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Peat

Edited by Bülent Topcuoğlu and Metin Turan

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and **Metin Turan**

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http://dx.doi.org/10.5772/intechopen.69565
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Contributors

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First published in London, United Kingdom, 2018 by IntechOpen
eBook (PDF) Published by IntechOpen, 2019
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, The Shard, 25th floor, 32 London Bridge Street
London, SE19SG – United Kingdom
Printed in Croatia

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Additional hard and PDF copies can be obtained from orders@intechopen.com

Peat
Edited by Bülent Topcuoğlu and Metin Turan

p. cm.

Print ISBN 978-1-78923-746-7

Online ISBN 978-1-78923-747-4

eBook (PDF) ISBN 978-1-83881-395-6

Meet the editors

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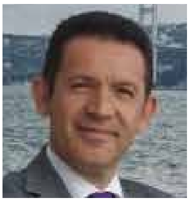

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Preface

Peat is mostly an organic material derived from plant deposits that accumulate in certain types of ecosystems. Peat material includes bog plants such as mosses, shrubs and sedges. Peatlands are wetlands that are characterized by semidecayed organic matter that is produced at a rate greater than its decomposition.

Peatlands or wetlands are regarded as the most important ecosystems on earth, with their biodiversity, natural functions, carbon–water cycle, and climate change and economic values. In the historical process, the first human settlements seem to have been concentrated in places defined as wetlands, such as deltas, flood plains, lakes, and rivers. Many communities such as the Egyptians, Mesopotamians, Chinese, Indians, and Aztecs have lived in wetlands for thousands of years and have cultivated crops and reared livestock in the fertile floodplain every year, as well as built great civilizations with opportunities provided by these wetlands.

In 1890, the source of mosquitos, which caused the deaths of millions of people, was discovered to be wetlands, and people's perception of wetlands began to change. It was subsequently assumed that the only and definitive solution to prevent malaria was to dry the marshes. Initially, only drying studies to prevent malaria disease were directed at floodplains and marshes, but along with developing technology this concept became available in other farming areas. In this process, Mediterranean countries have lost close to 70% of their wetlands. However, as a result of the drying out of wetlands, most of the arable land has been inaccessible to desired agricultural production; in some places it has become inefficient in a short time due to salinization, burning of peat, and wind erosion. In addition to the deterioration and climatic changes occurring in the water regime of the region, problems have arisen that cannot be compensated for, such as the loss or extinction of many living species. Following these developments, wetland conservation programs based on ecological, social, and economic analyses have been developed, with a number of conservation measures being taken to protect wetlands in many countries under the influence of non-governmental organizations and other nature conservation organizations.

Today, peat material is used in many sectors and demand for peat is increasing in many countries. Peat is now being used in cultured mushroom production, soil cultivation, feed rations, barn and poultry farming, medicine and balneology, heavy metal adsorption, aquarium media conditioners, food fumigation, packaging and insulation materials, alcohol, and carotene and humic acid production. It is also used in many fields as a raw material. Most peat has been used as a form of energy for at least 2000 years. Understanding the natural characteristics and functions of peat is important for its correct and safe use. Today, the visible effects of global warming and climate change are being felt everywhere, and freshwater resources are rapidly being depleted and polluted. In this respect, protecting wetlands and delivering health to future generations is one of our most important responsibilities.

The editors of this book are enormously grateful to all the contributing authors for sharing their knowledge and insight in this interdisciplinary project. The publication of this book is of high importance for researchers, scientists, and engineers in relevant fields with expertise in soil science, horticultural sciences, hydrology, forestry, climatology, geophysics, environmental sciences, geography, geoecology, civil and geotechnical engineering, and other disciplines who contribute and share their findings to take this area forward for future research.

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Section 1

Peatland Function on Ecosystem and Biodiversity

Chapter 1

Introductory Chapter: Introduction to Peat

Bülent Topcuoğlu and Metin Turan

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79418

1. Peat formation and characteristics

The word known peat is growth on organic systems where the plant growth is fast, but soils are defined as a partially decomposed organic matter deposit due to poor aeration and low temperature grades [1]. Peat is also named as turf and turba in different literatures owing to its unique property to natural areas called peatlands, bogs, mires, moors, or muskegs. The formation of such deposits is not related to particular climate regions, but it can occur wherever appropriate conditions are present. Organic soils are presented in all the continents of the world. Organic soils are mainly presented under tropical climates with above 60° northern latitudes, and about 450–500 million hectares of total world reserved areas. It is documented that about 150 million hectares of organic lands and about two-third of the world reserves are found in Russia and Canada [2].

Swamps, stagnant waters and pasturelands of the shallow ground water areas have suitable conditions for the accumulation of organic matter. In such places, plants lose their vitality and are covered with water because thousands of growing plants remain in the water. The water interrupts their association with the air and provides partial protection for organic matter and hence preventing them from being quickly decayed. Decomposition is mainly accomplished by fungi, anaerobic bacteria, algae and microscopic water creatures. They breakdown organic structures, release some gases, and thus help humus synthesis. As this process continues, the organic mass becomes brown, and even black. If this decomposition process progressed, the organic matter mass turns into a true organic soil profile. The humus formed here is almost identical to the formation of the ligno-protein complex and polyuronite which is predominant in mineral soils. In addition, triglycerides hydrolyze, yielding fatty acids and glycerol throughout decomposition [3]. This facilitates practicality of soil microbiology.

In the peatland, a plant generation accumulates following another and hence stratification can occur. Due to the accumulation of organic matter, water is gradually withdrawn from the surrounding areas of the marshes and changing plant species. In the course of time, deep water deposits give their places to the sedges and carex plants. These also leave their places to various mosses. These areas are dominated by shrubs, and finally by broad-leaved and coniferous forest trees.

The formation of peat is a relatively short biochemical process under the influence of aerobic microorganisms in the surface depths of the deposits during periods of low subsoil water. As the peat which is formed in the peat-producing layer becomes subjected to anaerobic conditions in the deeper layers of the deposit, it be preserved and shows comparatively little change in time [4]. In detail, the glycerin is quickly used in the form of carbon and oxygen by microbes under anaerobic conditions [3]. The residual fatty acids comparatively persevere by stable parts of the peat. These substances that might be obtained with non-aqueous organic solvents are together referred to bitumens. For instance, humic acids are thought to create strait from polymer or like microbiologic products.

Peats, which does not have consensus on classification, are trying to be classified in different countries and with specific requirements of different disciplines. Present classification systems are categorized based on the topography and geomorphology, surface vegetation, chemical, botanical, physical properties and genetic processes within the peatswamp [5]. Depending on the differences in their physical and chemical structures and their presence in the medium, these organic substances have been given various names. The physical, chemical and biological differences between organic soils are due to the climatic, topographic, hydrological, geological and botanical properties of the environment in which they occur [6, 7]. Organic soils are distinguished by Soil Taxonomy as the Order of Histosols. Generally, Histosols has an organic matter more than half of the upper 80 cm [8]. Organic soils are commonly named mucks and peats. Unsaturated conditions for more than a few days, organic carbon content of these soils expected to be more than 20%.

Depending on the usage purposes, peat can be characterized in numerous ways. Assessing of peat materials for different purposes requires emphasis on distinctive characteristics. The most relevant characteristics of peats for many disciplines are listed in **Table 1** [5].

Chemical properties	Physical properties
Composition (organic compounds; elemental)	Moisture relationships (water retention; available water content; hydraulic conductivity; water holding capacity)
Acidity (pH)	
Exchange characteristic (cation exchange capacity; exchangeable cations)	Bulk density (non-specific; specific)
Organic carbon	Porosity
Nitrogen; phosphorus; sulfur; trace elements	Texture (loss on ignition)
Free lime ($CaCO_3$)	Irreversible drying
	Swelling and shrinking

Table 1. The most relevant chemical and physical characteristics of peats [5].

The physical and chemical properties of the peats show a wide variation. Peat is found abundantly in nature in various forms whereas it is 80–90% water in its formation [3]. The chemical properties of peat differ extensively and within particularized bonds owing to the chemical reactions as part of its formation. However, it is currently fulfilled that the fundamental properties of peats help to sorption and ion exchange. A comparison of some chemical properties of loamy textured mineral soils and various peats is given in **Table 2**.

The characteristic of microbial composition of the peat production is a well-documented difficulty for incessant large-scale processing. Peats are chemically organic material, which leaves diminutive ash after it burned. Peat may be characterized by their ash content and acidity. High-moor sphagnum peats are simply marginally decomposed with high polysaccharide content and comparatively high O_2, and lower C and H concentrations in comparison to low-moor peats [3]. The peat is originated to have proteins, carbohydrates, lipids and polyphenols such as lignin whereas, nucleic acids, pigments, alkaloids, vitamins and other organic materials are existing in small amounts, along with inorganic materials [3]. Various B vitamins were found in peat [10]. Currently, the chemical and physical properties of peat have created significant environmental concerns. Number of studies has been appointed to full-scale plant operations and hence made significant production capacity of active carbon potentially by peat pyrolysis and peat coke production [3]. Pyrolysis alters peat from a material including H and O_2 with a very high carbon concentration. Peat coke might be utilized like decolorizing and de-odorizing agent and a filter medium [3]. Activated carbons are arranged in different grades from peat. Diverse properties are necessary for different responsibilities such as water purification, the removal of organics from starch, sugars and color and gas and vapor adsorption.

