DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS
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MERJE LESTA

Evaluation of regulation functions of rural landscapes for the optimal siting of treatment wetlands and mitigation of greenhouse gas emissions

TARTU UNIVERSITY
PRESS

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Author's contribution

Publication I: The author is partly responsible for data collection (about 50%), calculations (about 75%) and writing the manuscript (about 80%).
Publication II: The author collected the data (about 50%) and was responsible for data analysis (about 80%) and also writing the manuscript (about 90%).
Publication III: The author participated in calculations (about 10%) and map creation (about 10%).
Publication IV: The author participated in calculations (about 10%).

ABSTRACT

In order to implement sustainable landscape planning, it is essential to have knowledge of landscape ecology and landscape evaluation principles. Landscapes (or ecosystems) accomplish many different functions. In this PhD dissertation we have proposed a few landscape evaluation methods in the context of regulation functions (waste treatment, water regulation, gas regulation etc.) of rural landscapes. We also determined the strategic value of the results and their usage in landscape or political planning. In addition to the regulation functions of constructed wetlands, biomass production of broad-leaved cattail and standing stock of N and P in its phytomass were evaluated.

First we demonstrate a method of complex landscape analysis in order to estimate the landscape suitability for the construction of surface flow wetlands (SFW) for wastewater treatment. This is a multilevel suitability analysis from a more general regional (landscape) assessment based on a map of landscape types (1:100,000) toward a detailed analysis based on aerial orthophotos and detailed soil maps (1:10,000). The assessment scheme consists of landscape classification according to the physical–chemical properties of landscape factors (soil conditions, landforms, hydrogeology, expert decisions concerning landscape values, and suitability analysis). The partial suitability values of SFWs are derived by summarizing expert values for landscape factors (each ranging from –1 to +1). By multiplying the summarized partial suitability values with nature protection values (ranging from 0 to 1), we obtain the final suitability value for each landscape type. Any kind of nature protection area has been considered unsuitable and excluded from regional-level analysis. The results of the regional analysis demonstrate that suitability is relatively equally distributed over the study area. The high suitability potential (classified as "very suitable") is relatively evenly distributed in lowland regions throughout the country. The share of "very suitable" and "suitable" areas in different counties varies from 5 to 23% and 7 to 49% respectively. The detailed analysis based on aerial orthophotos showed that areas suitable for SFWs can also be found within areas determined to be unsuitable based on the less detailed map of landscape types, whereas differences are much greater between settlements chosen for the detailed suitability analysis.

Broadleaved cattail (*Typha latifolia L.*) biomass production and the nitrogen (N) and phosphorus (P) content in phytomass in three treatment wetland systems were also evaluated.

Suitable areas for treatment wetlands for raw material production in Estonia were proposed. The average aboveground biomass of *T. latifolia* varied from 0.37 to 1.76 kg DW m^{-2} in autumn and from 0.33 to 1.38 kg DW m^{-2} in winter. The greatest average nitrogen (22,950 mg N kg^{-1}) concentration was found in spadixes in 2002, and the phosphorus (6,500 mg P kg^{-1}) concentration was measured in roots–rhizomes in 2003. Average standing stock of nitrogen and phosphorus was higher in aboveground than belowground phytomass. In FWS

CWs with high hydraulic and nutrient loadings, however, the harvesting of aboveground biomass is not an effective means for the removal of nutrients. Cattail biomass is a valuable insulation material, whereas the fibre from spadixes mixed with clay gives elasticity to clay plasters. According to our estimates, about 5,412 km^2 could be used for *Typha* cultivation in Estonia.

The emission of greenhouse gases (GHG) methane (CH_4) and nitrous oxide (N_2O) is a well studied environmental phenomenon. There are, however, few estimates of fluxes at landscape level that could be useful for regional and local authorities to develop measures and land use policy and landscape management practices for the minimization of land-use-based GHG emissions. As part of the gas regulation function, CH_4 and N_2O emissions from the main land use types of rural landscapes were estimated using data from the literature. The data from more than 1100 study sites/experiments in the temperate and boreal zone published from the early 1980s to 2008 in 190 scientific papers indexed by the ISI Web of Science were taken into account. Based on that information, the emission potential of CH_4 and N_2O from rural landscapes in Estonia (total area 42,685 km^2) was assessed. Median values of CH_4 and N_2O fluxes from an analysis of the literature were multiplied with the total area of relevant areas' cover/use types. According to that, fens and transitional bogs are estimated to exchange CH_4 between the soil and atmosphere at a rate of 11,188 tons per year (this and all following calculations are based on median values from an analysis of the literature). This estimation is followed by deciduous forests on hydromorphic soils and raised/oligotrophic bogs on hydromorphic soils with CH_4 fluxes as high as 9,396 tons year $^{-1}$ and 6,558 tons year $^{-1}$ respectively. Surprisingly high values of CH_4 consumption ("–" flux) were found in mixed forests (–1,780 and –944 t CH_4 year^{-1} for hydromorphic and automorphic soils, respectively). Arable lands and grasslands showed a relatively low methane consumption capacity, ranging from –166 t CH_4 year^{-1} in arable lands on automorphic soils to –42 t CH_4 year^{-1} in grasslands on hydromorphic soils. The highest values for annual N_2O exchange were calculated for coniferous forests on hydromorphic soils (3,180 tons year^{-1}), mixed forests on hydromorphic soils, (2,411 tons year^{-1}), and intensively arable lands on hydromorphic soils (1,362 tons year^{-1}). These results are important in terms of the further involvement of land-use based greenhouse gas (GHG) emission values for the calculation of the global warming potential of rural landscapes and the estimation of carbon taxes.

Our methods for the evaluation of landscape regulation functions contribute to sustainable landscape planning and management and enable better implementation of principles for the multifunctional use of rural landscapes. The method for the optimal location of treatment wetlands has been successfully used in other parts of Europe, in particular for the assessment of regulation function for agricultural landscapes in Aragon, Spain.

The GIS-based assessment of landscape functions serves as a promising tool for landscape planning and management.

1. INTRODUCTION

1.1. Landscape evaluation for planning purposes

Sustainable approaches for landscape planning have become more important over the past decades. In order to implement sustainable landscape planning, it is essential to possess knowledge of landscape ecology and evaluation principles. Landscape evaluation based on numerous kinds of land use types on different scales and by various interest groups (land owners, ecologists, economists, the national government etc) is an extremely difficult task.

In order to reflect publications on the estimation of landscape evaluation for planning purposes, papers published in international peer-reviewed journals that are indexed by the Institute of Science Information (ISI) Web of Science from the years 1985 to 2009 were analyzed. The terms “landscape function(s)”, “landscape service(s)”, “landscape potential(s)”, “landscape evaluation”, “landscape assessment”, “landscape diagnosis” and “landscape analysis” were searched both as separate items and also in combination with the term “landscape planning”. These terms and combination of terms were to appear in the titles, abstracts and/or key words of papers searched to take them into account. Articles that were completely off topic were discounted.

Based on this analysis, the term “landscape analysis” received more records than any of the other terms, i.e. 303 in total. It was followed by “landscape function(s)” and “landscape assessment” that also appeared relatively frequently (140 and 107 records respectively). Much less were reflected terms like “landscape service(s)”, “landscape diagnosis” and “landscape potential(s)” (5, 6, 17 respectively), whereas “landscape evaluation” was recorded 65 times. The analysis also showed that the terms that appeared most frequently were also used more abundantly in publications since the late 90s, which refers to the higher number of articles containing the terms mentioned in recent years (Figure 1).

The same pattern of results can be obtained when these terms are searched in combination with the term “landscape planning”. Evidently, many fewer records are found, but the distribution among the terms is roughly the same (Figure 2). “Landscape function(s)” is most frequently used in combination with “landscape planning” in research articles written in recent years. Decidedly, the results of this literature overview analysis support the knowledge of an increasing need for research into the evaluation of landscape functions in order to support policy decisions, as this would play an important role in ensuring the sustainability of humans in the biosphere.

In order to make the decision-making process in future landscapes more effective, the use of ecological process knowledge should be successfully adapted in different steps of the planning cycle. In the first steps of the landscape planning cycle, the current situation of the planning area and its future goals for possible functions of the area should be compared. Clearly defined goals and quantitative measures are essential to assess the ecological functioning of the landscape *(Opdam et al., 2002)*.

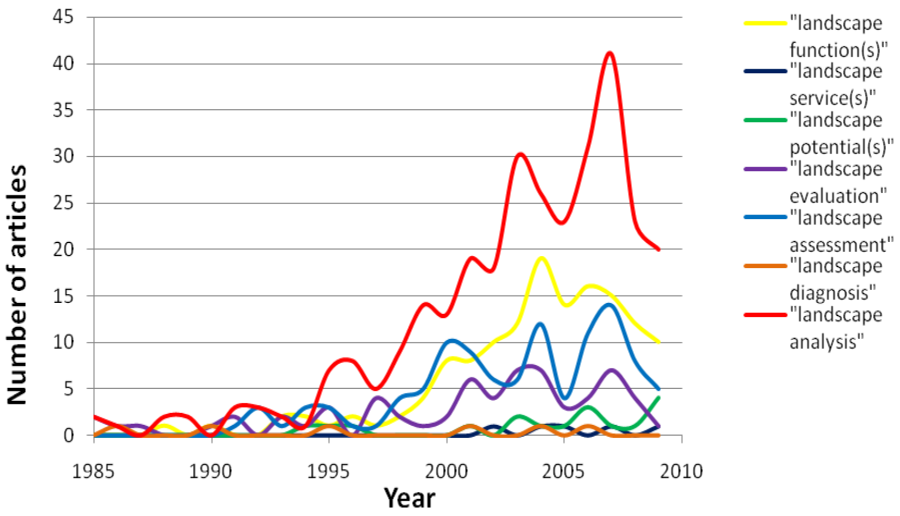

Figure 1. The number of articles published by year containing the terms "landscape function(s)", "landscape service(s)", "landscape potential(s)", "landscape evaluation", "landscape assessment", "landscape diagnosis" and "landscape analysis" in international peer-reviewed journals indexed by the Institute of Science Information (ISI) Web of Science from the year 1985 to 2009.

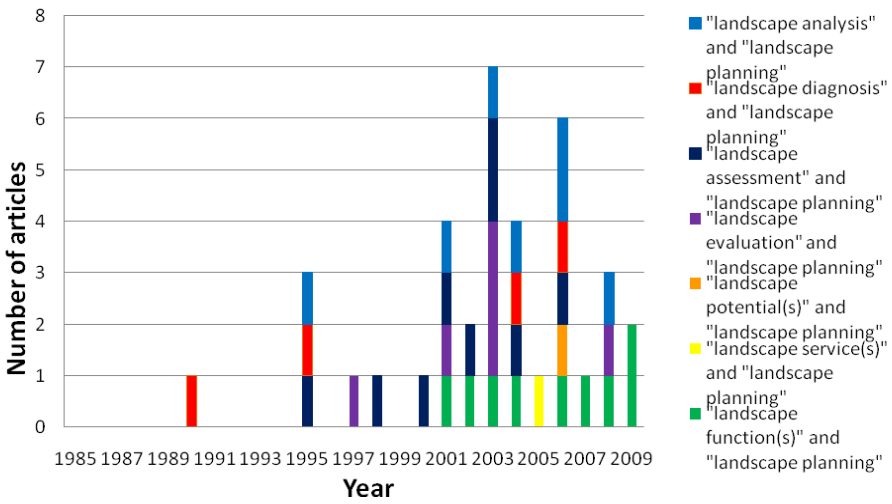

Figure 2. The number of articles published by year containing the terms "landscape function(s)", "landscape service(s)", "landscape potential(s)", "landscape evaluation", "landscape assessment", "landscape diagnosis" and "landscape analysis" in combination with the term "landscape planning" in international peer-reviewed journals indexed by the Institute of Science Information (ISI) Web of Science from the year 1985 to 2009.

