turbines let us create a map of the distribution of the brownness index throughout Estonia. The 100-point scale for brownness index values were presented for each 1-km² cell in the gridded map (Fig. 4). Dark-brown areas represented the national capital area (Tallinn) in the north and other large towns, as well as mining and industrial areas in the northeast. Lighter brown colors indicate airports, various settlements, transport networks with intensive traffic, powerlines 35 kV, and wind farms. Somewhat surprisingly, the rural area south of Tartu (the second-largest town in the south) had strong brown tones (i.e., a high brownness index), despite being a relatively sparsely settled region. This is mainly due to the dense network of secondary roads and the large number of small settlements and dwellings in this area. Lighter brown areas represent intensively managed agricultural fields, small settlements, and various small mining areas.

3.3. Map of Estonia’s green infrastructure

Areas in Fig. 3 with greenness index > 60.2 (the upper 25% quartile) served as the core elements of the green infrastructure (GI), as they had the highest biodiversity and highest level of ecosystem services (Fig. 5). The light-green areas, with a greenness index between the median value of 47.4 and the upper 25% quartile (60.2) represented buffer zones and corridors between the core sites.

The synthetic map of Estonia’s GI coincides well with earlier maps based on the concept of ecological networks (Jagomägi, 1983; Remm et al., 2004) as well as with a legislative expert-knowledge-based but “hand-made” GI map of Estonia (Sepp and Kaasik, 2002). In all of these maps, several features were clearly distinguishable: (1) the “ecological axis” of Estonia, which Lippmaan (1935) called Estonia intermedia—an extensive zone of forests and wetlands reaching from the Gulf of Finland coast in the north to the southwestern border, dividing Estonia into a more maritime western part and a more continental eastern part; (2) large regions of forests and wetlands on the shores of Lake Peipsi; (3) forests and natural meadows in the western parts of the largest Estonian islands (Saaremaa and Hiiumaa); (4) large forested areas in the south and southeast of the country; and (5) forested and wetland areas in the western part of the country’s center.

3.4. Map of Estonia’s brown infrastructure

Areas of significant human influence indicated by darker brown, with a brownness index value > 52 (the top 25% quartile) represent core elements of the map of Estonia’s BI (Fig. 6). These are mainly towns, mining and industrial sites, and other areas with high anthropogenic pressure. The largest anthropogenic pressure (i.e., the maximum brownness index) appeared in the vicinity of towns (near Tallinn in the north and Tartu in the south) and along the northern coast, where much of Estonia’s industrial region is located. The roadside areas as well as small settlements, residential areas, and summer cottages in the southeast also had relatively high brownness index values (from 22 to 51), which we defined as moderate human influence. The relatively high brownness index values for the scattered dwellings in the southeast are likely to be due to the dense network of secondary roads that fragments the large semi-natural ecosystems in this area.

Table 3

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Content</th>
<th>Normalisation of layer value</th>
<th>Proportion (%) of the total greenness or brownness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green LULC per km² (LULC_g)</td>
<td>Expert scores (Table 1) multiplied by the LULC 1 km × 1 km unit area</td>
<td>100 points</td>
<td>Sum = 100</td>
</tr>
<tr>
<td>Nature conservation areas per km² (N)</td>
<td>Expert scores (Table 2) used as exponent (Area_upper/2) for nature conservation areas per km²</td>
<td>5-quantiles, 0...5 points</td>
<td>5</td>
</tr>
<tr>
<td>Soil taxonomic diversity per km² (S)</td>
<td>Simpson’s diversity index for soil taxons per km²</td>
<td>10-quantiles, 0...10 points</td>
<td>10</td>
</tr>
<tr>
<td>Relief complexity in km² (R)</td>
<td>Total length of elevation isolines per km²</td>
<td>5-quantiles, 0...5 points</td>
<td>5</td>
</tr>
<tr>
<td>Hedgerow density per km² (H)</td>
<td>Hedgerows from ENTD, density per km²</td>
<td>10-quantiles, 0...10 points</td>
<td>10</td>
</tr>
<tr>
<td>Water course density per km² (W)</td>
<td>Water courses from ENTD, density per km²</td>
<td>10-quantiles, 0...10 points</td>
<td>10</td>
</tr>
<tr>
<td>Brown LULC per km² (LULC_b)</td>
<td>Settlements (area)</td>
<td>100 points</td>
<td>Sum = 100</td>
</tr>
<tr>
<td>Road density per km² (RD)</td>
<td>Roads from ENTD, density per km²</td>
<td>60-quantiles, 0...60 points</td>
<td>60</td>
</tr>
<tr>
<td>Traffic intensity per km² (T)</td>
<td>Number of vehicles per year</td>
<td>15-quantiles, 0...15 points</td>
<td>15</td>
</tr>
<tr>
<td>Power line density per km² (PW)</td>
<td>Power lines from ENTD, density per km²</td>
<td>10-quantiles, 0...10 points</td>
<td>10</td>
</tr>
<tr>
<td>Wind turbine density (WT)</td>
<td>Presence of wind turbines (yes/no)</td>
<td>0 points if no wind turbine exists and 5 points if one or more wind turbines is present in the grid cell</td>
<td>5</td>
</tr>
</tbody>
</table>