		Peat types			
Property	**Unit**	**Sphagnum**	**Fibrous reed sedge**	**Decomposed reed sedge**	**Peat humus**
Peat weight	gL^{-1}	88	160	240	320
Water content		930	890	835	780
Total weight		1018	1050	1075	1100
Water content	% WB	91	85	78	71
Water content	% DB	970	554	346	242
		Soil types			
Property	**Unit**	**Loam soil**	**Sphagnum peat**	**Woody peat**	**Muck**
CEC by weight	meq^{-1} 100 g	12	100	90	200
CEC by volume	meq^{-1} 100 ml	14	8	14	60

Table 2. Some physical characteristics of peat types and a comparison of cation exchange capacity (CEC) of mineral and various organic soils [9].

2. Peatlands and wetland ecosystems

Peatlands are wetland ecosystems that affect the balance of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) on a global scale. These gases are main GHG emissions from agricultural lands and responsible for 18% of the global greenhouse gases [11]. Peatlands are formed by the limited decomposition and accumulation of plant material in previous geological periods. It is also a source of coal, lignite and natural gas, and considered as fossil fuels formation. Pyrolysis can be an example of these processes, which is a potential process to produce active carbons [3]. Steam or carbon dioxide might be utilized to improve the char formation and post charring acid washing might be utilized to increase surface activity [3]. Due to their rich organic material, peatlands have been used to meet the basic needs of the local people in the past. However, they are recently more into prominence with one of the largest carbon deposits in the biosphere from the perspective of climate change, and regulation of water regime and biodiversity conservation functions [12].

Peatlands play a significant role in the global carbon dioxide cycles by carbon sequestration in its different strata of their ecosystem. These strata are known as biomass, dead cover, peat layer, mineral topsoil and pore water. Each stratum has its own dynamics and cycles. Not only the amounts of carbon in these ecosystems are still unknown but also, the quality and quantity of soil organic carbon is important for agroecosystems. For instance, Lehmann [13] has stated the importance of understanding both the quality and quantity of organic amendments and their impact on microbial diversity and soil structure. Moreover, Ozlu [14] has stated importance in different source of carbon inputs such as manure and inorganic fertilizers and reported the types and doses of organic amendments. In addition, there is insufficient information about the change in carbon dynamics in these ecosystems over time. So far, there are different results for the same areas in peatlands by using different calculation methods. These different methods are used based on determination of peat volume, calculation of carbon intensity and dating methods [15]. It is documented that peatlands store more than 550 Gt of carbon with a 3% area covered in total. This amount equals to 75% of atmospheric carbon and 30% of worldwide carbon. Peatland also stores twice as much carbon as all forest biomass in the world and this indicates that peatlands are the second most important long-term carbon storage after the oceans [16]. The global ecosystemic carbon dioxide cycle would hardly be influenced at all by destruction of the peatlands as carbon accumulating ecosystems. Peatland ecosystem has also an adsorptive function for the elements, which have been released in toxic amounts into the environment. Peat destruction can result severe environmental degradation and often toxic heavy metals.

Today, one of the miracles of nature is increasing in importance and gaining importance for organic soils. The first use of organic soils began as fuel in the Caucasus and Siberia. In the following years, organic soils had been used as fertilizer and flowerpot soils due to its suitable physical and chemical properties. Owing to its high-water retention capacity, porosity and many others suitable physical properties, peat is an extremely useful material as a plant growth medium. Peats are also widely used especially in organic agriculture and soilless culture applications. Today, there is a growing demand in this field. Organic soils have been used in cultured mushroom production, soil cultivation and animal feeding. Organic soils are also used in many fields outside of agriculture as direct and raw materials such as in the field of medicine and balneology, heavy metal adsorption, aquarium conditioning, food production, packaging and insulation, alcohol production, carotene and humic acid production.

The limited presence of organic soils in certain regions of our world and the prevalence of agricultural and industrial uses indicate the importance of these lands in terms of environmental impacts, economic values and their rational use. Managing the sustainability of production in agriculture and industrial areas and conserving of environmental values with the right strategies, the balance of conservation and use of natural resources is of utmost importance for the future of planet.

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Salt Marsh Peat Dispersal: Habitat for Fishes, Decapod Crustaceans, and Bivalves

Kenneth W. Able, Christina J. Welsh and
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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74087

Abstract

Salt marshes, especially those of *Spartina alterniflora*, are among the most productive habitats on Earth. The peat that is formed and accumulates there, as below-ground biomass, can be dispersed in a number of ways, through calving off the marsh edge along bays, in creeks, and other locations as occurs in the Mullica River – Great Bay estuary in southern New Jersey. Based on a variety of sampling approaches, including those collected by sidescan sonar and direct collection, we provide new insights into the ecological role of dispersed peat. Some of this is ice rafted on the marsh surface during storms. Elsewhere, and most commonly, it falls into the intertidal channels or flats where it may continue to support the growth of *Spartina*, and associated invertebrates such as *Geukensia demissa*. If it is deposited subtidally these may not be as likely, but in these situations the peat provides structured habitat for other animals such as fishes, crabs, shrimps, and bivalves.

Keywords: peat reefs, salt marshes, habitat complexity, fishes, macroinvertebrates

1. Introduction

Salt marshes are some of the most productive ecosystems on Earth. How that production is dispersed is a frequent focus, particularly in the form of detritus [1–3]. Other, unrecognized forms of dispersal, such as that for salt marsh peat, are infrequently studied. Peat in salt marshes results from the degradation of roots, stems and leaves of marsh plants, particularly *Spartina alterniflora* and *S. patens* [4, 5], and accumulates at a greater rate than decomposition.

This occurs in New Jersey east coast marshes as well, where estimates of the accumulation of this below ground have been determined [6–8]. Erosional processes in coastal salt marshes lead to peat breaking away from the marsh edge and falling into the channel to form peat reefs or being ice rafted from the edge to other locations. When ice dispersed salt marsh peat away from the edge of a channel, a large proportion of this peat was rafted to the lower intertidal while other pieces of peat were carried to the marsh surface [9]. The response of the marsh vegetation and associated fauna, such as *Geukensia demissa*, varied with the deposition site and the amount of ice that they were exposed to [10]. When deposited in the water, peat reefs are large pieces of live and decomposing plant material and associated sediments that separate from the marsh surface and form intertidal and subtidal structures of varying sizes in channels. While their existence, including as mud boulders [11], has been documented for many decades, it is only with new bottom imaging technology that it is possible to easily map these underwater structures.

One of the main causes of separation of marsh peat from the marsh platform is the bank being undercut by the current because the lower mud layer is less stable than the peat, and washes away first [12–14]. This leads to a peat overhang that then breaks off and falls away from the marsh edge into intertidal and subtidal waters. Three distinct forms of slump are observed during this process [15]. Rotational slump occurs when the peat slides down the bank on its side, with the marsh vegetation facing the bank. Non-rotational subsidence occurs when the block does not move, but sinks straight downwards, creating a ledge. Freefall slump occurs when the peat fractures cleanly from the bank and falls away from the marsh into the channel, as in peat reefs. The timing and size of bank failures is influenced by geological factors specific to each marsh, such as peat thickness and channel depth [14, 16]. High storm frequency leads to higher rates of erosion, which can cause seasonal and geographical variation among otherwise similar salt marshes [17]. Peat reef formation may be enhanced by eutrophication as well [18]. It has been shown that other marshes in the northeastern U.S. experience bank failure [14, 16, 19–21], but marshes there have not been observed to experience extreme channel migration [22]. A study in Sapelo Island, Georgia showed that the water volume of a coastal salt marsh had not changed significantly in 200 years, meaning erosion and deposition were in equilibrium in that system [17].

The subsurface peat reefs are fairly resilient. For example, a study conducted at Nauset Marsh in Cape Cod, Massachusetts established that a 2-meter long peat reef that had fallen into a tidal creek has a lifespan between 7.5 and 15 years before it erodes away [14], meaning there is enough time for it to be colonized by a variety of organisms [19]. Various crustaceans were found year-round on the peat reefs, including juvenile *Homarus americanus* and structure-seeking fish species. However, these sites have historically been difficult to survey. Long-term datasets of finfish populations throughout these marsh systems have been collected, but sites with peat reef bottom structure are seldom effectively sampled due to gear limitations. Thus, we know little of their structural and functional significance [23, 24] because peat reefs are difficult to detect in subtidal locations and even more difficult to sample. The purpose of this paper is to characterize patterns of marsh peat dispersal, i.e. peat reef formation and ice rafting, and faunal use in a relatively undisturbed estuary dominated by salt marshes. To accomplish this we used a number of techniques including subsurface sidescan surveys and in situ sampling during the summer and fall in 2017.