1.2. Landscape functions

Landscapes (or ecosystems) accomplish many different functions. Although there has been much debate among scientists over the terms “functions”, “goods” and „services“ in the context of landscape (ecosystem) functions and services *(Millennium Ecosystem Assessment, 2005)*, one could define „landscape functions“ as „…the capacity of ecosystems to provide goods and services that satisfy human needs, directly or indirectly“ *(de Groot et al., 2002)*. In the *Millennium Ecosystem Assessment* (MEA)*(2005),* ecosystem services are defined as „the benefits people derive from ecosystems“, distinguishing the „functions“ as the actual process that provides those goods and services for society. Studies have, however, shown that the distinction between landscape functions and services is not always uncomplicated and clear *(de Groot and Hein, 2007)*. In order to be able to evaluate landscape functions, many different classifications have been compiled.

De Groot and Hein (2007) have determined four categories of landscape functions that can be applied at different scales, such as plot, ecosystem or landscape. These are provisioning functions, regulation functions, habitat functions and cultural and amenity functions.

(1) Provisioning functions are divided into two subcategories – production functions and carrier functions. *Production functions* reflect resources such as products from natural ecosystems (wood from natural forests, fish from the ocean, freshwater etc). *Carrier functions*, on the other hand, rely on goods and services that are available due to human manipulation of natural productivity (cultivation, energy conversion etc.) (2) Regulation functions provide direct benefits from ecosystem processes related to climate, biogeochemical cycles, earth surface processes and biological processes. Very often an important spatial aspect has to be taken into account with these services. (3) Habitat functions play an important role in the maintenance of biodiversity and evolutionary processes. Examples of goods and services for habitat functions are as a refugium for wildlife and also the nursery function. (4) Cultural and amenity functions refer to the non-material benefits that can be obtained from landscapes. These benefits may be gained through recreation, relaxation, cognitive development or spiritual reflection by actually visiting the area or enjoying the landscape indirectly. Indirect enjoyment could also be one’s satisfaction from the knowledge that the particular landscape or ecosystem carries historic, inspirational, scientific or educational value.

In addition to the classification described above, the *Millennium Ecosystem Assessment* (2005) also contains a category called „supporting services/ functions“ that reflect ecological processes (soil formation, nutrient cycling, primary production, etc) that are essential for ecosystems’ and landscapes’ functioning *(de Groot and Hein, 2007)*.

Another considerable classification of landscape functions has been developed by *Bastian and Schreiber* (1999). Detailed description is provided (Table 1).

Table 1. Landscape functions by Bastian and Schreiber (adapted from *Bastian and Schreiber, 1999*).

1) Production functions (economic functions)		
Availability of renewable resources		Availability of non-renewable resources
Biomass *Plant biomass* – *arable fields (husbandry)* – *permanent grassland* – *special crops* – *wood* *Animal biomass* – *game* – *edible fish*	Water – *surface water* – *ground water*	Mineral raw materials, building materials Fossil fuels

2) Regulation functions (ecological functions)			
Regulation of matter and energy flows			Regulation and regeneration of populations and biocoenoses
Pedological functions (soil)	Hydrological functions (water)	Meteorological functions (climate / air)	Biotic reproduction and regeneration
– *Soil protection against erosion* – *Soil protection against waterlogging* – *Soil protection against dehydration* – *Soil protection against compression* – *Decomposition of foreign matters (filtration, buffer and transformation function)*	– *Ground water recharge / infiltration* – *Water retention / discharge balance* – *Self-purification of surface water*	– *Temperature balance* – *Increasing air humidity / evaporation* – *Windfield influence*	– *Regulation of organism populations (e.g. pests)* – *Preserving the variety of species and life forms* – *Habitat function*

3) **Habitat functions (social functions)**			
Psychological functions	Information functions	Human-ecological functions	Recreational function
– *Esthetical function (scenery)* – *Ethical function (gene pool, historical landscape as cultural heritage)*	– *function for science and education* – *(bio-)indication for states of the environment*	– *bio-climatic (meteorological) impacts* – *filtration and buffer functions or chemical impacts (soil / water / air)* – *acoustic effects (noise protection)*	*As a complex of psychological and human-ecological functions*

Following the classifications by *de Groot and Hein (2007)* and *de Groot et al. (2002)*, landscape functions such as production (provisioning), regulation, habitat, cultural and amenity functions were searched as terms in combination with the term „landscape" and „landscape planning" within papers published in international peer-reviewed journals indexed by the ISI Web of Science from the years 1985 to 2009. These terms, in combination with „landscape planning", gave no results at all. The „provisioning function" and „production function" appeared more frequently than others, followed by the term „habitat function", which was also reflected in a number of articles. „Regulation function" and „cultural/amenity function" both occurred in two records. If one examines the results in two separate periods of time, from 1980 to 2000 and from 2001 to 2009, it is evident that more articles were published in the later period. Before the year 2000 the term „regulation function" did not appear in any published articles until two publications in recent years (Figure 3). This also shows that landscape functions are more often associated with research of habitat or the production function of ecosystems and landscapes. Less attention has been paid to the regulation function of landscapes that significantly benefits the sustainability of the Earth's ecosystems.

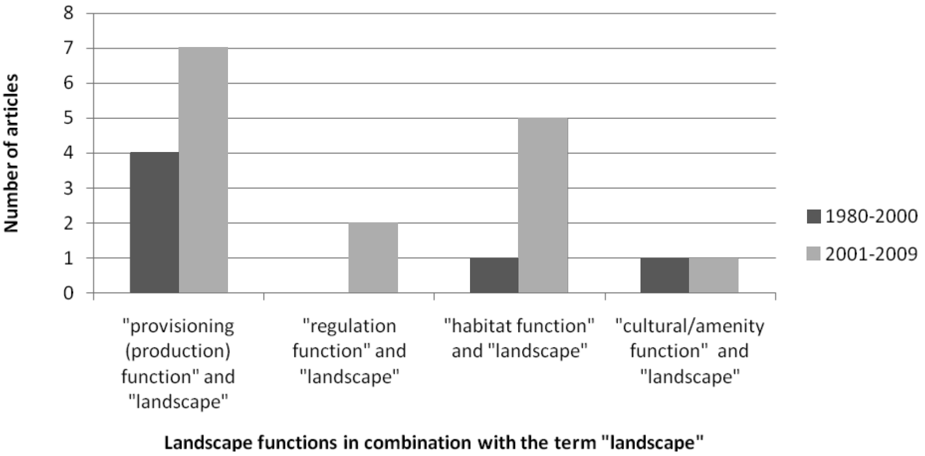

Figure 3. The number of articles in the periods 1980–2000 and 2001–2009 containing the terms "production (provisioning) function", "regulation function", "habitat function", "cultural/amenity function" in combination with the term "landscape" in international peer-reviewed journals indexed by the Institute of Science Information (ISI) Web of Science.

Landscape and ecosystem valuation through landscape functions and multi-functionality has therefore become more important in policy making in the last decade *(Willemen et al., 2008; Wiggering et al., 2006; Willemen et al., 2009)*. *Benayas et al., (2009)* have suggested that restoration actions consentrated on enhancing biodiversity in various landscapes should also support increased provision of ecosystem services. Because ecosystem services are very difficult to adequately quantify, especially in comparison with economic services, they have received too little attention in policy making in the past *(Costanza et al., 1997)*. However, the quantification and evaluation of landscape functions has been a topic of research for many scientists *(de Groot and Hein, 2007; Willemen et al., 2008; Bastian, 2000; Costanza, 1997)* in recent decades. Before economic valuation can take place, landscape functions need to be quantified using the most suitable indicators, some of which are described by *de Groot and Hein (2007)*.

Willemen et al., (2008) have presented three methods with which to map and quantify landscape functions, one of which is based on linking landscape functions to land cover or spatial policy data. The second method proposed by the authors is based on empirical predictions using spatial indicators, and the third considers decision rules based on literature reviews *(Willemen et al., 2008)*. It is also essential to consider spatial and temporal scales of ecosystem services, because landscapes can perform many different functions that could be spatially overlapping in the short-term or in the long-term. Furthermore, most landscape functions are executed at ecological scales that do not coincide with institutional scales (international, state, municipal, family etc).

Nevertheless, more precise landscape evaluation methods are needed for macro-, meso- and micro-scale landscape planning purposes.

1.3. Regulation functions of landscapes

Regulation functions are performed at different scales by semi-natural and natural ecosystems. These functions regulate essential ecological processes based on bio-geochemical cycles and other processes within the biosphere. Many direct and indirect benefits such as clean water, air and soil are provided to humans by regulation functions. In order to be able to benefit from these functions in the future, we need to make sure that these natural ecosystems and processes will continuously and consistently exist. It is unfortunate that the indirect benefits of regulation functions are often not detected until they are completely lost or disturbed to a great extent. The most important regulation functions are gas regulation, climate regulation, disturbance prevention, water regulation, water supply, soil retention, soil formation, nutrient cycling, waste treatment, pollination and biological control. Gas regulation is important for the chemical balance in the atmosphere and oceans upon which life on earth depends. Alterations in that balance may have considerable impacts (positive or negative) on natural, social and economic processes. The maintenance of clean air and the prevention of diseases are the main services provided by the gas regulation function. Climate regulation, on the other hand, is related to services that play an important role in maintaining a favourable climate on local and global scales. Preferential climate conditions are also important for crop productivity, recreation, cultural activities and especially human health. Some atmospheric gases have greenhouse properties and therefore gas regulation also contributes to climate regulation. The disturbance prevention function refers to ecosystems' abilities to „buffer“ natural hazards and devastating natural events such as droughts, storms or floods. The water regulation function differs from the previous disturbance prevention function in its capability to maintain „normal“ conditions in a watershed instead of preventing extremely disruptive natural events. Ecosystem services such as natural irrigation and drainage maintenance or the regulation of channel flow are a few examples of functions that regulate the derivation of water. The water supply function, which is basically the storage, filtering and retention of water, mainly in water bodies such as aquifers, streams and lakes, is also mentioned. The water supply function focuses primarily on storage capacity, and is thus dependent on the ecosystems' role in hydrological cycles.

Proper land evaluation procedure also demands to evaluate soil properties. Soil related regulation functions are soil retention and soil formation, first of which depends mainly on vegetation cover and root systems and being very important in a sense of maintaining terrestrial ecosystem, from human point of view mainly agricultural productivity. Surface roughness related processes of runoff and soil loss is studied by *Helming et al. (1998).* Landscape zoning at different levels and scales with different aims based on soil information is crucial for development of ecological economy and for special cases of land uses *(Mander et al., 2000)*.

Nutrient cycling is one of the functions upon which life on earth depends. It also contributes to gas-, climate- and water-regulation functions. One of the regulation functions that is more closely examined in this study is the waste treatment function of landscapes and ecosystems. To some extent, natural and semi-natural systems are capable of storing and recycling human waste. For example, wetlands and other similar systems are able to purify considerable amounts of organic wastes produced by humans and their activities. Pollination and biological control are also very important regulation functions related to the reproduction of plants and the prevention of the outbreak of pests and diseases that could be very harmful to humans *(de Groot et al., 2002 and de Groot, 2006)*.

1.4. Constructed wetlands mainly performing water-related regulation functions

Waste treatment (e.g. water purification), as one of the regulation functions mentioned by *de Groot et al. (2002)* and *de Groot and Hein (2007)*, can be performed by constructed wetlands (CW). In addition to water purification qualities, CWs can also provide certain extra benefits, for instance wildlife habitat functions and amenity functions (recreation, research, education) *(Rousseau et al., 2006)*. Cattails, which have a high reproductive potential, are very part of natural and constructed treatment wetland ecosystems *(Kadlec and Knight, 1996; Vymazal, 2007)*, and can therefore be used for raw material production (production function) *(Maddison et al., 2009; Paper III)*. An overview table of landscape functions related to CWs is presented (Table 2). There is some experience in Estonia in the use of cattail as a construction material. Cattail chips mixed with clay are used in the production of safe and cost-efficient building blocks *(Mauring, 2003)*. Free water surface (FWS) wetlands covered by cattails can also be considered to be valuable biotopes supporting biodiversity *(Lacki et al., 1991; Kadlec and Knight, 1996; Wild et al., 2001)*. In the context of global warming potential (GWP), CWs' emissions of green house gases (GHG) are considered to be relatively high, although their global influence is not significant *(Teiter and Mander, 2005).* Free water surface wetlands (FWSW) can have higher emissions of CH_4 and N_2O than sub-surface flow CWs *(Mander et al., 2003)*.