28
3.5. Map of conflict hotspots

The conflict map generated based on the greenness and brownness index values (Fig. 7) shows high variation in the intensity of the conflict. The strongest conflicts appear in urbanized areas (the capital city of Tallinn on the northern coast, number 1 in the map; the second-largest town, Tartu, in the south, number 2 in the map; and the town of Pärnu on the southwestern coast, number 4 in the map), but the intensity was

Fig. 3. The distribution of the greenness index for Estonia. Values were calculated from enhanced CORINE land cover maps (forests, pastures, wetlands, coastal and riparian areas), the soil taxonomic diversity map, the relief complexity map, the hedgerow density map, and the water course density map (see the text for details).

Fig. 4. The distribution of the brownness index for Estonia. Values were calculated from the enhanced CORINE land cover map (built-up areas, mining areas, airports), road network density, traffic intensity, power line density, and presence of wind turbines (see the text for details).
also high in the scattered settlement areas in the southeast. The latter finding is somewhat surprising because the southeastern part of Estonia, and especially the three moraine–hilly areas in Karula National Park and the Otepää and Haanja nature parks, are the largest landscape protection areas in Estonia because of their high scenic value and recreational potential. The main anthropogenic pressures in this region relate to the well-developed and dense network of roads, a re-intensification of agricultural production, intensification of forest harvesting, and a growing number of small residential areas and summer cottages. These factors are all leading to landscape fragmentation and creating a pollution load on the region’s aquatic ecosystems and groundwater. Similar phenomena and conflicts appear in the rural landscapes of the suburbs Viljandi (number 3 in the map) and Rakvere (number 5 in the map).

Overlapping the map of conflict hotspots between Estonia’s green and brown infrastructures and the GI map reveals priority sites for the implementation of ecological engineering or other measures (Fig. 8). This map is useful for more thorough landscape planning and the application of ecological engineering or other measures to reduce the BI’s adverse impacts on the GI. The most severe conflicts are in the north and in northeastern Estonia (example areas A, B, and C in the map), with a scattered pattern of high conflict combined with high nature values in southeastern Estonia (example area D in the map) and the two large islands.

### 3.6. Examples of ecological engineering solutions in areas of intense conflict

To demonstrate possible mitigation solutions, we chose four conflict hotspots from Fig. 8 for which ecological engineering solutions are recommended. Fig. 9 shows local-scale details of these hotspots.

These four areas of conflict can be described as follows:

In area A, we can see intense conflicts between intensive sub-urbanization, traffic intensification, and development of a road network with a missing green belt around large towns and coastal zones for this example, on the Viimsi peninsula in the suburbs of Tallinn (Fig. 9A). To reduce this conflict, a system of green areas, hedgerows, artificial wetlands, and a coastal buffer zone should be established or restored to guarantee connectivity among the ecologically important core areas.

In area B, we can see conflicts between roads and migration corridors (the Tallinn–Pärnu railroad, projected Rail Baltica area, and the Keila River area, and Rapla County in northern Estonia (Fig. 9B). Here, ecoducts or other migration aids must be created to restore connectivity for wildlife, and riparian buffer zones should be maintained, managed, or re-established.