2. Study site

The Mullica River - Great Bay estuary in southern New Jersey (**Table 1**, **Figure 1**) is dominated by tidal salt marshes [25, 26]. This system is relatively unaffected by urbanization due to the small

Sample Number	Location	Marsh seascape type	Dominant marsh vegetation	Approximate salinity (ppt)	Transect length (m)	Range of depths surveyed (m)	Range of depths for peat reefs (m)	Density of peat reefs (Reefs per 100 m of bank scanned)
1	Little Sheepshead Creek	Thoroughfare	*S. alterniflora*	25–32	1910	0.6–6.8	0.8–6.7	6.79
2	Big Sheepshead Creek	Thoroughfare	*S. alterniflora*	26–31	2350	0.0–4.3	0.7–3.4	0.70
3	Jimmies Creek	Thoroughfare	*S. alterniflora*	26–30	3680	0.3–3.9	0.5–3.7	0.76
4	Little Thorofare	Thoroughfare	*S. alterniflora*	26–30	2960	0.5–7.6	0.5–7.4	5.47
5	Big Thorofare	Thoroughfare	*S. alterniflora*	24–30	3440	0.0–5.8	0.6–4.6	0.74
6A	Seven Islands	Island Thoroughfare	*S. alterniflora*	28–30	1450	2.6–5.2	3.3–5.2	10.07
6B	Seven Islands	Island Thoroughfare	*S. alterniflora*	28–30	1560	0.5–3.5	1.4–3.5	1.15
6C	Seven Islands	Island Thoroughfare	*S. alterniflora*	28–30	1220	0.7–4.0	2.4–3.9	4.02
6D	Seven Islands	Island	*S. alterniflora*	28–30	1650	0.6–3.4	2.5–2.9	3.19
6E	Seven Islands	Island	*S. alterniflora*	28–30	1670	0.4–7.0	1.0–7.0	35.21
7A	Story Island	Island	*S. alterniflora*	28–31	5270	0.5–7.7	0.7–6.3	1.14
7B	Story Island	Island	*S. alterniflora*	28–31	1320	0.5–4.2	0.9–4.3	2.65
7C	Story Island	Island	*S. alterniflora*	28–31	1450	0.7–4.5	2.6–4.4	10.62
7D	Story Island	Island	*S. alterniflora*	28–31	4740	0.7–3.0	0.7–1.7	1.20
8	Motts Creek	Thoroughfare	*S. alterniflora*	16–25	5940	0.8–7.8	1.3–7.5	0.73
9	Nacote Creek	River	*S. alterniflora*	9–23	7040	1.4–7.5	2.0–6.9	0.12
10	Ballanger Creek	Creek	*S. alterniflora*	13–21	4450	0.6–7.8	0.8–7.2	0.12
11	Mathis Thorofare	Thoroughfare	*S. alterniflora*	13–21	5330	0.7–7.7	1.0–4.5	0.51

Sample Number	Location	Marsh seascape type	Dominant marsh vegetation	Approximate salinity (ppt)	Transect length (m)	Range of depths surveyed (m)	Range of depths for peat reefs (m)	Density of peat reefs (Reefs per 100 m of bank scanned)
12	Bass River	River	*S. alterniflora*	15–20	5210	1.0–8.3	2.2–7.2	0.47
13	Wading River (Lower)	River	*S. alterniflora*	7–12	4740	1.4–9.3	No Reefs	0.00
14A	Fence Creek	Creek	*Spartina/ Phragmites*	5–15	630	0.7–2.4	1.2–1.9	0.56
14B	Jerry Creek	Creek	*Spartina/ Phragmites*	5–15	1290	0.5–2.3	0.9–1.8	0.35
15	Teal Creek	Creek	*Spartina/ Phragmites*	0–7	1190	0.6–3.1	1.2–1.3	0.13

Sampling number corresponds to numbers on **Figure 1**. Marsh seascape types refer to Thoroughfares = open-ended connections through marshes with tidal flow in both directions along marsh edge; Creeks = dead end creeks with only one water access point; River = longer than creeks but with only one water access point; Island = water access to marsh edge at all points

Table 1. Sampling effort by location for determining distribution and abundance of peat reefs based on sidescan transects in the Mullica River – Great Bay estuary during summer and fall 2017.

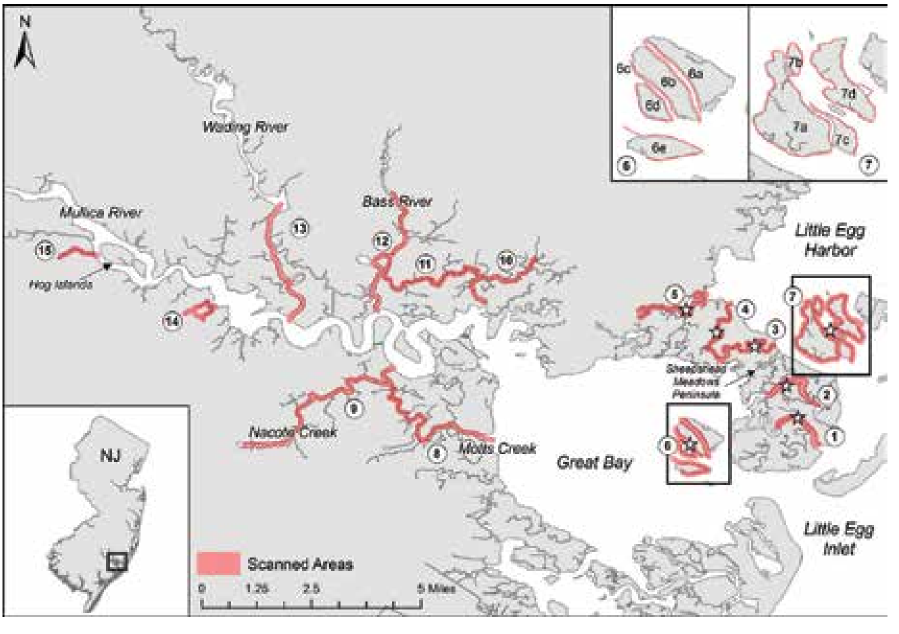

Figure 1. Sidescan sonar sampling locations in the Mullica River – Great Bay estuary in southern New Jersey, USA (see inset). Numbers correspond to location names: 1 = Little Sheepshead Creek, 2 = Big Sheepshead Creek, 3 = Jimmies Creek, 4 = Little Thorofare, 5 = Big Thorofare, 6A - E = Seven Islands (see inset), 7A - D = Story Island (see inset), 8 = Motts Creek, 9 = Nacote Creek, 10 = Ballanger Creek, 11 = Mathis Thorofare, 12 = Bass River, 13 = Wading River, 14 = Jerry and Fence Creeks, 15 = Teal Creek. Stars indicate locations of peat reef faunal sampling.

human population living in the watershed [23, 25, 27], so it can be assumed that human impact on the natural processes here is minimal. The marsh surface in the lower estuary, at higher salinities, is dominated by *Spartina alterniflora* cordgrass, including the Sheepshead Meadows peninsula [28], which builds up on the marsh surface to form a 0.5 m deep layer of peat [6].

Within these marshes the morphology of channels can vary along the salinity gradient and presumably along a creek development gradient. Dead end creeks dominated by *Spartina alterniflora* in the lower, higher salinity estuary and *Spartina cynosuroides* in the upper estuary are the most common. In the upper estuary, at lower salinities, the marshes are dominated by invading *Phragmites* [26, 29, 30] and have a more diverse freshwater flora. Thoroughfares connecting bays and other waterways are most common in the lower estuary, such as in Sheepshead Meadows, and the channels through the flood tidal delta in the vicinity of Little Egg Inlet in Great Bay (Seven Islands) and Little Egg Harbor (Story Islands area). Throughout the lower estuary the marshes, which are dominated by *S. alterniflora*, sit on top of deep sediments (approximately 9 m) based on surveys of the length of the support pilings for the Rutgers University Marine Field Station [31], and multibeam imagery of the Sheepshead Meadows peninsula [26].

3. Methods

3.1. Peat reef mapping

Fifteen locations of varying depths (**Table 1**, **Figure 1**) were sampled during the summer and fall of 2017. Some of the representative sites include Little Thorofare, Big Thorofare, Little Sheepshead, Big Sheepshead and Jimmies Creek in the Sheepshead Meadows. The mouths of these waterways are between 2 and 6 km from the Little Egg Inlet, so they experience a 1 m range in tidal influence and a salinity range of 23.6–34.5 ppt [27]. The average depth in each creek ranges from 0.7 m to 4.2 m (**Table 1**). All of these creeks, thoroughfares, and channels are stable features, as they are evident on aerial photographs from the 1930s (historicaerials.com).