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Table 2. Typology of landscape functions and the role of CWs (partially adapted from *de Groot et al., 2002* and *Millennium Assessment, 2005*)

	Ecosystem (landscape) Functions		**Short Description**	**Constructed wetlands' goods and services**
1	**Provisioning Functions**	Production Functions	Resources from un-manipulated ecosystems	
		Carrier Functions	Use of space to (enhance) supply resources or other goods and services	Raw material production (Cattail for construction materials); aquaculture
2	**Regulation Functions**		Direct benefits from ecosystem processes	Waste treatment (e.g. water purification); Water regulation (storage, buffer); Gas regulation
3	**Habitat Functions**		Maintenance of biodiversity and evolutionary processes	Refugium for wildlife
4	**Cultural & Amenity Functions**		Non-material benefits	Eco-tourism; Recreation; Research & Education

The main output of constructed wetlands, however, is water pollution control. Constructed wetlands are divided into two main categories depending on the water flow type. There are surface-flow and subsurface-flow CWs. Surface-flow wetlands *(SFW; Kadlec and Knight, 1996)* are economically more attractive because their creation requires less capital than the subsurface-flow CW creation. Constructed wetlands are generally sited in local depressions of plains and uplands and definitely outside floodplains, in order to avoid damaging natural wetlands and other aquatic resources. In addition to the creation of new constructed wetlands, it is also possible to restore once degraded wetland systems. Restored wetlands can somewhat compensate the loss of wetland functions caused by human development activities. However, free water surface wetland (FWSW) creation depends on the availability of land that can support the creation of a wetland. Surface-flow wetlands (SFW) and free water surface wetlands (FWSW) are used as synonyms throughout this PhD thesis. The most important prerequisite is that underlying strata should be saturated with or impervious to water. It is also extremely important to consider the wetlands' role within the watershed and also within the broader context of the region's ecosystem. Constructed wetlands cannot impact surface waters or groundwater and also surrounding and upstream land uses. It is also important to consider the wetland's location in relation to wildlife corridors *(Guiding..., 1999; Kadlec and Knight, 1996)*.

Therefore wetland planning is quite a complex analytical task that should be performed in the context of broader watershed planning. Such an analysis could help planners and engineers to see potentials and also possible conflicts before they begin to design a single wetland. Based on trustworthy cartographic data, the reservation of areas of interest for water treatment purposes can be allowed. Thematic map data would also more easily support communication with other planning sectors, and would make the application of FWSW technology more efficient. Therefore geographic information systems (GIS) technology is widely used in connection with wetland management. Numerous studies have focused on the detection, classification and mapping of existing wetlands *(Rebelo et al., 2009; MacAlister and Mahaxay, 2009; Espinar and Serrano, 2009).* GIS technology is also applied for the evaluation of wetlands as described by *Reiss and Brown (2007),* and *Liu et al. (2006)*. GIS-based methods are also used for wetland restoration modelling (*White and Fennessy, 2005),* groundwater vulnerability assessment *(Pathak et al., 2009),* wetland conservation *(McCauley and Jenkins, 2005)* and many other purposes on different scales. In connection with the usage of GIS methods for various studies of landscape ecology and landscape analysis, scaling and data accuracy problems are discussed *(Chang and Kim, 2004)*. Various combinations of data and methods are used for landscape analysis. The semi-automated GIS approach for geomorphometric landscape analysis is described by *Klingseisen et al. (2008).* In addition to widely used vector data overlay GIS analysis for ecological studies, land-use management and planning, various newer methods are described by *Myint and Wang (2006)* and *Moreno et al. (2008)*, including cellular automata and Markov chain modelling.

The location, sizing and design parameters of constructed wetlands have been determined through a few investigations *(Scholz et al., 2007; Harrington et al., 2005; Trepel and Palmeri, 2002b)* concerning wetland influent characteristics and volumes of incoming waters along with local site conditions. There are also a few approaches to the suitability analysis of wetlands in the context of landscape functions *(McCartney and Houghton-Carr, 2009).*

1.5. Objectives

(1) To determine the proportion of suitable areas for SFW construction in Estonia (*Paper I, Mauring et al., 2003; Paper II, Lesta et al., 2007*).

(2) To ascertain what pattern is formed as a result of landscape analysis and how many actual wastewater sources fall close enough to the potential treatment site (e.g. how many practical hints can the analysis provide) (*Paper I, Mauring et al., 2003; Paper II, Lesta et al., 2007*).

(3) To determine the strategic value of the results and how the results can be used as a thematic layer in every landscape or in political planning (*Paper I, Mauring et al., 2003; Paper II, Lesta et al., 2007*).

(4) To evaluate the annual biomass production and to determine the standing stock of N and P in the phytomass of broad-leaved cattail (*Typha latifolia L.*) in FWS constructed wetlands and semi-natural treatment wetlands in Estonia. Based on the GIS analysis of various cartographic sources, to determine the location of suitable areas for treatment wetlands for raw material production (*Paper III, Maddison et al., 2009*).

(5) To estimate CH_4 and N_2O emissions from the main land use types of rural landscapes using data from the literature and, based on this information, to assess the emission potential of CH_4 and N_2O (gas regulation) from rural landscapes in Estonia (*Paper IV, Mander et al., submitted*).

2. MATERIALS AND METHODS

2.1. Estimation of landscape potential for construction of SFWs for wastewater treatment as one of the regulation functions of landscapes

2.1.1. Study area

For smaller scale analysis, at first only three counties of south-eastern Estonia with a total area of 7463 km^2 were chosen (for more detailed information see paper I). After the initial analysis was successfully conducted, the whole territory of Estonia (45,227.6 km^2) was chosen as the study area. Estonia is divided into 15 counties. The area belongs to three main watersheds (Figure 4).

Specific data for 15 counties are given (see *Table 1*; *Paper II*). Estonia is relatively sparsely populated: there are 3.4 ha of land per capita and 4200 ha of land per point pollution source. Two main boundaries influence the pattern of land use and landscape features in Estonia. First, according to *Varep (1964)*, the upper limit of local glacial lakes divides Estonia into two parts, Lower and Upper Estonia.

The lower part of Estonia is mostly plain, containing large bogs and forests. It has been determined that Lower Estonia was once the bottom of the sea or local glacial lakes. Upper Estonia, on the other hand, was never fully flooded. Therefore the landscape pattern of Upper Estonia is also much more varied, containing different kinds of glacial, glacioflucial and glaciolimnic landforms (drumlins, eskers, kames, etc.). It is important to keep in mind this division in evaluating the age and condition of soils and landscapes. In addition, the border between Ordovician/Silurian and Devonian bedrock formations also influences soils and vegetation. Ordovician and Silurian limestones are the cause of more alkaline soils north of the border. More acidic soils can be found in the southern part of Estonia, where Devonian sandstones occur.

In the northern and western parts, the layer of Quaternary deposits above the Paleozoic bedrock is thinner than in the southern part of the country. This factor makes groundwater quality more vulnerable in the northern and western parts of Estonia *(Arold, 2001)*.

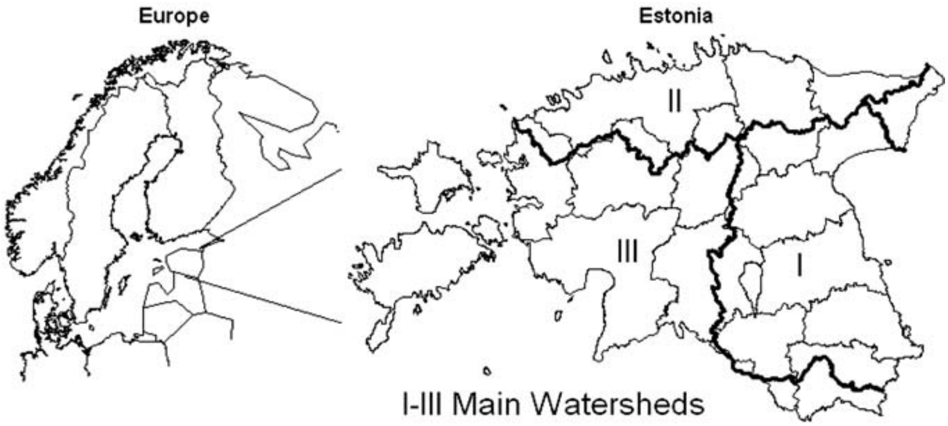

Figure 4. The location of the study area and a map of Estonia's main watersheds. I, Lake Peipsi; II Gulf of Finland; III, Gulf of Riga.

Climatically, Estonia is located in a transitional zone between maritime and continental climates. Therefore meteorological and phenological conditions between the western and eastern areas of the country exhibit great differences *(Jaagus and Ahas, 2000)*. For quite a long period of time, the eutrophication of water bodies has been one of the most serious environmental problems in Estonia *(Loigu and Leisk, 1996)*. Since the 1990s, water quality in freshwater water bodies in Estonia has significantly improved due to a decrease in agricultural production *(Mander et al., 2000; Iital et al., 2005)*. Nevertheless, there are still many villages and farmsteads in the Estonian countryside that are not connected to any sewage systems, and therefore are noticeable sources of pollutants. According to European Union (EU) regulations, appropriate wastewater treatment in small settlements and densely populated villages in Estonia must be provided by the end of 2010 (*Riigikontroll, 2007)*. Therefore the importance of on-site small wastewater treatment systems such as constructed wetlands remains relatively high *(Mander and Mauring, 1997)*.

Estonia is realitively flat land and soil erosion potential is comparatively low to harm essentially landscapes, small lakes or wetlands. Eroded soils together with their deluvial and cumulic soils comprised 2.1% of Estonian territory *(Reintam et al., 2003)*. In topographically complex areas, tillage erosion rates appear to be equal or exceed water erosion rates, and soil redistribution by tillage contributes to landscape sensitivity to water erosion *(Poesen et al., 1990)*. Recent developments in agriculture had reduced remarkably cropping, which in turn resulted in a decline of erosion even on the end-moranic hills of Southeast Estonia. Soil erosion could depend besides topography also from inherent soil properties, such as texture , organic matter content etc. (*Römkens et al., 2001)*. As Estonian soils susceptible to erosion are devoleped mostly on tills and soil texture derived from them is loamy, water erosion do not present a natural hazard.

2.1.2 Data sources

For the estimation of landscape potential for the construction of free water surface wetlands in order to economically treat wastewater, various kinds of landscape data were collected and systematized. Thematic information was gathered from earlier fieldwork and inventories. Data about valuable biotopes, protected and designated areas were also used in the suitability analysis. One of the data providers was the Ministry of the Environment. Water use and wastewater treatment data was collected from the authorities of all counties in Estonia. Data about valuable wetlands were also taken into account. These data were derived from the literature *(Leibak and Lutsar, 1996; Paal et al., 1998)*. The location of the main wastewater treatment plants in Estonia is shown in Figure 5.

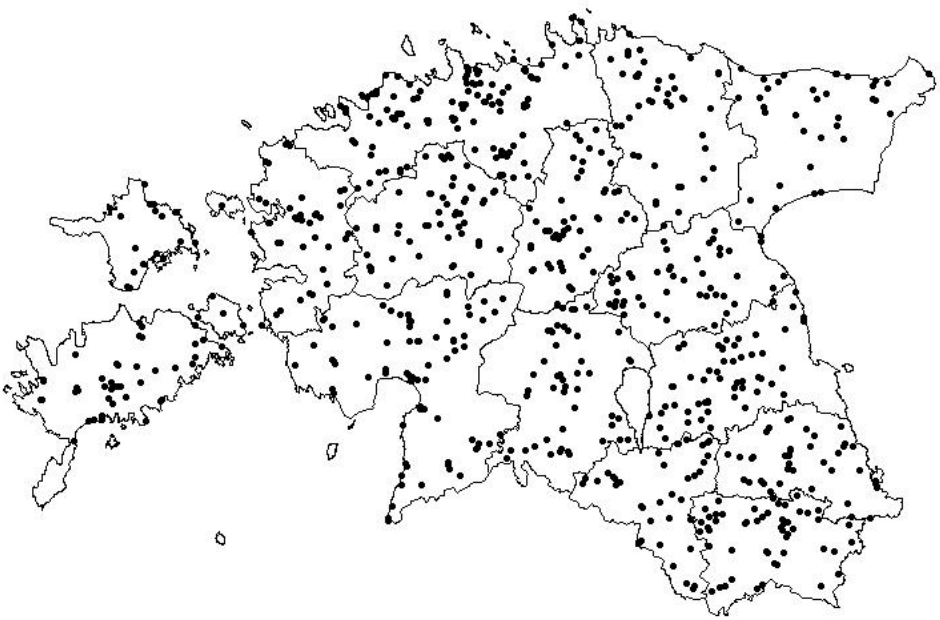

Figure 5. The main wastewater purification plants in the study area (state of the art of 2007; Paper II).