In area C, we can see conflicts between mining areas (the Oru peat extraction area and the Sirgala oil shale open-pit mining area) and surrounding natural ecosystems such as raised bogs, a kame landscape with lakes and boreal coniferous forests (the Kurtna kame field, Ida–Viru County in northeastern Estonia; Fig. 9C). Restoration of the peat extraction areas and open-pit mining areas must be done, and management of the restored open-pit mining area (in the upper northern corner of Fig. 9C) should be implemented, along with maintenance of a buffer zone between the protected kame field landscape and the mining complex.

In area D, we see conflicts between rural settlements and intensive agricultural areas and bodies of water and groundwater in the Valgjärv parish within the Otepää heights moraine–hilly landscape in southern Estonia’s Valga County (Fig. 9D). The establishment of constructed wetlands and riparian buffer zones, and maintenance of the mosaic landscape pattern and the corridors connecting core areas, is
Fig. 6. The map of Estonia’s brown infrastructure (BI) based on values of the brownness index in Fig. 4. Areas with a brownness index value < 22 (the median) were defined as not part of the BI, whereas areas with a value of 22–51 (the top 25% quartile) were defined as having moderate human influence and areas with a value > 51 were defined as having significant human influence. Note the polarized distribution of anthropogenic pressures: the main centers are in the capital city of Tallinn in the northwest (number 1 in the map) and its suburbs, and in the southeast, around the towns of Tartu (2 in the map) and Viljandi (3 in the map).

Fig. 7. The synthetic map of the distribution of the GI vs BI conflicts (= the greenness index minus the brownness index) in Estonia. The greatest conflict intensity appear in urbanized areas such as the capital city of Tallinn (number 1 in the map) on the northern coast, the second-largest town of Tartu (number 2 in the map) in the south, and the town of Pärnu (number 4 in the map) on the southwestern coast, but there are also scattered settlement areas with high conflict values in the southeast. Similarly, conflicts appear along the network of main roads (black lines).
4. Discussion

4.1. The green infrastructure can guide landscape-level ecological engineering

The idea of integrating ecological engineering with the GI has been proposed previously (Mitsch and Jørgensen, 2004; Jørgensen, 2009; Brüll et al., 2011). Likewise, several works in landscape ecology proposed similar approaches for the implementation of detailed measures for biodiversity protection and landscape management in a traditional ecological engineering context (Forman and Godron, 1986; Jongman et al., 2004; Opdam et al., 2006; Weber et al., 2008). However, none of this previous work provided a spatially explicit distribution of the GI based on expert-assigned weights for each land use, or combined this index with quantification of the brown infrastructure to allow calculation of the difference between the greenness and brownness indices (i.e., the magnitude of the conflict between the two infrastructures).

Global warming complicates such efforts because it will change the underlying constraints on ecosystem health. For example, severe changes in hydrological regimes of various catchments have been predicted, with serious impacts in some parts of the world. There will also be related effects that are the consequences of these changes. Together with increasing anthropogenic pressure (intensive land use, fertilization, and pesticide use), changes in hydrological regimes driven by global warming will significantly alter the carbon (C) and nitrogen (N) cycles in agricultural landscapes, creating potential threats to water quality (Verhoeven et al., 2006).

In rural areas, watershed (catchment) planning and ecological engineering or other measures can be used to create an optimal pattern for the green infrastructure that will buffer ecosystems against such changes; this will include the creation of artificial wetlands and riparian buffer zones (Kuusemets and Mander, 1999; Kikas et al., 2017). In combination with carefully chosen agricultural technology that reduces the conflict with nature, this green infrastructure will help stakeholders to mitigate the hydrological alterations and the resulting changes in C and N cycling by minimizing N leaching and runoff, while maximizing C sequestration and minimizing emission of greenhouse gases in the landscape (Mander and Uuemaa, 2017; Tournebize et al., 2017). In future research, expert assessment of the weights of these functions and services can be used to adjust the weights used for each of the LULC types in our analysis. Vymazal (2011) highlighted the landscape-level importance of various wetland functions (hydrological, biogeochemical, and ecological) and ecosystem services (provisioning, regulating, cultural, and supporting services). For example, establishment of riparian forests in area A of Figs. 8 and 9 could simultaneously help regulate flooding and reduce soil erosion, provide habitats for various species, and act as a barrier to wind and noise.