Bottom images of the study sites were mapped using a Helix 10 Humminbird side imaging sonar in the summer and fall of 2017. Data was collected at high tide to reflect the maximum possible number of submerged peat reefs, and because the shallower creeks cannot be accessed by boat at low tide. Both banks of the creek were scanned in narrower creeks (Teal Creek, Fence Creek, Jerry Creek, Bass River, Mathis Thorofare, Motts Creek, Little Thorofare, Jimmies Creek), while only one bank of the wider creeks and rivers were scanned (Wading River, Ballanger Creek, Nacote Creek, Big Thorofare, Big Sheepshead Creek, Little Sheepshead Creek).The recordings were downloaded to the program HumViewer and the locations of individual peat reefs were manually plotted using the Waypoints feature of Humviewer. Peat reef length was measured using the HumViewer program. GPS coordinates and depth of the peat reefs were downloaded to Google Earth and ArcGIS to create a map that showed distribution patterns of the peat reefs throughout the study area (**Figure 1**). Abundance in creeks was categorized as number of reefs per 100 m of marsh bank scanned (**Table 1**).

3.2. Faunal sampling

Field sampling was done in the summer and fall of 2017 to see which organisms utilize peat reefs as habitat relative to adjacent areas without peat reefs. The peat reefs and accompanying organisms were collected in large, enclosable mesh (4.8 mm) bags that surrounded the reef. These were returned to the laboratory for additional analysis. This technique was limited to peat reefs that were small enough and in water less than 2 m deep so that they could easily be collected. An additional seine haul with a 7.6 m, (4.8 mm) mesh seine net was performed adjacent to peat reefs in an area where no reefs were present. The collected reefs were measured (length, width, height) and volume was determined by water displacement. All fish, shrimp, crabs, and bivalves in each collection were removed, identified, measured, and expressed as catch-per-unit-effort, or CPUE (**Table 2**). Most fish and shrimp were measured as total length, fish with forked tails were measured as fork length, and crabs were measured as carapace width. Some components of the fauna at each study site/habitat type (e.g. fish, macroinvertebrates) were identified, measured, and released in the field. Others were removed from the peat reefs in the laboratory and then released.

Species/taxa	Abundance at peat reef (CPUE)	Length – range at peat reef (mm)	Abundance adjacent to peat reef (CPUE)	Length – range adjacent to peat reef (mm)
Fish	44.9	—	120.6	—
Apeltes quadracus	0.1	37–38	0.0	—
Bairdiella chrysoura	3.9	36–94	0.0	—
Chaetodon ocellatus	0.1	28	0.0	—
Cyprinodon variegatus	0.0	—	0.3	26–40
Etropus microstomus	0.0	—	0.1	48
Fundulus heteroclitus	15.1	26–112	64.2	26–95
Fundulus majalis	0.0	—	1.1	52–100
Gerreidae sp.	0.1	33–34	0.0	—
Gobiesox strumosus	0.1	49	0.0	—
Gobiosoma bosc	3.1	23–51	0.3	31–43
Menidia menidia	22.2	27–81	54.6	22–107
Menidia sp.	0.0	—	0.1	27
Opsanus tau	0.1	187	0.0	—
Tautoga onitis	0.1	57	0.0	—
Crabs	18.7	—	4.7	—
Callinectes sapidus	2.8	7–107	4.5	8–125
Carcinus maenas	0.1	15	0.0	—
Dyspanopeus sayi	3.7	5.2–21.5	0.2	8.4–12.5
Eurypanopeus depressus	0.1	9.2–10.7	0.0	—
Hemigrapsus sangueineas	0.1	21.8	0.0	—

Species/taxa	Abundance at peat reef (CPUE)	Length – range at peat reef (mm)	Abundance adjacent to peat reef (CPUE)	Length – range adjacent to peat reef (mm)
Panopeidae sp.	2.4	5.3–23.3	0.0	—
Panopeus herbstii	8.7	4.4–39.4	0.0	—
Uca pugnax	0.4	9.5–14.2	0.0	—
Uca sp.	0.5	3.6–11.0	0.1	15.6
Shrimp	46.1	—	24.2	—
Crangon septemspinosa	0.3	25.4–30.4	0.8	19.8–29.0
Palaemonetes intermedius	0.5	18.2–32.7	0.0	—
Palaemonetes pugio	15.1	16.8–41.6	11.2	19.6–41.8
Palaemonetes vulgaris	28.6	23.3–32.9	11.8	24.5–36.0
Palaemonidae sp.	2.0	24.1–33.2	0.3	26.9
Bivalves	230.5	—	0.0	—
Crassostrea virginica	1.4	24–145	0.0	—
Geukensia demissa	228.6	5–113	0.0	—
Mytilus edulis	0.2	16–25	0.0	—
Petricolaria pholadiformis	0.1	19	0.0	—
Tellina agilis	0.1	10	0.0	—

See **Figure 1** for location of samples. Fish and shrimp measured as total length, crabs as carapace width, and bivalves as valve length

Table 2. Faunal species composition of peat reefs and adjacent sites lacking peat reefs based on in situ sampling in a variety of marsh seascapes.

4. Results

4.1. Peat reef formation

The formation of peat reefs in the study watershed occurs at the marsh edge when marsh peat and the associated marsh vegetation, fauna, and sediments calve off or split off from the marsh platform (**Figure 2**). Most are then either deposited in the low intertidal or subtidal portions of the adjacent waterway. These are evident and can be mapped because they are clearly visible on sidescan sonar images (**Figure 3**). Based on this approach, the in situ estimates ranged from 0.1 to 15.0 m in length (n = 1916), with most from 0.7 to 4.0 m (**Figure 4**).

Intertidal and shallow subtidal peat reefs that could be observed from the surface often still contained the *Spartina alterniflora* vegetation of the same apparent density, length, and orientation of the stems as they were on the marsh surface, thus identifying those that had recently split off from the marsh platform. These were often dominated by individuals or large clumps

Figure 2. Peat reef formation at deeper side of channel, in Little Sheepshead Creek – note scalloped marsh edge (top), in initial stage as pieces of marsh surface separate from the rest of the marsh platform (middle), and intertidal peat reef at edge of marsh thoroughfare (bottom).

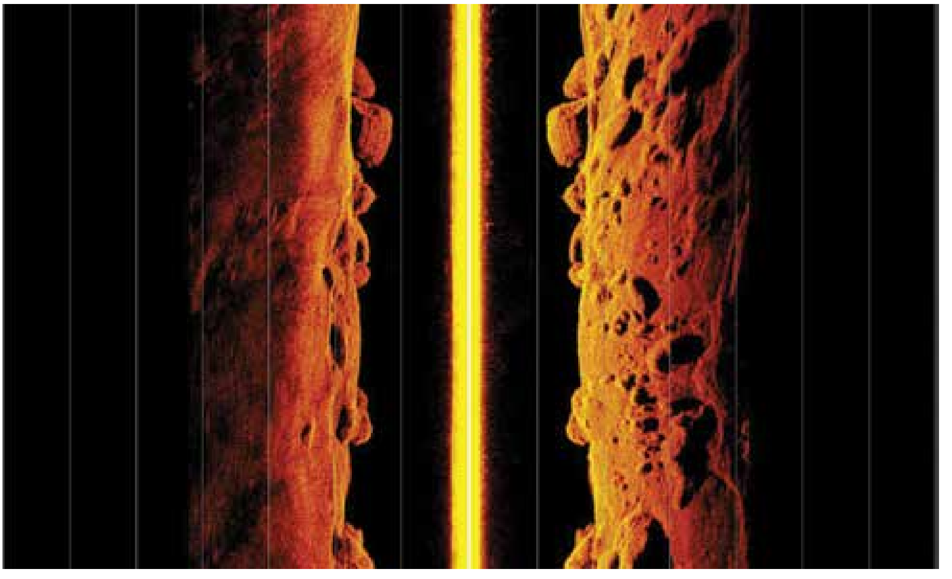

Figure 3. Sidescan sonar images of representative subtidal peat reefs within the Seven Islands study area. The sidescan image indicates that the boat passed directly over the largest pieces of peat thus they are reflected on each side. On the right side of the image smaller pieces of peat are evident.