Because of the need for stronger water protection regulations, information on sensitive rivers and lakes is also extremely important to consider in the process of planning CWs (*Figure 4; Paper II*). Protected, designated and valuable natural/seminatural areas that are considered unsuitable for SFW construction are shown on the map in Figure 6. Most of the data were stored in a database at a scale of 1:10,000, including base data (forest, agricultural land, grassland, bog, lake, road, settlement, etc.), aerial photographs (both black and white and CIR orthophotos), soil data (texture, water, regime, soil reaction, etc.) and valuable ecosystems (protected plant and animal species habitats, valuable sites, water bodies and wetlands, etc.). Only the landscape synthesis map, composed by *Arold (2001)* was on a scale of 1:100,000. This map was used as the basis for further detailed analysis and is compiled through the synthesis of information on soil cover, geological conditions and hydrological regime.

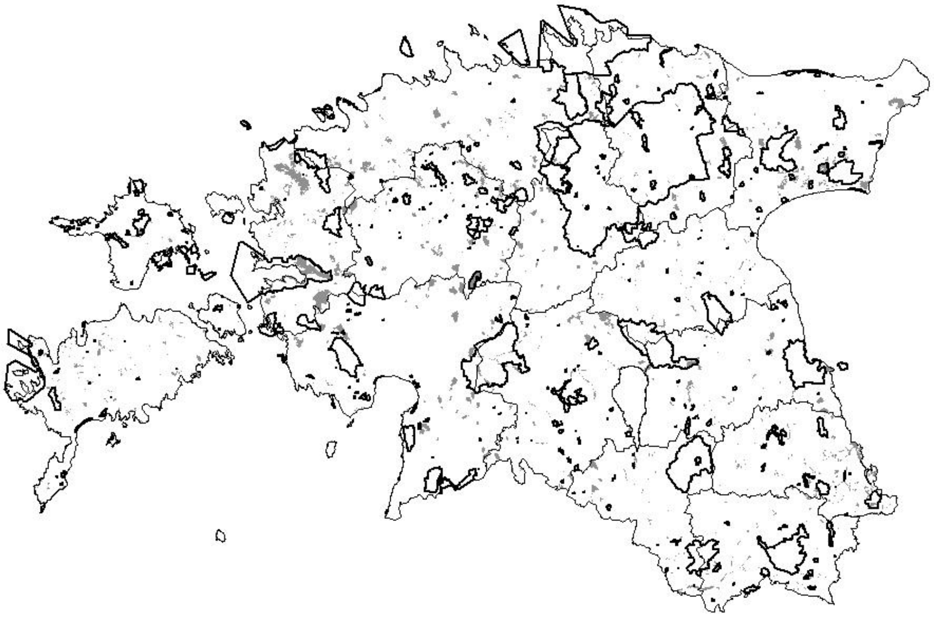

Figure 6. Protected areas in the study area (state of the art of 2007; Paper II).

2.1.3. Data analysis

The GIS-based suitability analysis performed is a multilevel process. The following three steps can be distinguished (*Figure 2; Paper II*):

1. Landscape classification according to the underlying strata (physical–chemical properties of landscape factors) which form geochores.

2. Expert decisions on landscape values. Combining the information from the first layer (physical–chemical properties) and the second layer (expert decisions reflecting community interests) makes it possible to form suitability classes of landscape types (geochores or landscape mesochores; *Bastian and Schreiber, 1999*) for wetland creation on a regional level.
3. Detailed suitability analysis at the construction scale. Performed on soil maps and aerial orthophotos (both at 1:10,000) which gives more adequate information on the local-scale suitability of SFW construction.

The regional (or landscape) level and the detailed level of suitability analysis correspond to the relevant hierarchical levels in landscape assessment for planning purposes *(Bastian and Schreiber, 1999; Bastian, 2000).*

2.1.3.1. Regional analysis

Based on the map of landscape types *(Arold, 2001)*, four suitability categories were established. These categories were called and valuated as follows: very suitable (+2), suitable (+1), neutral (0) and unsuitable (from –1 to –3) (*Table 3; Paper II)*. These four categories were combined, summarizing the following partial suitability values of landscape factors:

(1) Soil cover (1:100,000): +1, clay, loamy, and peat soils; 0, automorphic sandy loam and loamy sand soils; –1, automorphic sandy and rendzic soils
(2) Landforms (1:100,000): +1, valleys, depressions; 0, plains; –1, hills, kames, drumlins, eskers, and all other positive landforms
(3) Hydrogeological conditions (groundwater vulnerability, see *Vrba and Zaporozec, 1994*): In this case, only the –1 value has been used for all karst conditions.

For instance, landscape types on clay soils and peatlands in valleys obtained the +2 value, moraine plains with loamy soils the +1 value, drumlins with loamy soils the 0 value, and limestone plateaus with loamy topsoil but karst conditions the –2 value. According to the landscape type classification, palustrine plains (fens) and varved-clay lacustrine–glacial plains were considered the most suitable landscape types for SFW construction. This is mainly because of the high capacity for wetland creation and the relatively low risk of groundwater pollution. Various (primeval) valley systems, moraine plains, alluvial plains, and abandoned peat mining areas also showed higher suitability for wetland construction. However, landscape types on limestone areas or sandy/gravelly deposits (kame and esker fields, dunes, and coastal ridges) and raised bogs were considered unsuitable for treatment wetland construction. For SFW construction, GIS-based area suitability evaluation consists of two main steps. In the first step, partial suitability is determined in an overall area based on physical properties. The second step consists of suitability assessment after the exclusion of areas with certain restrictions. For instance, these areas include nature protection sites, valuable biotopes, etc.

In the first step of spatial GIS analysis, map algebra is used on the basis of an additive scale in which values of 1, 0, or –1 are omitted according to the properties of the feature, where 1 shows favourable, 0 neutral, and –1 unfavourable conditions for construction of an SFW.

$$psSFW = soil + landform + hydrogeology \quad (1)$$

where psSFW is the partial suitability for the construction of a free water surface wetland; soil is the soil conditions (+1, 0, or –1 according to favorability); landform is +1, 0, or –1 according to favourability; and hydrogeology is 0 for all regions except karst regions, for which it is –1.

In the second step of the analysis, a multiplicative scale is used for GIS layers containing information about protected, designated, and valuable natural/ seminatural areas, because it allows the use of the zero value to mark absolutely unsuitable conditions and thus to exclude these areas from further analysis (Eq. 2). This means that if any layer contains information indicating that this area is unsuitable (value 0) for the construction of an SFW wetland, the entire area is considered to be absolutely unsuitable regardless of the value of any other GIS layers.

$$sSFW = (protected\ X\ designated\ X\ valuable)\ X\ psFWSW \quad (2)$$

where sSFW is the suitability for construction of a free water surface wetland, "protected" are protected areas (values 1 or 0), "designated" are the areas nationally designated for nature conservation (values 1 or 0), "valuable" is a valuable natural or seminatural ecosystem (values 1 or 0), and psSFW is the partial suitability for the construction of a free water surface wetland.

2.1.3.2. Detailed analysis

For the detailed analysis, orthophotos and a soil map of 1:10,000 were used. Information on all protected areas was also considered. Thirty regions around the existing settlements were chosen for detailed analysis. Two areas in each county were chosen, based on the suitability results of the regional scale analysis. Thus one of the two areas was located predominantly in a suitable region of the county and the other predominantly in an unsuitable region. For more detailed information, see *Paper II*. The basis for their selection was the information derived from Arold's *(2001)* landscape map. The suitability classes were chosen similarly to those in the regional analysis: very suitable (+2), suitable (+1), neutral (0), and unsuitable areas (from –1 to –3). The partial suitability values for detailed soil conditions (1:10,000) and land use categories (orthophotos) concern SFW creation, and soil types were classified in three categories: suitable (+1), Gleysols and Histosols; neutral (0), automorphic clay and loamy soils; and unsuitable (–1), automorphic sandy and rendzic soils *(Table 4, Paper II)*. In terms of land use categories, abandoned agricultural and forest land and peat production areas obtained the value +1, low-productivity agricultural and forest land *(Astover et al., 2006)* 0, and productive agricultural/forest land and developed areas –1. All manner of protected areas obtained the unsuitable value and were excluded at this level of the hierarchy. For the detailed soil-based analysis at scale 1:10,000 based on aerial orthophotos, the calculation algorithm for partial suitability was slightly modified: the feature ''landforms'' was omitted, because at this scale soil properties already very accurately reflect relative height differences and generally follow landforms. Instead, hydrogeology factor was introduced because at the very local scale this factor has great importance. As a result, Eq. (1) for regional analysis was altered as follows for local detailed assessment (see also *Table 4, Paper II*):

$$\text{psSFW} = \text{soil} + \text{landuse} + \text{hydrogeology} \tag{3}$$

where psSFW is partial suitability for the construction of a free water surface wetland; "soil" is the soil conditions (+1, 0, or –1 according to favorability); "land use" is +1 (open land), 0 (Young Forest, bush), or –1 (mature forest) according to favorability; and "hydrogeology" is 0 for all regions except karst regions, for which it is –1. Except for areas with neutral soil types, all of the detailed suitability classes were marked on the orthophotos. A summary of the soil-based assessment is presented (*Table 4; Paper II*). Gleysols and Histosols are preferred for treatment wetland construction, whereas sandy soils, thin rendzic and eroded soils are unsuitable.

2.2. Dynamics of cattail populations in treatment wetlands in Estonia

2.2.1. Site description

Common cattail and reed biomass production and cattail nutrient standing stock were studied in three wetlands in Estonia. The first of the study sites is the subsurface flow semi-natural wetland in Tänassilma (58°22′W 25°31′N), and two others are FWS CWs in Põltsamaa (58°38′W 25°58′N) and Häädemeeste (58°5′W 24°29′N) *(Maddison et al., 2005)*.

The Tänassilma semi-natural wetland, which has a total area of 228 ha, is located in a primeval valley at the head of the Tänassilma River. The wetland has been adapted to a high pollutant load of 15,000 population equivalents. The upper reach of the wetland was formerly grassland and former swamp, which after the period when wastewater was discharged into the wetland underwent a change in its species diversity, and dense stands of broadleaved cattail began to prevail. Now this area acts as a root system and a peat filter *(Nõges and Järvet, 2002)*.

The Põltsamaa CW is a cascade of four serpentine ponds with a total area of 1.2 ha. This system is located in the flood plain of the Põltsamaa River. The system is designed for the secondary treatment of wastewater from a conventional treatment plant. The system treats wastewater from the town of Põltsamaa (~5000 inhabitants) and from the food processing industry. Cattail plants were planted in the soil at the bottom of the second and third ponds, and young reed plants were planted in the fourth pond in a later period. Within just a few years, cattail colonised all of the ponds.

The Häädemeeste wastewater treatment system consists of a conventional treatment plant, five infiltration ponds (total area 0.23 ha) planted with common reed and a cattail (*T. latifolia L.*) free water wetland (0.72 ha). The system is located half a kilometre from the Baltic Sea coast and treats the municipal water of the settlement of Häädemeeste. The primary purpose of the wetland is the removal of N and P *(Mauring, 2002)*.

The average annual wastewater and nutrient loadings of the studied areas are presented (*Table 1; Paper III*) (Ministry of the Environment, 2004). For a more detailed description see *Paper III*.

The sampling and analysis of plant biomass was mostly carried out by M. Maddison and is described in *Maddison et al. (2009), Paper III*.