Rey et al. (2015) showed that integrating ecological engineering with ecological intensification (i.e., organic agriculture) based on improved management practices and ecosystem services within a framework that can be broadly applied can help researchers, project designers, and managers improve their assessments of the links between practices, ecosystem structure and functions, and (ultimately) ecosystem services. This, in turn, will foster improved meta-analyses, cost-benefit analyses, and life-cycle analyses and the associated evaluations of ecosystem management approaches, and will encourage planners to establish ecosystem management specifications that are adapted to their specific management area and objectives.

Simultaneously, taking advantage of the multifunctionality of the GI and the need to improve our use of all ecosystem services (e.g., provisioning by biomass production, regulating by protecting water quality and mitigating greenhouse gases, habitat improvement, and cultural
services) will help landscapes to adapt better to climate change. Such a framework represents a context in which extant and new research can be placed.

Although we have focused on ecological engineering measures in the present paper, we also note that other measures (e.g., legislation to control land-use changes, education of the public about more sustainable behavior) could be added to our framework. This would require the participation of professionals from other areas of expertise, such as policy development and knowledge transfer. In doing so, it will form the basis for a new and interdisciplinary research agenda.

During the optimization of both ecological and economic factors, Liu et al. (2016) selected the most cost-efficient green infrastructure practices to reduce runoff and nonpoint source pollutants. Likewise, Kruusmets and Mander (1999) showed that ecotechnological measures such as riparian buffer zones and constructed wetlands for treating polluted water can significantly decrease nutrient runoff from small catchments. In urban areas, implementation of ecological engineering or other measures to improve the GI will help cities to adapt to climate change (Grimm et al., 2000; Gill et al., 2007; Pataki et al., 2011). For instance, Johnson et al. (2014) found that stormwater control measures can be based on a form of green infrastructure, and that integrating them with restored and degraded urban stream networks significantly decreased total dissolved nitrogen concentrations in the water. Pennino et al. (2016) found that urbanized watersheds could achieve improved stormwater management by improving the capacity of the GI to handle urban runoff. A system of rain gardens, detention ponds, bioswales, riparian wetlands, and green roofs reduced exports of NO$_3^-$ by 44% and total nitrogen by 48% compared to watersheds with minimal GI. Tzoulas et al. (2007) noted that the conceptual GI framework accounts for many dynamic factors, and their complex interactions, that affect ecosystem health and human health in urban areas.

Costanza et al. (2006) demonstrated that the integration of ecological engineering with ecological economics and the GI concept could avoid or greatly mitigate the devastating results of Katrina-like hurricanes in New Orleans and the Mississippi delta. More generally, coastlines can be protected by conserving coastal sand dunes, mangrove swamps, salt marshes, and coral or oyster reefs. The loss of these buffers can be irreversible without impractically large investments in restoration, and this has led to increasingly wide use of built structures, soft engineering, ecological restoration, and combined approaches (Palmer et al. 2015).

### 4.2. Integration of green infrastructures with landscape planning concepts

Our approach is consistent with the landscape planning concept. However, although the value judgments used to calculate the greenness and brownness indices are based on expert opinion, the more important point is that our approach is based on spatial analysis to support spatially explicit delineation of the areas with the most severe conflicts. This is similar to the approach of Meyer and Grabau (2008). They stressed that an integrative planning framework based on spatial analysis can solve conflicts among multiple functions at a landscape level, and that together with ecological engineering or other measures, it can reduce anthropogenic pressures on nature. Bastian and Schreiber (1999) proposed seven main steps in comprehensive landscape planning:

1. Definition of the problem (determination of the planning context, priorities, and prerequisites).
2. Inventory, analysis, and diagnosis (determination of the potential...
ecosystem services and natural constraints).
3. Planning of the concept (elaboration of objectives for protection of nature and landscape management alternatives).
4. Action plan (definition of requirements and measures necessary to achieve those objectives).
5. Product generation: a landscape planning program, regional landscape plan, landscape plan, and open-space master plan.
6. Implementation (the realization of planning measures through various organizations and authorities).
7. Review (evaluation of the implementation, whether it met the planning objectives, any necessary alterations).