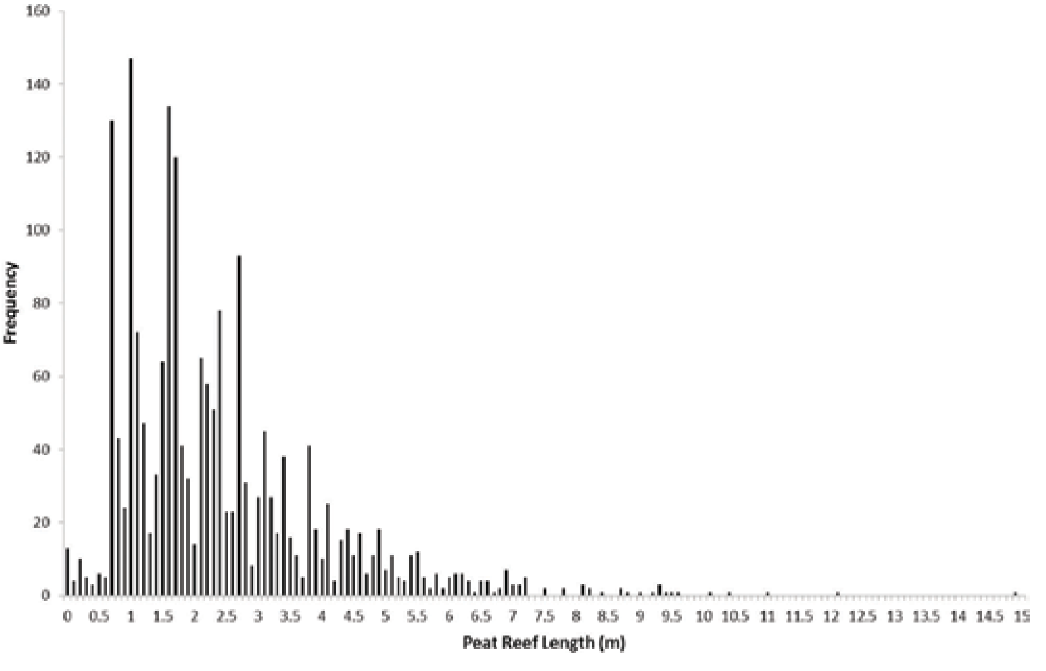

Figure 4. Frequency distribution of intertidal and subtidal peat reef length based on sidescan sonar estimates in the study area.

of *Geukensia demissa*. On some occasions, it was apparent that an individual peat reef had been deposited for at least two vegetation-growing seasons because the original vegetation, now decomposing due to near-constant immersion, was oriented at an angle toward the center of the channel. This was accompanied by new vegetation, from the current growing season, that was typically closer to the water surface and oriented vertically on the peat reef. At longer durations, or perhaps slightly deeper as well, the peat reefs lacked the original *S. alterniflora* vegetation. These often had *Ulva lactuca* and other macroalgae growing or accumulating on the reefs.

In other instances, during cold winters, individual peat reefs were ice rafted on to the marsh surface (**Figure 5**). In the following spring, *S. alterniflora* was still growing from them. Over time, the associated vegetation was less robust, the *G. demissa* died with the shells deposited on the marsh surface, and the mass of the peat reef, including sediments, was reduced. After approximately 1 year, only some sediment and shells remained.

4.2. Distribution of peat reefs

Based on sidescan sonar surveys throughout the salinity gradient in the Mullica River — Great Bay estuary, the highest densities occurred in the lower, saltier portions of the estuary (**Figure 1**, **Table 1**). Transect length, number of banks scanned, and water depth may have influenced the estimates of peat reef distribution and density. Transect lengths ranged from short creeks at the upper end of the estuary (Fence = 630 m, Jerry = 1290 m, Teal Creek = 1190 m) to much longer for several rivers (Bass River = 5210 m, Wading River = 4740 m, Nacote Creek = 7040 m) and thoroughfares (Motts Creek = 5940 m, Mathis Thorofare = 5330 m) (**Table 1**, **Figure 1**). The depth varied between and within transects (**Table 1**). Some of the deepest depths (>6 m) occurred in thoroughfares, some creeks, and rivers and ranged to 7.2 m. All of these types of marsh seascape had variable depths and the deeper holes were irregular in occurrence (**Figures 6**, **7**, **8**). Many of the deepest holes occurred in bends in thoroughfares and creeks (personal observation).

The density of peat reefs also varied independently of marsh seascape type (**Table 1**, **Figures 6–8**). Some of the highest and lowest densities occurred in thoroughfares, including those around islands. Peat reef densities in rivers and creeks were typically lower. The variability that occurred is evident when individual peat reefs are mapped along the transects of the Sheepshead Meadows (**Figure 9**). In some thoroughfares the peat reefs are quite sporadic or in distinct patches (Big Thorofare, Jimmies Creek, Little Sheepshead Creek). In others, they are more or less continuous, as in Little Thorofare.

The size of peat reefs, based on sidescan sonar images, ranged from 0.1 to 15.0 m in length (**Figure 4**). The reefs that were sampled in situ and brought back to the laboratory were smaller and collected primarily from the Sheepshead Meadows, Seven Islands, and Story Islands (**Figure 1**). These came from 0.5 to 1.4 m water depth and ranged from, 23 to 13 cm in length, 15 to 50 cm in width, 13 to 51 cm in height, 0.5 to 77 liters in volume, and 3.1 to 73.0 kg in weight.

4.3. Associated fauna

A variety of fishes (n = 14 species), crabs (n = 7 species), shrimps (n = 4 species) and bivalves (n = 5 species), were collected at peat reefs and on adjacent substrate without

Figure 5. Ice rafted peat reef after a storm (top left) and its remains, including *Geukensia demissa* shells (top right) and after one year (bottom).

peat, with some species having a distinct pattern based on occurrence and abundance (**Table 2**). All faunal groups had more species collected on peat reefs. Also individuals of a single species were typically more abundant on peat reefs. This was most obvious for bivalves and crabs but also occurred for fish and shrimp. The most striking example is for the bivalves (n = 3227 individuals), all of which occurred only on the peat reef.

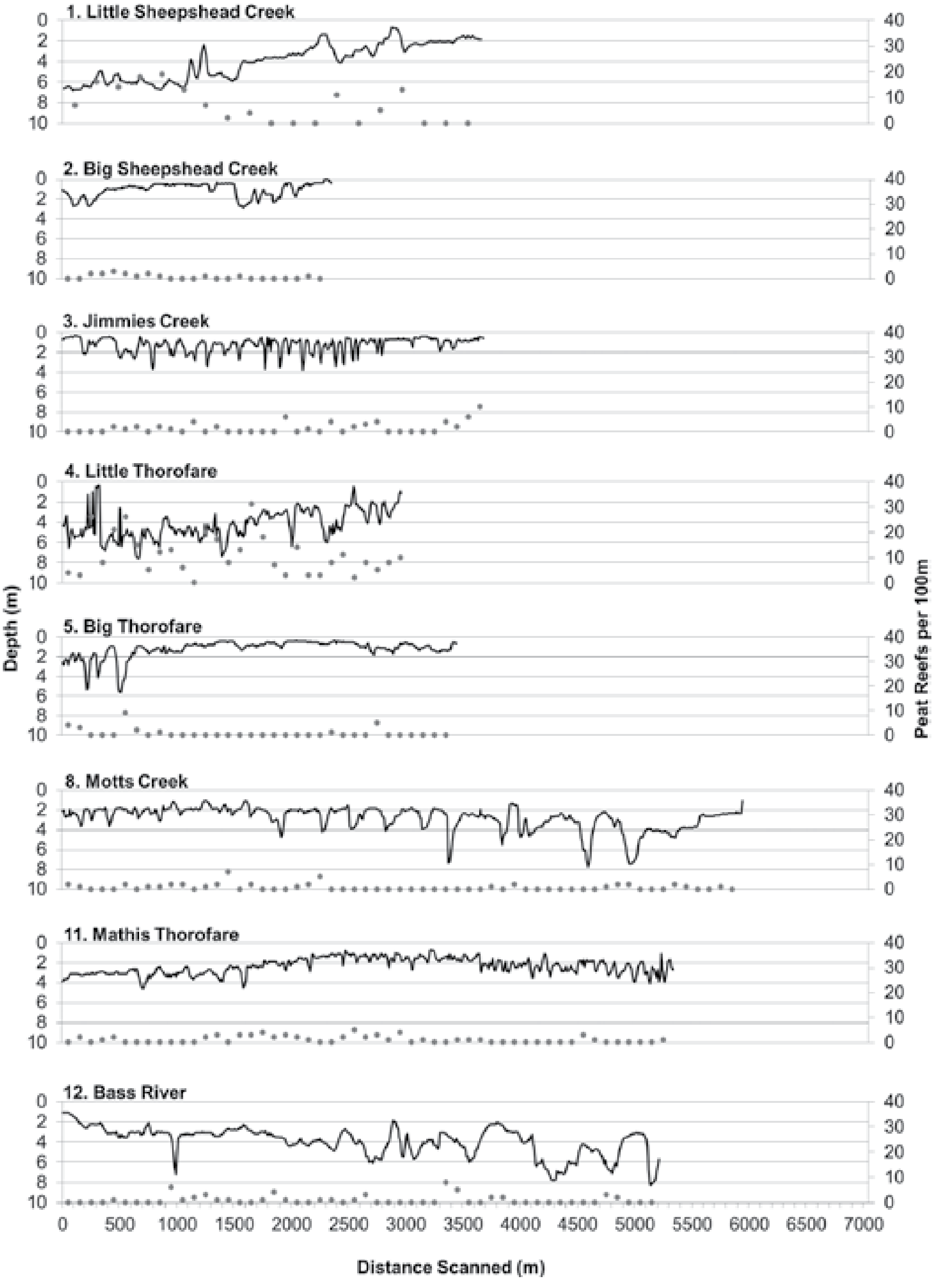

Figure 6. Depth profiles and distribution of peat reefs along sidescan sonar transects in various creeks and thoroughfares throughout the Mullica River – Great Bay estuary. See **Figure 1** for location of sites. Sites with very low peat reef densities or very short transects (see **Table 1**) are not included. Line indicates creek depth. Individual points depict number of peat reefs per 100 m. Scans of thoroughfares run west to east while creek scans run from upper creek to the mouth of the creek. Only one bank of Big Thorofare, Little Sheepshead Creek, Big Sheepshead Creek, Ballanger Creek, Motts Creek, and Wading River was scanned. All other locations were scanned on both banks.