2.2.2. GIS and statistical analysis

To determine suitable areas for cattail cultivation, various GIS data layers were used in the overlay analysis. First, eutrophic peat soils and Gleysols were selected from a 1:100,000 soil map. According to the CORINE 2000 land cover map, forested areas were excluded. Settlements according to the 1:50,000 base map and protected areas, planned protected areas, valuable habitats, areas designated for the Natura 2000 network from the Estonian Nature Infosystem and 200-m-wide buffer zones on the coastlines of the sea, lakes and rivers were also excluded.

In addition, the statistical analysis was carried out using the STATISTICA 7.0 (StatSoft Inc.) program. The normality of the variables was verified using the Lilliefors' and Shapiro–Wilk's W-tests. Biomass production and nutrient content variables were normally distributed. 95% confidence intervals were used to compare mean values of the results. The level of significance $\alpha = 0.05$ was accepted in all cases.

2.3. Assessment of methane and nitrous oxide fluxes in rural landscapes

2.3.1. Study area and literature analysis

The study area consists of the entire rural area of Estonia for the assessment of methane and nitrous oxide fluxes in its rural landscapes (Figure 1). The author of this PhD thesis concentrated mostly on the concept of the gas regulation function of different land cover types (*Paper IV)*.

The data for this study was gathered using 190 scientific papers indexed by the ISI Web of Science published from the early 1980s to 2008. Of these papers, data from more than 1100 study sites/experiments in the temperate and boreal zone were analysed. Study sites that were taken into account were located predominantly in the Northern Hemisphere.

One of the important preconditions for the selection of appropriate data was investigations' coverage of at least a one year period. Data from the analyses that made it possible to create an annual estimate (estimation of fluxes from both warm and cold periods) have also been taken into account. CH_4 and N_2O fluxes from arable lands, grasslands, abandoned (set-aside) agricultural lands, forests, peatlands and freshwater marshes examined in scientific papers were included in the current study. The distinctions between the following land-use types was made: (1) intensively used arable land (conventional farms and areas with high fertilisation rates); (2) less intensively used arable land (organic agriculture and minimally-fertilised conventional fields); (3) intensively managed (fertilised) grasslands; (4) less intensively managed grasslands (mostly un-fertilised) grasslands; (5) abandoned (set-aside) agricultural land; (6) deciduous forests; (7) coniferous forests; (8) mixed deciduous-coniferous forests; (9) fens and transitional fens; (10) raised/oligotrophic bogs and woodland bogs; (11) freshwater marshes; (12) various peatlands (drained and restored peatlands, peat production areas). Land use types 1–8 were analysed for both automorphic soils and hydromorphic soils. As concerns peatlands and marshes (types 9–11), both undisturbed and drained variants have been taken into account. Few data were found for moorlands and blanket bogs in the literature. However, due to the insignificant presence of their analogues (moors and heathlands) in Estonia, they were not taken into account. All anthropogenic areas (towns, settlements, roads, industrial territories, quarries), lakes and rivers were also excluded from this assessment.

2.3.2. Digital map data sources

For the analysis of area-based CH_4 and N_2O gas emissions from non-urban landscapes in Estonia, the following digital map data sources were used: (1) Estonian soil map, (2) the map of Estonian drainage systems and (3) the Corine Land Cover map of Estonia.

The nominal scale of the soil map is 1:200,000, and the minimum size of mapping units is 2 hectares, with an average of 419 ha and a maximum size of 17,201 ha. The digital soil map has 54 soil type classes, and soil texture data is given separately for topsoil and deeper layer(s).

The digital map of Estonian drainage systems has a nominal scale of 1:10,000, with the smallest mapped drainage system having an area of 0.5 ha, the average area of drainage systems being 221 ha and the largest drainage unit having an area of 4271 ha. For calculation of GHG fluxes, only partial separation of drained and non-drained areas could be made due to the insufficient spatial accuracy of drainage map. Thus the influence of water table changes on GHG flux is embedded in the summary values for different land-use types.

The digital map of Corine Land Cover from which land use and land cover information was derived represents conditions in the year 2000. The nominal scale of the map is 1:100,000, the smallest mapping unit corresponds to 25 ha, the average size of land cover units is 127 ha and the largest land cover unit has a size of 25,805 ha.

2.3.3. GIS analysis

GIS map algebra was used to estimate greenhouse gases emission from non-urban landscapes in Estonia. In order to determine automorphic and hydromorphic soils, the soil map and digital map of Estonian drainage systems were geometrically intersected. This output map was in turn overlaid and intersected by the Corine Land Cover map in order to define soil types for different land use units. The transitional matrix was created and used to relate Estonia's Corine land cover units to land use classes established on the basis of the literature review and statistical analysis (*Table 1, Paper IV*). For instance, intensively used arable land by land use classes created on the basis of the literature corresponds to arable land, annual crops associated with permanent crops, complex cultivation patterns and fruit trees and berry plantations in the Corine land cover nomenclature. For a more detailed description of the transformation of main land use classes from the literature analysis of CH_4 and N_2O emission to the Corine land cover nomenclature see *Paper IV* (*Table 1*; *Paper IV*).

3. RESULTS AND DISCUSSION

3.1. Estimation of landscape potential for construction of SFWs for wastewater treatment as one of the regulation functions of landscapes

3.1.1. Regional analysis

The results of the landscape analysis show that suitability for SFW construction is distributed relatively equally over the study area (Table 5; Figures 7 and 8). Unsurprisingly, areas classified as ''very suitable'' are concentrated mostly in lowland regions: western Estonia, Pärnu, Võrtsjärv, Peipsi, and the Võru-Hargla Lowlands. In general, the proximity of major river valleys can also be qualified as a very suitable situation for SFWs. According to the results of the study, relatively large areas with high potential for SFW construction can be found throughout Estonia. In upland areas, very poor potential (classified as ''unsuitable'') predominates. Large areas of unsuitable land are located in protected areas, for instance the Pandivere water protection area in the northern part of Estonia. Suitable and neutral areas cover larger proportions of the study area. To sum up very suitable and suitable areas, 42% of the study area has good potential for SFW construction. Of that area, very suitable areas make up 16% and suitable areas 25% of the total. The results of the GIS analysis indicate that the variation between the 15 counties of Estonia is not great. The lowest percentage for very suitable was found to be 5%, and the highest was 23%. The percentage for suitable areas varies from 7 to 49%. The more detailed variation of suitable and very suitable areas in different counties of Estonia is described in Table 5. If one considers very suitable and suitable areas together as possessing good potential for the construction of SFWs, then the best preconditions are in regions located in the western, central and eastern lowland counties. The results of this analysis are very practical for regional level water pollution control planners. It is more preferable for engineers to focus on high potential areas.

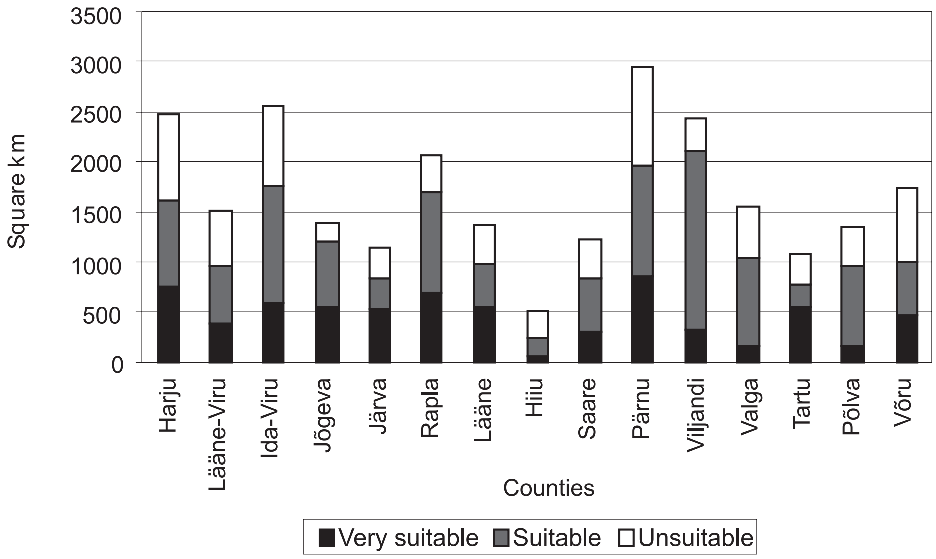

Figure 7. Share of suitability classes of the 15 counties studied.

Table 5. Distribution of suitability for surface flow treatment wetlands construction in the counties studied, according to the results of the landscape analysis[a].

County	Very suitable km^2	Suitable km^2	Very suitable + suitable km^2	Very suitable + suitable % of the county's area
Harju	**753**	859	1612	38
Lääne-Viru	383	577	960	28
Ida-Viru	593	**1175**	**1768**	**53**
Jõgeva	549	665	1214	47
Järva	521	324	845	32
Rapla	**696**	1009	1705	**58**
Lääne	536	441	977	41
Hiiu	52	178	230	23
Saare	304	539	843	29
Pärnu	**867**	**1095**	**1962**	41
Viljandi	322	**1779**	**2101**	**62**
Valga	153	882	1035	51
Tartu	534	226	760	26
Põlva	160	790	950	44
Võru	454	548	1002	43
TOTAL	**6877**	**11,087**	**17,964**	**42**

[a] Highest values in bold.

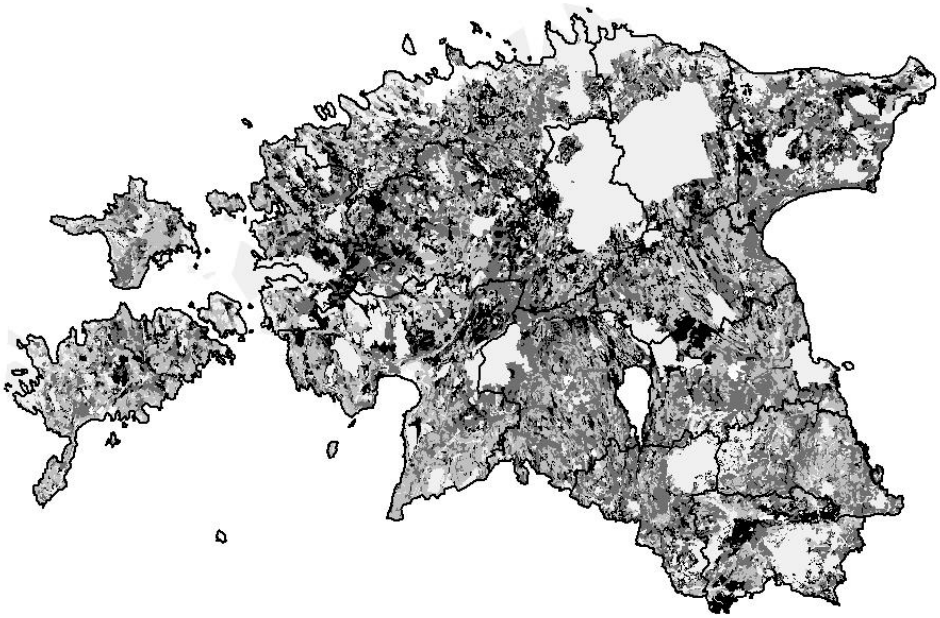

Figure 8. Overall suitability for location of surface flow treatment wetlands in Estonia. Black: very suitable; dark grey: suitable; grey: neutral; light grey: unsuitable.

3.1.2. Detailed analysis

According to the detailed analysis, the presence of areas in the vicinity (1 km radius) of the 30 selected settlements that are categorized as very suitable and suitable for SFW construction is shown (Table 6; *Paper II)*. For the detailed analysis, two settlements from each county were selected. The selection was based on a regional analysis of landscape. According to this, one settlement is located in a predominantly suitable area, and the other in a predominantly unsuitable area of each county. Based on orthophotos and the soil map (1:10,000) of the areas around the chosen settlements, in most cases one can find optimal sites for SFW construction within unsuitable areas. Detailed numbers of suitable and very suitable areas around settlements in each county are shown (*Table 6*; *Paper II)*. The maps representing the results of the detailed suitability analysis for SFW construction are shown in Figures 9 and 10, which graphically demonstrate that there is a relatively high proportion of suitable patches even in areas classified as unsuitable. These are typically small in size but the effectiveness of their usage depends on the design and requirements of particular SFWs. However, in areas classified as suitable on the basis of landscape analysis, the proportion of suitable patches is also higher.