Landscape analysis is similar to the methodology of green infrastructure elaboration discussed in the present paper, as it involves the evaluation of landscape elements, their spatial pattern, and their temporal trends, as well as evaluation of the dynamics of the landscape and land-use patterns. It is supported by landscape diagnosis to compare the landscape’s potential with social requirements for the landscape (Bastian and Schreiber, 1999). By conducting this comprehensive, multilevel hierarchical analysis of the landscape system, researchers, planners, and managers can elaborate a landscape program, regional landscape plan, landscape plan, and open-space master plan. Identifying conflict hotspots where it will be necessary to implement ecological engineering or other measures, based on the analysis of conflicts between the green and brown infrastructures, can create a bridge between the general landscape program (i.e., regional landscape plans) and more detailed landscape plans (e.g., the open-space master plan). The methodology that we have proposed will reveal valuable natural and semi-natural components of the GI and problematic areas where this infrastructure conflicts with the BI, revealing a need for ecological engineering or other measures to mitigate or eliminate the problem.

In this paper, we demonstrated for the first time that both the GI and the BI are important components of landscape management, and that the conflicts between the two infrastructures serve as an important link between landscape-level planning and ecological engineering.

5. Conclusions

Based on spatially explicit analysis of Estonia’s green and brown infrastructures, we developed a methodology for identifying conflict hotspots between the two. For the first time, we combined greenness and brownness indices to quantify the strengths of these conflicts. Using the two indices, we produced maps of the conflict between the two infrastructures to support landscape-level planning and environmental management, thereby linking coarse-scale landscape planning programs with more detailed local-scale landscape plans.

By identifying hotspots where conflicts between the two infrastructures arise, it becomes possible to identify where ecological engineering or other measures should be implemented to mitigate or eliminate the conflict. Our study of Estonia revealed examples of conflicts between the valuable natural areas, which support biodiversity and regulate the provision of ecosystem services, and the areas most severely influenced by human activities (mining areas, roads, intensive agriculture, and settlements). Ecological engineering include the construction of buffer ecosystems, such as wetlands that are capable of capturing and treating wastewater, agricultural runoff, and stormwater; the construction of ecoducts and other wildlife migration corridors; the development of areas of organic agriculture (ecological intensification); and restoration of mining areas. Other measures that are alternatives to engineering solutions can be considered, such as conducting knowledge transfer initiatives to improve awareness of residents of an area where conflicts exist so they can adopt alternative solutions such as organic agriculture that would reduce the magnitude of the conflict.

Our results suggest that green infrastructures cannot be separated from ecological engineering and landscape planning, and that they must be considered simultaneously with the brown infrastructure to focus efforts on the most important problems. Our proposed methodology can be applied anywhere that the necessary spatially explicit data is available.

Acknowledgments

This study was supported by the Estonian Research Council (grant no. IUT2-16 and IUT21-1), by the EU through the European Regional Development Fund (Centres of Excellence ENVIRON and EcolChange), by the Marie Skłodowska-Curie Actions individual fellowships offered by the Research Executive Agency Horizon 2020 Programme (grant agreement number 660391), and by the Ernst Jaakson stipend from the University of Tartu Foundation.

References

EC, 2013. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Green Infrastructure (GI) — Enhancing Europe’s Natural Capital’ (COM/2013) 249 final (5 June 2013). European Commission, Brussels.
Estonian Land Board Nature Information System information page Available at:http://loodus.keskkonnainfo.ee/eelis/default.aspx?state=1;-164545161;est;eelisand;;&
Estonian Land Board Estonian Soil Map Available at: http://geoportaal.maaamet.ee/docs/ETAK/ENTD_overview.pdf?t=02.03.2018.
Estonian Land Board Soil Information System Available at: http://loodus.kskkonnaminfo.ee/eels/default.aspx?state=1;164545161;est;eelisand;&
Estonian Land Board Elevation Data Available at: http://geoportaal.maaamet.ee/eng/Maps-and-Data/Topographic-Data/Elevation-data-p308.html accessed 02.03.2018.
Estonian Land Board Administration, 2017. Results of traffic density study 2016 (in Estonian) Available at: https://www.mnt.ee/sites/default/files/content-editors/Falld/ Liiklusloendus/2016/aruanne_2016.pdf (accessed 02.03.2018).
the role of the green infrastructure. Built Environ. 33 (1), 115–133.