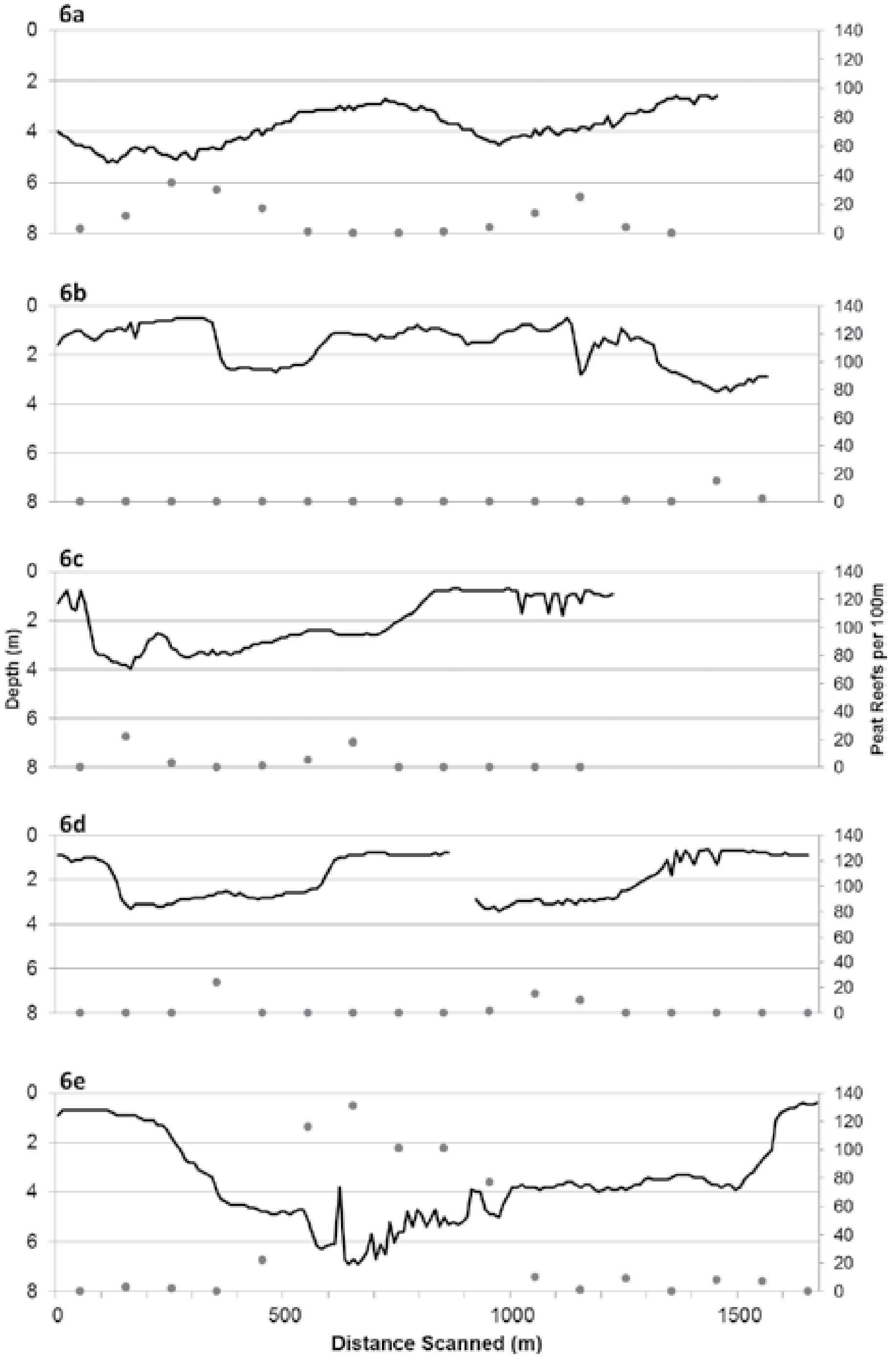

Figure 7. Small scale distribution and depth of peat reefs along sidescan sonar transects at Seven Islands. See **Figure 1** for location of sites. Line indicates creek depth. Individual points depict number of peat reefs per 100 m. One bank was scanned per transect. Scans of thoroughfares (6a, 6b, 6c) run northwest to southeast. The island scan 6d runs counter-clockwise starting at the northern point; there is a 50 m gap between two scans that circle the island. 6e runs clockwise starting at the northern side of the island.

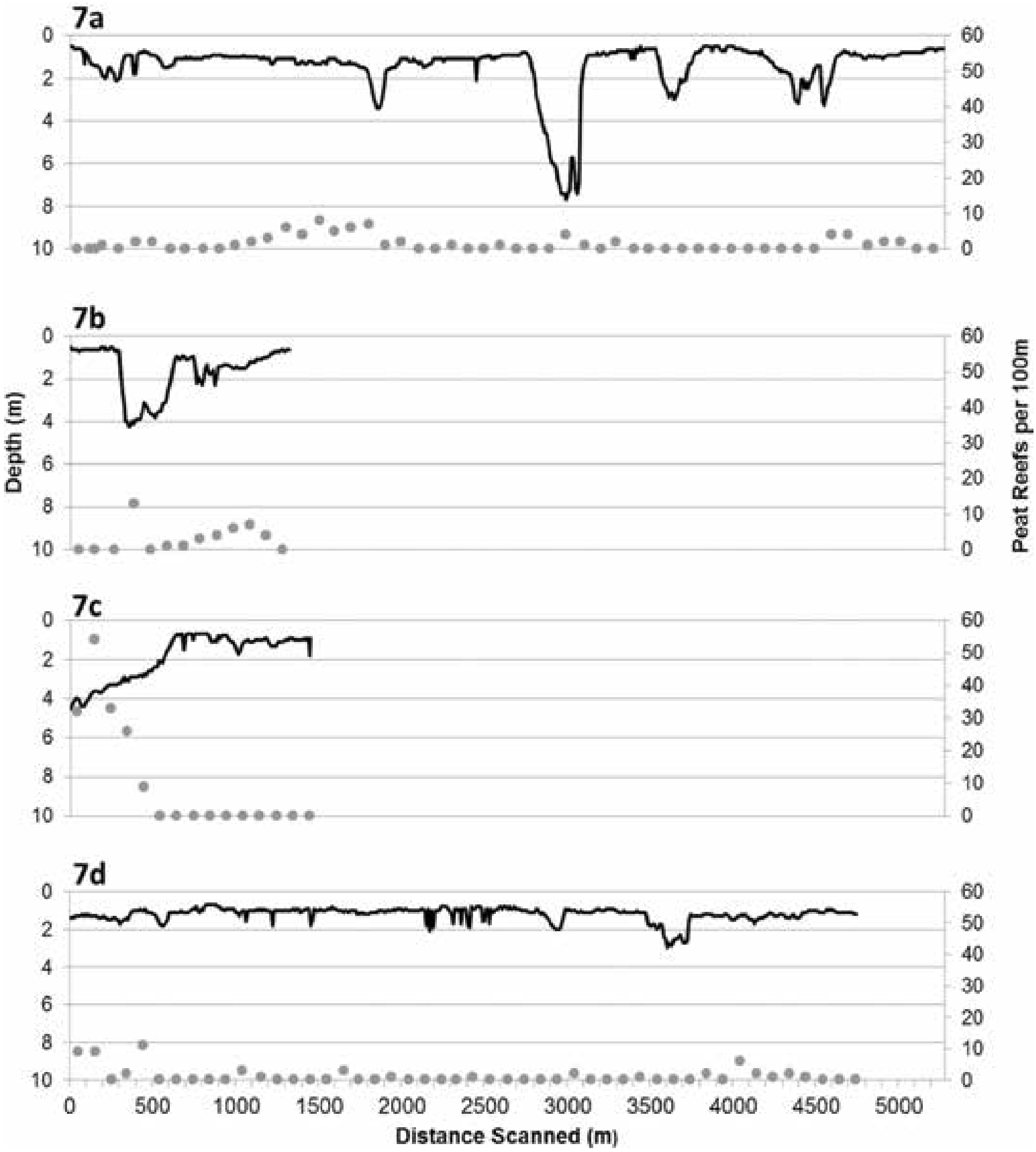

Figure 8. Depth profiles and distribution of peat reefs along sidescan sonar transects at Story Island area. See **Figure 1** for location of sites. Line Indicates creek depth. Individual points depict number of peat reefs per 100 m. One bank was scanned per transect. Scans of thoroughfares (7c) run northwest to southeast, the island scans (7a, 7d) run counter-clockwise starting at the northern point, 7b starts at the western side of the island.