9

3.1.3. Strategic value of landscape analysis results

The results of this landscape analysis successfully demonstrate the potential of such an analysis to facilitate the pre-selection of areas of interest for SFW creation for planners and engineers.

The developed methodology is quite similar to many of the suitability analyses commonly used in landscape planning *(Kheir et al., 2008; Remm et al., 2004)*, regional (environmental) planning *(Magoni and Steiner, 2001)* and natural resource management *(Brown, 2005)*. It is also used for the management of land *(Baja et al., 2007)* and water *(Schlüter et al., 2006),* and also for the assessment of land use changes *(Benini, et al., 2009; Podmanicky, et al., 2009)*. The habitat suitability index devised in the 1980s *(Wakeley, 1988)* and widely used for the modelling and management of both aquatic (*Ahmadi-Nedushan et al., 2006)* and terrestrial habitats *(Dussault et al., 2006)* is one of the best examples for the evaluation and assessment of landscape functions and capabilities. In addition, landscape functions for monitoring and the integration to land use decision-making in the spatial planning context has been described by *Wolf and Meyer (2009).* The approach for the estimation of landscape potential for SFW construction was quite simple, arguing only the direct assessment of landscape factors and land use categories by multiplying the partial sustainability values (ranging from 0 to 1) without adding categorical rankings *(Baja et al., 2002)* or weighting factors *(Ahmadi-Nedushan et al., 2006)*. Using the fuzzy modelling approach *(Baja et al., 2002; Schlüter et al., 2006)* would in some cases make the further development of such methodologies even more valuable, by making the suitability scale more sensitive and flexible. Nevertheless, simple methods are often more practicable, offering environmental managers, planners and decision-makers rough but acceptable results. One of the advantages of this method is that data are relatively easily accessible. Because of the ease of combining different databases, the working abilities of administrative officials using those large databases on both regional and local levels are greatly enhanced. One of the great advantages of this information is that it can be shared by many users at low cost. This study demonstrates that this method and the database can be effectively used to support the thematic planning of water pollution control. The basic data pertaining to soil, vegetation, elevation and geological situation can be combined with specific monitoring/research data and formulated as supporting thematic maps, allowing researchers to create a more dynamic planning process. An overview of natural potentials and sensible and valuable sites permits the development of a spatial strategy that can greatly extend the concept of ecological engineering *(Herricks and Suen, 2006)*. For instance, suitable sites for wetland-based treatment methods can be proposed and selected according to certain predefined criteria *(Trepel and Palmeri, 2002a)*.

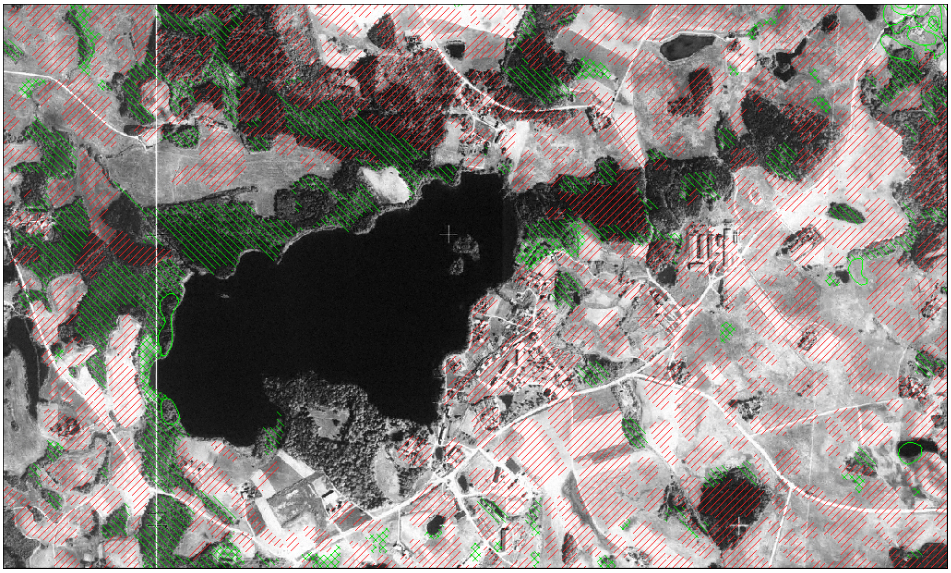

Figure 9. Example of a detailed suitability analysis map based on orthophotos and soil maps (1:10,000). The overall suitability ranking assigned on the basis of the landscape analysis was „unsuitable.“ Pink diagonal lines: unsuitable areas; green diagonal lines: suitable areas; crossed green lines: very suitable areas; unlined: neutral areas.

Figure 10. Example of the detailed suitability analysis map based on aerial orthophotos and soil maps (1:10,000). The overall suitability ranking on the basis of the landscape analysis was „suitable“. Pink diagonal lines: unsuitable areas; green diagonal lines: suitable areas; crossed green lines: very suitable areas; unlined: neutral areas.

Different scenarios can be visualized and used for purposes of argumentation. A simple vicinity analysis can indicate the potential for the rebuilding and post-treatment of existing pollution sources. Continuous information throughout the region, on the other hand, allows the identification of sites with high potential for extensive and more economical sewage treatment methods in the process of site selection for urban or industrial development. It is believed that the results of this landscape analysis will serve as a good basis for the focusing of wetland engineering interest and also for the further modelling and quantifying of nutrient flows, as demonstrated by *Trepel and Palmeri (2002a,b)*. In addition, the results of this study can be considered as a valuable basis for focusing on the regulation functions of rural landscapes.

3.2. Dynamics of cattail populations in treatment wetlands in Estonia

3.2.1. Biomass

Semi-natural and constructed wetlands are multifunctional, meaning that at one single location different landscape functions can be provided. In case of this study, regulation function (wastewater treatment) and provisioning function (production of raw material) in addition to other wetland functions are provided (*Wild et al., 2001*). Biomass of cattail and reed that are most common plants used in treatment wetlands, are also valuable raw materials for ecologically friendly construction *(Mander et al., 2001)* and biomass fuel *(Ciria et al., 2005)*. All parts of aboveground biomass of cattail and shopped shoots of reed can be used for construction. Cattail shoots and leaves are used to make chip mass and insulation blocks that are healthy and cost-efficient. In addition, the seeds from cattail spadixes can be used as fibre-wool and spadixes mixed with clay gives elasticity to clay plasters. These materials have good thermal insulation properties which makes them especially valuable in construction. Houses being built of abovementioned materials are considered to be very healthy because of the stable humidity levels in rooms throughout the different seasons of year *(Maddison et al., 2009)*.

To evaluate raw material production function of studied wetlands, the average aboveground biomass of *T. latifolia L.* and *P. australis* were measured. The average aboveground biomass of *T. latifolia* varied from 0.37 to 1.76 kg DW m^{-2} in autumn and from 0.33 to 1.38 kg DW m^{-2} in winter for the three wetlands throughout the study period. The corresponding results for *P. australis* were from 0.61 to 1.32 kg DW m^{-2} and from 0.61 to 1.02 kg DW m^{-2} kg, respectively (*Figure 1; Paper III*).

The results showed that 1 ha of constructed wetlands can annually produce enough raw cattail materials for the insulation of up to three houses and fibre material up to 25 houses. The more detailed results for the differences in reed and cattail aboveground phytomass values between the three studied wetlands are shown *(Figure 1; Paper III)*. Estimated biomass of cattail shoots, phytomass of cattail litter and average biomass of spadixes were also measured and compared between Tänassilma, Häädemeeste and Põltsamaa systems in autumn and winter period *(Paper III)*. The average aboveground biomass of reed did not vary significantly from cattail. Cattail phytomass loss was less when there were more spadixes in autumn. This is because fruiting shoots are more weather resistant *(Linde et al., 1976)*.

The average aboveground cattail biomass values (0.3–1.8 kg DW m^{-2}) in Tänassilma semi-natural wetland and Põltsamaa and Häädemeeste CWs were lower than reported by *Toet et al. (2005)*: 2.09 kg m^{-2}, *Ennabili et al. (1998)*: 2.16 kg m^{-2} and *Fernandez and de Miguel (2005)*: 2.23 kg m^{-2}, but were similar to those found in Germany (1.3–1.45 kg m^{-2}; *Wild et al., 2002*).

Cattail biomass has a large temporal and spatial variation in productivity, which makes it somewhat difficult to use them as a raw material for building and fibre production. In addition, the alternation between a year of high production and year of low production gives no stability in relation to raw material production. It is possible that heavy fruiting of cattail may also produce an imbalance within the plant which affects the next year's production *(Linde et al., 1976)*. Production variation of spadixes in Häädemeeste, Põltsamaa and Tänassilma wetlands in different years were partly caused by colonization of reed and heavy fruiting shoots' inability to stand up on floating mats (more detailed description in *Paper III*).

Cattail and reed biomass variation in productivity is affected by conditions provided by constructed wetlands, which differ from conditions elsewhere in their habitats. Therefore, more research in CWs role as stable provisioning of raw material production is needed.

3.2.2. Nutrients

One of the regulation functions' biophysical indicators is the role of vegetation and biota in removal or breakdown of nutrients and toxic compounds. The results of the analysis performed by my co-authors describe nitrogen and phosphorus concentrations measured in different parts of the plants in Tänassilma, Põltsamaa and Häädemeeste wastewater treatment wetlands in the years 2002–2006 (*Paper III*). According to that, the greatest average nitrogen concentration (22.95 g N kg^{-1}) was found in spadixes in 2002, and phosphorus (6.5 g P kg^{-1}) concentration was measured in roots–rhizomes in 2003. For spadixes the maximum average P concentration was measured at 4.76 g kg^{-1}, while in the case of litter the greatest P concentration was 2.7 g kg^{-1}. N and P concentrations in cattail shoots and litter were lower in winter than in autumn, but were higher in spadixes and roots–rhizomes (for more detailed results see

Table 3; *Paper III*). Average nitrogen and phosphorus standing stock was higher in aboveground than belowground phytomass (Table 3; *Paper III*). The average standing stock of nutrients in Tänassilma, Põltsamaa and Häädemeeste belowground phytomass varied from 11.6 to 19.4 g N m^{-2} and from 1.6 to 4.6 g P m^{-2} and aboveground from 17.0 to 32.3 g N m^{-2} and from 2.6 to 6.0 g P m^{-2}. The corresponding results in winter were 4.4–7.5 g N m^{-2} and 0.6–1.0 g P m^{-2}. The standing stock of nutrients depends on both the elements' concentrations in the plant tissue as well as on the amount of plant biomass *(Vymazal, 2004)*. It is recommended that the harvesting of cattail be undertaken after nutrient translocation because *P. australis* translocates reserve products very late in the season and harvesting it during the growing season may lead to serious damage to the stand *(Vymazal, 2004)*. The nutrient balance of CWs depends on many factors and can also vary from year to year. For instance, low hydraulic and nutrient loadings in subsurface CWs may lead to significant nutrient removal. On the other hand, filter material and sediments can hold a pool of nutrients and play more important role in phytomass production than direct wastewater inflow. Thus the calculation of removal efficiency based only on initial wastewater loadings and annual nutrient uptake does not provide adequate results. Therefore, removed nutrients via the harvesting of aboveground biomass from heavily loaded CWs in temperate and cold climates yield a very small portion of the inflow load, and harvesting does not usually increase removal efficiency *(Vymazal, 2004)*. Harvesting may be feasible if there is an application for macrophytes, e.g. construction *(Mauring, 2003)* or energy production *(Mander et al., 2001b; Ciria et al., 2005)*. However, the stability of cattail re-growth after harvesting has not been thoroughly researched *(Hellsten et al., 1999)*.

3.2.3. Suitable areas for energy and treatment wetlands in Estonia

As part of the study, a simple overlay suitability analysis was made in order to estimate the potential for energy and treatment wetland location in Estonia. Because of the higher value of areas performing other landscape functions, they were excluded. According to *Mander et al. (2001b),* there is a relatively high percentage of wet and moist land in Estonia. In terms of soil cover, peat soils cover 21% (9497 km^2) of Estonian territory, and Gleysols cover even more – 33% (15,138 km^2). As mentioned above, because of the higher value of other landscape functions overlapping peat soils and Gleysol cover, not all of this territory can be considered suitable for *Typha* plantation. Unsuitable largely overlapping areal categories such as forest (21 198 km^2), the Natura 2000 network (21,1053 ha), protected areas (5919 km^2), special areas of conservation (7500 km^2), valuable habitats (231 km^2), planned protected areas (995 km^2), settlements (1365 km^2) and a 200-m-wide coastal buffer zone at water bodies

($7684\ km^2$) were excluded. Hence, $5412\ km^2$ of potential territory for energy and treatment wetlands remained. It was estimated that about 464,000 ha of the potential polygons are larger than $10\ km^2$ (*Figure 2; Paper III*). Cattail and reed plantation are not the only possible land use for these potential areas. In existing peat-mining areas, restoration should be undertaken after the excavation of peat deposits. Thus these areas can be considered to be potential biomass production wetlands.

3.3. Assessment of methane and nitrous oxide fluxes in rural landscapes

3.3.1. Literature analysis

The results of the assessment of CH_4 and N_2O fluxes in rural landscapes in order to contribute to gas regulation are described (*Figures 1–7; Paper IV*). The literature sources served as a base for calculating methane and nitrous oxide emissions from various landscape types (*Table 3, Paper IV*).

The median values of methane and nitrous oxide emissions from different land use types (conventional arable lands, organic arable lands, unfertilized grasslands, fertilized grasslands, set aside and successional areas, deciduous forests, coniferous forests, mixed forests, different kinds of natural wetlands and drained natural wetlands) on both automorphic and hydromorphic soils based on literature data were calculated. The highest median values for CH_4 emission were found for drained and restored peatlands (262.8 kg CH_4-C ha^{-1} $year^{-1}$), natural wetlands – freshwater marshes (177.2 kg CH_4-C ha^{-1} $year^{-1}$), fens/traditional bogs (160 kg CH_4-C ha^{-1} $year^{-1}$), various peatlands (64.5 kg CH_4-C ha^{-1} $year^{-1}$) and raised/oligotrophic bogs (51.7 kg CH_4-C ha^{-1} $year^{-1}$). The lowest median values for CH_4 emission were found for mixed forests on automorphic soils (–3.5 kg CH_4-C ha^{-1} $year^{-1}$), one of the natural wetland types – moorlands and blanket bogs (–2.0 kg CH_4-C ha^{-1} $year^{-1}$), deciduous forests on automorphic soils (–1.7 kg CH_4-C ha^{-1} $year^{-1}$) and both coniferous forests on automorphic soils and unfertilized grasslands on automorphic soils (–1.5 kg CH_4-C ha^{-1} $year^{-1}$).

The highest median values for N_2O emission were found for drained and restored peatlands (7.2 kg N_2O-N ha^{-1} $year^{-1}$), drained freshwater marshes and set aside and successional areas on hydromorphic soils (both 5.2 kg N_2O-N ha^{-1} $year^{-1}$), fertilized grasslands on hydromorphic soils (4.7 kg N_2O-N ha^{-1} $year^{-1}$) and conventional arable land on hydromorphic soils (4.5 kg N_2O-N ha^{-1} $year^{-1}$). The lowest median values for N_2O emission were found for raised/oligotrophic bogs (0.0 kg N_2O-N ha^{-1} $year^{-1}$), fens/transitional fens (bogs) and unfertilized grasslands on automorphic soils (both 0.2 kg N_2O-N ha^{-1} $year^{-1}$), deciduous forests on automorphic soils (0.5 kg N_2O-N ha^{-1} $year^{-1}$) and freshwater marshes and drained woodland bogs (both 0.6 kg N_2O-N ha^{-1} $year^{-1}$).

The summary results, based on all of the literature sources used, show that natural peatlands and marshes are the land use types with highest emissions of methane, followed by drained peatlands and marshes (106.0 and 3.7 kg CH_4-C ha^{-1} $year^{-1}$ respectively). In the case of nitrous oxide emissions, the highest median values of emissions are related to drained peatlands and marshes and arable land (2.3 and 1.5 kg N_2O-N ha^{-1} $year^{-1}$ respectively). For a more detailed description, see *(Paper IV)*.

3.3.2. GIS analysis results

Based on the transformation of the main land use classes from the literature analysis of CH_4 and N_2O emissions to the Corine land cover nomenclature (*Table 1; Paper IV*), the estimation of the annual exchange of CH_4 and N_2O between the soil and atmosphere in various land cover units on different soils in Estonia is presented (see *Table 3 and 4; Paper IV*). Median values of CH_4 and N_2O fluxes were multiplied by the total area of relevant areas' cover/use types. On that basis, fens and traditional bogs on hydromorphic soils are estimated to exchange 11,188 tons (t) of CH_4 between the soil and atmosphere annually. This estimation is followed by deciduous forests on hydromorphic soils and raised/oligotrophic bogs on hydromorphic soils, which have CH_4 fluxes as high as 9,396 t $year^{-1}$ and 6,558 t $year^{-1}$ respectively. The highest estimated negative fluxes of CH_4 are from mixed forests on hydromorphic soils (–1780 t $year^{-1}$), mixed forests on automorphic soils (–944 tons $year^{-1}$) and from coniferous forests on automorphic soils (–622 t $year^{-1}$).

The highest values for the annual exchange of N_2O were calculated for coniferous forests on hydromorphic soils (3,180 t $year^{-1}$), mixed forests on hydromorphic soils (2,411 t $year^{-1}$) and intensively arable lands on hydromorphic soils (1,362 t $year^{-1}$). The lowest value for the annual exchange of N_2O between soil and atmosphere was ascribed to freshwater marshes on hydromorphic soils (0.08 t $year^{-1}$). The spatial distribution of annual CH_4 and N_2O emissions in Estonia is presented (*Figures 8 and 9; Paper IV)*. The spatial distribution pattern of methane emissions closely coincides with the location of Gleysols and Histosols, especially in large peatland areas, whereas the spatial distribution pattern of methane emissions is consistent with the location of large forests and agricultural fields in Estonia (*Paper IV*).

For the optimization of GHG fluxes, the following principles can be listed: (1) avoidance of drainage on peatland soils (minimizes N_2O and CO_2 emissions), (2) preferred development of organic agriculture (less fertilization decreases emissions from most agricultural areas), (3) plantation of short-rotation energy forests and energy crops (preferably on automorphic soils; will

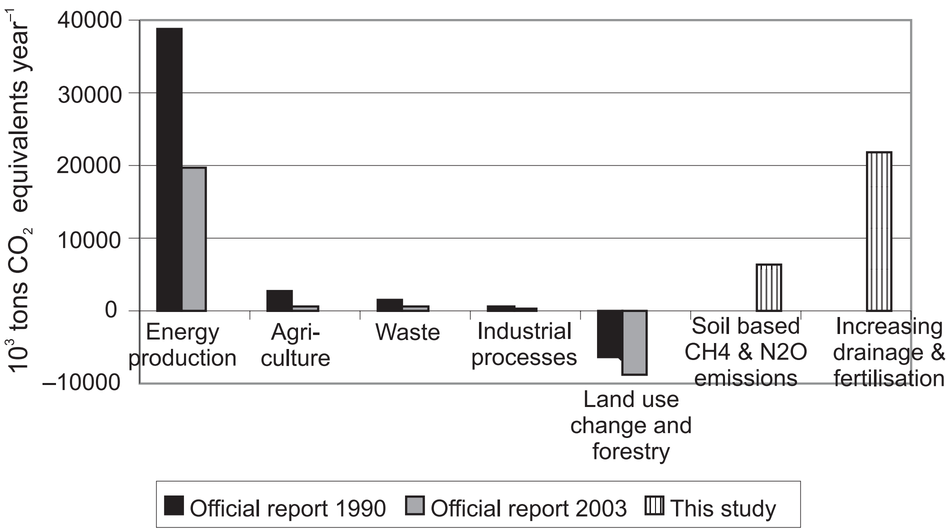

Figure 11. Estonian official report (*Punning et al., 2005*) on GHG emission by economic sectors and this study.

help sequestrate CO_2 and consume CH_4). In hot spots like riparian zones and wastewater treatment, special management (selective cutting of trees in riparian forests, more efficient pre-treatment of wastewater) can be undertaken. The restoration of drained peatlands will result in continuous high nitrous oxide emissions.

Over a 100-year time span, the radiative force (Global Warming Potential; GWP) of CH_4 is 25 times higher than that of the same amount of CO_2, whereas N_2O is as much as 296 times more powerful (IPCC, 2007). According to that, the GWP of all land use types is 5.44 million t CO_2 equivalents whereas N_2O is responsible for 5.14 million t CO_2 eq. This is about 30% of GWP from oil shale burning in Estonia (*Punning et al., 2005; Paper IV*).

Therefore the results are extremely important, because land-use-based greenhouse gas (GHG) emission has not been taken into account in calculating carbon taxes. According to Estonian official report's data from the years 1990 and 2003, land use change and forestry are considered as consumers rather than emitters of GHGs (Figure 11). Our results show the opposite trend.

This study clearly demonstrated one of the methods for the evaluation of gas regulation functions of landscapes.

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4. CONCLUSIONS

In order to provide engineers, planning agencies and policy makers with methods to help make more balanced landscape planning decisions, landscape functions must be evaluated. This study has mainly focused on the estimation of regulation functions of rural landscapes, i.e. water regulation, waste treatment, gas regulation, and to some extent also production function, as well as waste treatment.

(1) To determine the proportion of suitable areas for the construction of SFWs for wastewater treatment in rural areas of Estonia, a simple GIS-based method was developed. The assessment is based on a two-step scheme that consists of landscape classification according to the physical–chemical properties of landscape factors, expert decisions concerning landscape values, and suitability analysis. This method demonstrated that in Estonia the share of very suitable areas for the construction of SFWs covers 16% of the entire country, and the share of suitable areas covers 25%.

(2) The pattern formed by GIS analysis showed that the variation between counties is not great. However, that high potential is mostly concentrated in lowland regions. The lowest percentage for very suitable areas was found to be 5%, and the highest 23%. The percentage for suitable areas varies from 7 to 49%. A detailed analysis showed that there is a certain proportion of small suitable patches even in areas classified as unsuitable (based on landscape analysis) for SFW creation in the vicinity (1 km radius) of the selected settlements (wastewater sources). However, in the areas classified as suitable on the basis of landscape analysis, the proportion of suitable patches is also higher.

(3) One of the great advantages of this information is that it can be shared by many users at low cost. It has been demonstrated that this method and the database can be used effectively to support the thematic planning of water pollution control. Also, different scenarios can be visualized and used for purposes of argumentation. A simple vicinity analysis can indicate the potential for the rebuilding and post-treatment of existing pollution sources. It is presumed that the proposed method will reduce planning costs considerably and lead to more precise and balanced decisions.

(4) The author also contributed to indication of suitable areas for treatment wetlands for raw material production as one of the landscape production functions. Thus annual biomass production was evaluated and the standing stock of N and P in the phytomass of broad-leaved cattail *(Typha latifolia L.)* was determined. Average aboveground biomass of *T. latifolia* varied from 0.3 to 1.8 kg DW m^{-2}. The average standing stock of nutrients in belowground phytomass varied from 11.6 to 19.4 g N m^{-2} and from 1.6 to 4.6 g P m^{-2} and aboveground from 17.0 to 32.3 g N m^{-2} and from 2.6 to 6.0 g P m^{-2}. The results showed that there is a great temporal and spatial variation in the productivity of cattails in CWs. This means that cattails are

difficult to use as a potential source of raw material for building and fibre production. Eliminating unsuitable sites like forests, the Natura 2000 network, protected areas, special areas for conservation, valuable habitats, planned protected areas, settlements and a 200 m wide coastal buffer zone at water bodies, 5,412 km^2 of potentially favourable sites for cattail treatment wetlands are left in Estonia.