Of these the most abundant, by far, was *Geukensia demissa*, with a mean abundance of over 200 individuals. The shrimp, (n = 964 individuals) *Palaemonetes vulgaris* had higher abundance on peat reefs but also occurred at relatively high abundance on adjacent substrate (**Table 2**). The mud crabs (n = 211 individuals), *Dyspanopeus sayi, Panopeus herbstii, Eurypanopeus depressus,* and unidentified panopeids were all abundant on peat reefs, as were fiddler crabs (n = 14 individuals) *Uca pugnax* and unidentified *Uca sp.* (**Table 2**). A few fish species were slightly more abundant in the adjacent substrates away from peat

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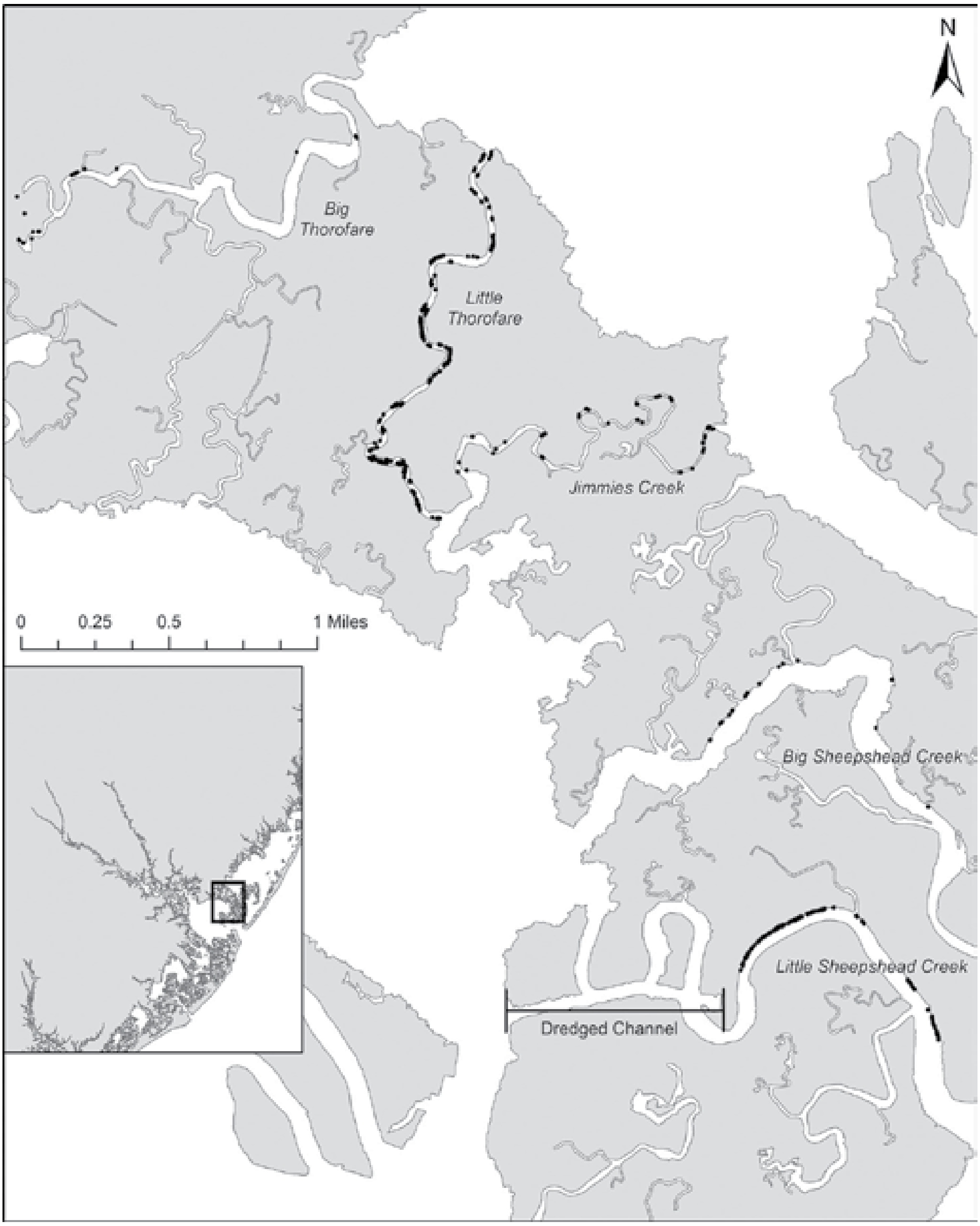

Figure 9. Distribution of individual peat reefs along marsh thoroughfares with some of the highest (Little Thorofare, Little Sheepshead Creek), moderate (Jimmies Creek), and lowest (Big Sheepshead Creek, Big Thorofare) densities. Note that altered portion (dredged channel) in Little Sheepshead Creek was not sampled. Only one bank of Big Thorofare, Little Sheepshead Creek, and Big Sheepshead Creek was scanned.

reefs (**Table 2**), including *Fundulus heteroclitus* and *Menidia menidia*, but in each case, the values were of the same order of magnitude. On most peat reefs, traces of *Spartina alterniflora, Ulva lactuca*, and other macroalgae were present. Where comparisons were possible, the lengths of individuals for all fauna were similar between peat reefs and the adjacent substrates (**Table 2**).

5. Discussion

5.1. Peat reefs in marsh seascapes

The wide distribution and abundance of forming and submerged peat reefs in the Mullica River — Great Bay estuary indicates that they may play significant roles in this relatively undisturbed ecosystem. This includes influences on the geomorphology and ecology based on our studies of peat reefs and the associated fauna, and the natural history of the system [32]. Also importantly, the findings from our study estuary probably reflect the importance of peat reefs in other estuaries. This is particularly likely in marshes in the northeastern United States, i.e. those stretching from Maine to southern New Jersey, that are characteristically composed of peat substrates [13, 33]. This general pattern is evident from other studies in Massachusetts marshes [14, 18, 19]. The frequency of occurrence of peat reefs may be less so in more southern marshes, from Delaware Bay and south to Florida, because marsh peat is less common [13, 33]. The difference may also be reflected in the more frequent occurrence of slump blocks in these southern marshes [13, 15].

Another source of geographical variation in marsh peat dispersal is ice rafting [9, 10]. It is much more likely that this will be a frequent occurrence in New England marshes because of the increasing frequency of ice formation at the colder temperatures in more northern marshes. In addition, the frequency of occurrences in the study estuary over time is likely to diminish because of increasing water temperatures and the decreasing frequency of cold winters in this estuary [34] and others [16] in the region. Variation in the occurrences of ice rafting could also occur because ice formation is more frequent in the upper portion of the estuary, which can be colder, as a result of the lower salinities there [34, 35] and distance from the moderating influence of the ocean [25].

The distribution of peat reefs in the study area, although quite variable, is influenced by marsh seascape type. The overall reduced number of peat reefs further up the estuary may be due to changes in vegetation along the salinity gradient. This appears most evident along the edges of low salinity creeks where the invasive form of *Phragmites australis* is common (personal observation), especially in late stages of the invasion [29]. It may be that the extensive and deep rhizome mat of this species prevents peat reef formation. The other component of marsh seascapes that may contribute to peat reef formation is the open and bi-directional flow of water, perhaps at higher speeds, that may occur in thoroughfares and around islands, where we report some of the highest densities of peat reefs. This is particularly evident at the end of the Sheepshead Meadows peninsula where high current speeds likely contributed to the accumulation of peat reefs in deep water [26]. Exceptions, such as in Big Sheepshead Creek, provide insights. A prominent sill is present at the easternmost end of this thoroughfare, which drastically reduces water flow and thus perhaps erosion at the marsh edge. This same process, but at much lower current speeds in dead end creeks, may account for the reduced number of peat reefs there.