(5) As part of the regulation functions of landscapes, gas regulation was estimated by assessing methane and nitrous oxide fluxes in rural landscapes in Estonia. Fens and traditional bogs on hydromorphic soils are estimated to exchange CH_4 between the soil and atmosphere at a rate of 11,188 t $year^{-1}$. This estimation is followed by deciduous forests on hydromorphic soils and raised/oligotrophic bogs on hydromorphic soils with fluxes of CH_4 as great as 9,396 t $year^{-1}$ and 6,558 t $year^{-1}$ respectively. The highest estimated negative fluxes of CH_4 are from mixed forests on hydromorphic soils (–1,780 t year¯1). On the other hand, the highest values for annual exchange of N_2O were calculated for coniferous forests on hydromorphic soils (3,180 t $year^{-1}$), mixed forests on hydromorphic soils (2,411 t $year^{-1}$) and intensively arable lands on hydromorphic soils (1,362 t $year^{-1}$). The lowest value for the annual exchange of N_2O between the soil and atmosphere was ascribed to freshwater marshes on hydromorphic soils (0.08 t $year^{-1}$). For the optimization of GHG fluxes, avoidance of drainage on peatland soils, preferred development of organic agriculture, and plantation of short-rotation energy forests and energy crops could be mentioned. In hot spots like riparian zones and wastewater treatment wetlands special management can be undertaken.

This study has been successful in taking a few steps further in the estimation of landscape regulation functions, thereby also contributing to the understanding of their concurrence with other landscape functions. The proposed relatively simple evaluation methods can be used by engineers, planners and policy makers in order to ensure the sustainability of the natural environment in which we live.

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SUMMARY IN ESTONIAN

Maastike regulatsioonifunktsioonide hindamine tehismärgalade rajamiseks ning kasvuhoonegaaside voo optimeerimiseks

Maastikuplaneerimises tasakaalukate otsuste tegemiseks inseneride, planeerimisagentuuride ja poliitikute poolt, on vajalik välja töötada erinevate maastikufunktsioonide hindamise alused. Käesolev doktoritöö on peamiselt keskendunud maastike regulatsioonifunktsioonide (vee regulatsioon, reovee puhastus, kasvuhoonegaaside regulatsioon) hindamisele.

Välja on töötatud GIS-il baseeruv meetod, mille alusel on võimalik hinnata maastiku potentsiaali avaveeliste märgalapuhastite rajamiseks reoveepuhastuse eesmärgil maapiirkondades. Kaheastmeline hindamisskeem koosneb maastike klassifitseerimisest lähtuvalt maastikufaktorite füüsikalis-keemilistest omadustest, maastike väärtuste eksperthinnangust ja sobivusanalüüsist. Sobivusanalüüsi osaväärtused maastikufaktoritele (iga faktori väärtus –1 kuni +1) märgalapuhastite rajamiseks sobivate alade leidmisel on saadud eksperthinnangute summeerimisel. Korrutades summeeritud sobivusanalüüsi osaväärtused looduskaitsealaste väärtustega (varieeruvad 0 kuni 1), leiti lõplik sobivusväärtus iga planeeritava või taastatava avaveelise märgala rajamiseks. Analüüsi läbiviimiseks regionaalsel tasandil kasutati topograafilisi ja maastikukaarte (1:100000) koos statistiliste andmebaasidega. Kohalikul või detailsel tasandil maastikuanalüüsi teostamiseks kasutati aerofotosid (ortofotod) ja maakasutuskaarte (1:10000). Veereostuse ohjamise, mis on üks maastiku regulatsioonifunktsioonidest, temaatiliseks planeerimiseks on andmekihid integreeritud ning neid on analüüsitud täiendavate temaatiliste andmetega. Baasandmed, mis puudutavad mullastikku, taimestikku, kõrgusandmeid ja (hüdro)geoloogilist ehitust, on kombineeritud spetsiifiliste vaatlus- või uurimisandmetega, mille tulemusel on koostatud otsuste tegemist toetav teemakaart. See võimaldab uurijatel näha tunduvalt „sügavamale“ ja tagada palju dünaamilisema planeerimisprotsessi. Lihtsa naabrusanalüüsiga on näidatud potentsiaalsed alad olemasolevate reostusallikate ümberehituseks või järelpuhastiga varustamiseks. Täielik ja järjepidev informatsioon lubab identifitseerida kõrge potentsiaaliga alad ulatusliku ja palju säästlikuma reovee puhastuse meetodi kasutuselevõtuks alavaliku protsessis linna või tööstuse arenduses. Käesolevas töös väljatöötatud meetod eeldatavalt vähendab planeerimiskulutusi ja ühtlasi viib täpsemate ning tasakaalukamate otsuste tegemiseni.

Meetod näitas, et väga sobivate alade osakaal avaveeliste märgalapuhastite rajamiseks Eestis on 16% ja sobivate osakaal 25% kogu riigi territooriumist. Tulemuste erinevus maakondade vahel ei ole suur, kuigi kõrgem potentsiaal on peamiselt koondunud madalamatele aladele. Väikseim väga sobivate alade osakaal oli 5% ja kõrgeim 23%. Protsentuaalselt varieerus sobivate alade osakaal 7st 49ni. Detailne analüüs näitas aga, et isegi aladel, mis regionaalse analüüsi järgi klassifitseerusid mittesobivate alla, sisaldub teatud arvul ka väiksemaid maastikuüksusi sobivate aladega. Siiski oli aladel, mis klassifitseerusid regionaalse maastikuanalüüsi järgi sobivateks, ka detailse analüüsi järgi sobivate maastikuüksuste osakaal märgalapuhastite rajamiseks suurem.

Lisaks väljapakutud GIS-meetodile maastiku potentsiaali hindamiseks märgalapuhastite rajamise eesmärgil, hinnati ka hüdromorfsete muldadega alade sobivust neil ehitusliku toormaterjali tootmise lisafunktsiooniga heitveepuhastus-tehismärgalade rajamiseks. Ühtlasi katab see hinnang ka maastiku produktsiooni funktsiooni analüüsi. Töö käigus hinnati laialehise hundinuia ja hariliku pilliroo aastast biomassi tootlikkust ja N ning P varu fütomassis kahes avaveelises märgalapuhastis ja ühes poollooduslikus märgalapuhastis Eestis. Hundinuia ja pilliroo keskmine maapealne biomass varieerus vastavalt 0.3–1.8 kg (kuivaines) m^{-2} ning 0.6 kuni 1.3 kg m^{-2}. Hundinuia maa-aluse biomassi kuivaine kaalunäitajad olid 0.61 kuni 1.31 kg m^{-2} ja pilliroo näitajad vastavalt 1.60 kuni 1.69 kg m^{-2}. Tulemused näitasid, et tehismärgalades kasvava hundinuia produktiivsuses esineb suuri ajalisi ja ruumilisi varieeruvusi, mis teeb selle kasutuse potentsiaalse toormaterjali allikana ehitusotstarbel ja kiutootmisel üsna raskeks. Seega on vajalik läbi viia täiendavaid uurimusi hundinuia produktiivsuse hindamiseks, sest suurenenud on vajadus hundinuia „villa”, kui väärtusliku ehitusmaterjali (nt savikrohvi komponendi) järele.

Hundinuia toitainete neelamise maht oli arvestatavalt kõrge. Keskmine N ja P kontsentratsioon oli kõrgem maa-aluses biomassi osas võrreldes maapealse osaga. Seejuures oli aga mõlema toitaine varu maa-aluses osas madalam kui maapealses osas. N ja P olid pärast viljakandvat perioodi kogutud reservorganitesse. Kogutud toitained aitavad taimel järgmisel kevadel luua uusi võrseid. Seetõttu soovitatakse hundinuia saagikoristustööd läbi viia pärast toit-ainete ümberasetsemist. Maapealse biomassi koristus omaks väga arvestatavat mõju toitainete eemaldamisele madalama hüdraulilise ja toitainete koormusega süsteemile (Tänassilma ja Häädemeeste), kuid ei mõjutaks oluliselt toitainete eemaldamist avaveeliste puhastusmärgalade süsteemist (Põltsamaa). Maapealse fütomassi eemaldamine võib olla teostatav, kui eemaldatavatele makrofüütidele on olemas rakendus nagu kasutamine ehitusmaterjalide koostises või energiatootmises. Siiski vajab hundinuia pikaajaline produktiivsus (eriti taastumine pärast saagikoristusperioodi) rohkem põhjalikke uurimusi.

GIS-analüüsi põhjal on Eestis 5412 km^2 potentsiaalselt sobilikke alasid hundinuia märgalapuhastite rajamiseks. Selle analüüsi käigus elimineeriti ebasobivad alad nagu metsad, Natura 2000 võrgustik, kaitse all olevad alad, kaitse eesmärgil eraldatud spetsiaalalad, väärtuslikud elupaigad, planeeritavad kaitsealad, asustusega kaetud alad ja 200 meetrit laiad puhvertsoonid veekogude kallastel. Ülejäänud sobivatest aladest suurema osa moodustavad kuivendatud turbakaevandusalad.

Ühe maastiku regulatsioonifunktsioonina hinnati ka kasvuhoonegaaside CH_4 ja N_2O emissiooni Eesti maapiirkpndades. Peamised maakasutuse tüübid, mis leiti CH_4 ja N_2O emissioonide kohta kirjanduse analüüsi käigus, viidi vastavusse Corine'i maakattetüüpide nomenklatuuriga. Vastavalt sellele arvutati välja hinnang aastaste CH_4 ja N_2O voogude kohta mulla ja atmosfääri vahel sõltuvalt maakatte tüübist erinevatel Eesti muldadel. Kirjanduse analüüsi põhjal leitud CH_4 ja N_2O voogude mediaanväärtused korrutati vastava maakattetüübi kogupindalaga. Tulemused näitasid, et madal- ja siirdesoodel ning rabadel on CH_4 emissiooni väärtus (kirjanduse analüüsil leitud mediaanväärtuste alusel) 11188 tonni aastas. Hinnanguliselt järgnevad sellele lehtmetsad hüdromorfsetel muldadel ja rabad (vastavalt 9396 ja 6558 tonni aastas). Suurim CH_4 sidumine oli segametsades (–1780 ja –944 tonni aastas vastavalt hüdromorfsetel ja automorfsetel muldadel) ja okaspuumetsades automorfsetel muldadel (–622 tonni CH_4 aastas). Põllumajanduslike muldade metaani sidumise potentsiaal osutus oodatust nõrgemaks (–166 t CH_4 automorfsetelt põllumuldadelt kuni –42 t CH_4 rohumaadelt hüdromorfsetel muldadel). Suurimad aastase N_2O voo väärtused hinnati okaspuumetsades hüdromorfsetel muldadel (3180 tonni aastas), segametsades hüdromorfsetel muldadel (2411 tonni aastas) ja intensiivselt kasutatavatel põllumaadel samuti hüdromorfsetel muldadel (1362 tonni aastas). Kasvuhoonegaaside voogude leevendamiseks saab välja tuua järgmised põhimõtted: (1) kuivenduse vältimine turvasmuldadel (minimiseerib N_2O and CO_2 emissiooni), (2) eelistatud on mahepõllumajanduse arendamine (vähem väetamist vähendab ka emissioone suuremalt osalt põllumajanduslikest aladest), (3) kiirekasvuliste energiametsade ja -võsade rajamine (eelistatult automorfsetele muldadele; aitab siduda nii CO_2 kui CH_4). Valupunktides nagu kaldatsoonides ja reoveepuhastus-tehismärgalades tuleks järgida vastavat majandamisskeemi (kaldaäärse metsa selektiivne raiumine, reovee efektiivsem eelpuhastus). Endiste turbatootmisalade taastamine toob kaasa olulise CO_2 emisiooni kahanemise, kuid metaaniemissiooni tõusu esimestel aastatel ning tõenäoliselt pikaajalise N_2O emissiooni.

Maastiku regulatsioonifunktsioonide hindamismetoodika väljatöötamine säästliku maastiku planeerimise eesmärgil on olulise tähendusega, kuna see võimaldab maastike multi-funktsionaalset kasutust ja toetab jätkusuutlikku arengut. Käesolevas töös välja töötatud meetod tehismärgalade optimaalseks paigutamiseks maastikul on leidnud kasutust ka teiste Euroopa piirkondade maastiku analüüsil näiteks Aragoonia põllumajandusmaastikel Hispaanias.

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