An earlier study in the same system found that waves, from storms or boat traffic, may also influence erosion at the edge and thus peat reef formation [14]. This same pattern has been identified from commercial boat traffic in other systems [36]. Another potential contributor is eutrophication influenced reduction in the structural integrity of creek banks [18]. Once peat reefs are formed they may last relatively long periods of time. Peat reefs in Nauset Marsh on Cape Cod were estimated to last 7.5–15 years [14].

5.2. Ecological significance of peat reefs

Intertidal and subtidal peat reefs provide relatively unrecognized habitat for estuarine flora and fauna that do not occur on the marsh platform as indicated in this study. The abundant mud crabs (*D. sayi, P. herbstii,* and unidentified panopeids), and shrimps (*P. vulgaris,*), are good examples. Alternatively, the *G. demissa* is transported from the marsh platform to the deeper intertidal and subtidal channels, where they survive for a while on peat reefs but not on the, presumably older, deeper ones (personal observations). Once immersed, several common fishes (*Bairdiella chrysoura, Gobiosoma bosc*), including some rarer ones, can also occur.

The complex structure of peat reefs, such as living and decaying *S. alterniflora*, rugose surface of the peat, macroalgae, and crab burrows, may provide increased habitat complexity that is seldom available in most marsh creek channels [19]. Peat reefs may provide food and refuge, and thus nurseries for fishes and crabs. In fact, laboratory studies have shown reduced predation on juvenile lobsters while associated with peat reefs [37, 38]. Further studies of the structural and functional significance should place them in the broader context of the coastal seascapes [39, 40]. Included in this broader understanding should be how peat reef production influences salt marsh channel morphology and sediment and nutrient transport from the edge of the marsh platform to intertidal and subtidal environments [41], and if this is likely to be influenced by sea level rise, as is currently occurring in the study estuary [42] and coastal eutrophication in general [18, 43].

Acknowledgements

This study could not have been completed without the laboratory and field support of the RUMFS staff. Of these, Roland Hagan, Thomas Johnson, Maggie Shaw, and Stacy VanMorter were particularly helpful. Rose Petrecca assisted by identifying invertebrates. Pat Filardi volunteered his time for the field sampling. Funding for Christina Welsh was provided by the Stacy Moore Hagan Memorial Undergraduate Estuarine Science Internship Program from Stockton University in collaboration with RUMFS. The Manasquan Marlin and Tuna Club donated the Helix 10 Humminbird sidescan sonar unit. We are grateful to all of the above.

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Peat Soils of the Everglades of Florida, USA

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72925

Abstract

In this chapter, we briefly discuss the development of the Everglades over the past 5 million years, the modifications made to the Everglades over the past century and a half and the quantification of the changes that have occurred to the peat soils of the Everglades due to natural and anthropogenic causes during this most recent period. Using Geographic Information Systems and historical data sets, we have been able to calculate the original peat volumes, the remaining peat volumes and thus, the amount lost over the past approximately 150 years. From these volume calculations and peat physical and chemical characterizations by the USEPA over a large area of the Everglades, we have estimated the mass of peat and carbon lost, 900 million metric tons and 300 million metric tons, respectively. The amount of peat lost has implications for hydrological, ecological and landscape restoration and habitat recovery for the Everglades.

Keywords: Everglades peats, subsidence, drainage, peat fires, ecological restoration

1. Introduction

The Everglades of the mid-1800s covered about 11,000 square kilometers (1.1 million hectares) and the basal peats have been estimated to have begun to develop approximately 5,000 years ago [1]. The historical landscape (**Figure 1**, left) is described by McVoy and colleagues [1] as having a custard apple swamp region, on the southeastern edge of Lake Okeechobee (Lake), a vast "impenetrable" sawgrass plain to the south of the Lake and a vast ridge and slough landscape which filled most of the rest of the Everglades to the south. The current Everglades is approximately 5,600 square kilometers (560,000 hectares) and is currently contained in what is known as the Everglades Protection Area (EPA) which is made up of five Water Conservation Areas (WCAs): WCA-1 or the Arthur R. Marshall Loxahatchee National Wildlife Refuge; WCA-2A; WCA-2B; WCA-3A and; WCA-3B as well as Everglades National Park (**Figure 1**, right). The EPA

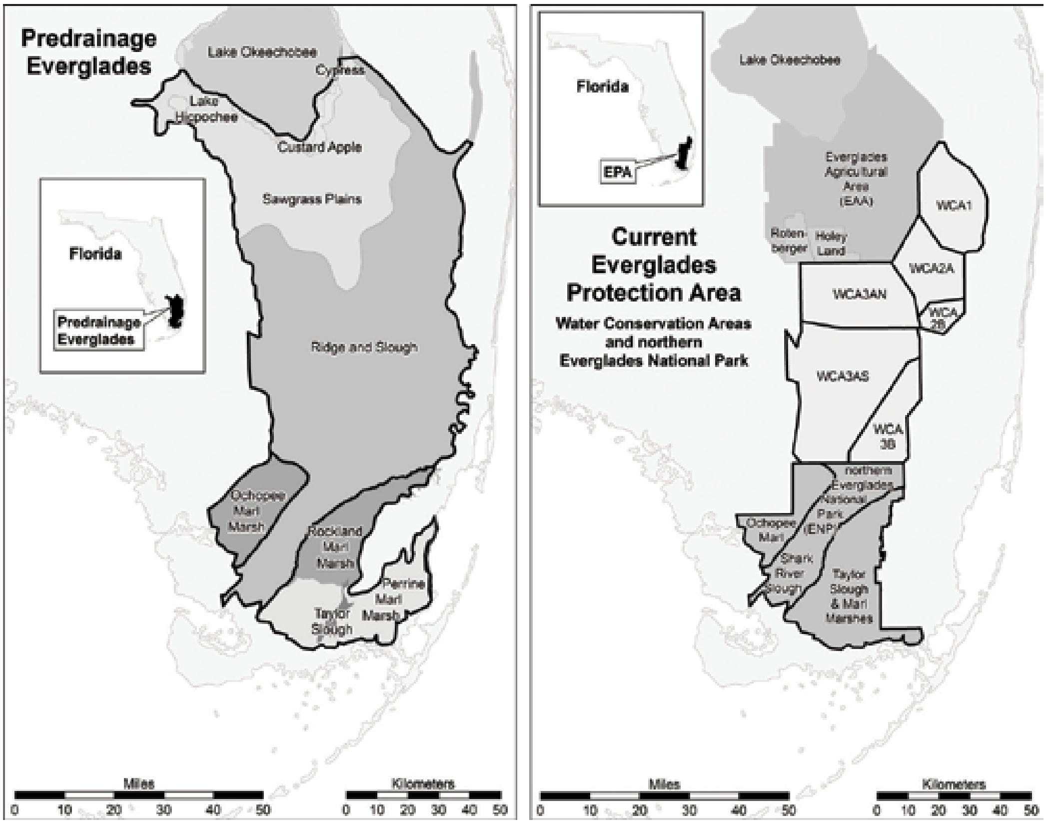

Figure 1. Historical predrainage Everglades landscapes, circa 1850 (left) and current Everglades footprint, including the EPA and EAA (right), modified from Hohner and Dreschel [2].

along with the Everglades Agricultural Area (EAA) are considered the current Everglades footprint (**Figure 1**, right). Geologically, south Florida, where the Everglades is located, is described as a pseudo-atoll surrounded by fossil reefs [3]. The central limestone bedrock that underlies the Everglades is relatively impermeable and formed over the past five million years [3]. A coastal ridge forms a barrier to the east which allowed the retention of water in the Everglades basin and the wet climate provided the environment for the growth of herbaceous vegetation and the consequent build-up of the peat soils, initially at a rate of about 7 cm per century with a rate of about 12 cm per century over the past millennia or so [4]. Prior to the 1800s, peat built up sufficiently to form a dam at the southern edge of the Lake which allowed water levels to rise and overflow to the south, continuously inundating the southern end of the Florida peninsula, particularly during the wet season (currently late May through mid-October). The peat that filled the Everglades basin had sufficient water-holding capacity to hold moisture during the dry season (currently mid-October through late May) during most years [1], thus allowing the preservation and accretion of the peats.

Human alterations to the Everglades landscape began in large part with the dredging of canals to drain the Kissimmee River Valley as well as lower the water level in the Lake [5]. The approach involved connecting the Kissimmee headwater lakes and building canals to allow water releases to the Gulf of Mexico and the Atlantic Ocean, reducing the water level in the Lake. This was to prevent overflow to the Everglades for the purpose of allowing the use of the region for agricultural and urban development. The first canal effort took place in the late 1800s with a connection from the Lake to the Caloosahatchee River. This effort was moderately successful in lowering the Lake stages, designated the Lake Okeechobee phase of Everglades drainage by McVoy and colleagues [1]. The draining of the Everglades began in earnest with the digging of four muck canals by 1917, carrying water from the Lake south to the east coast [5]. These canals (from the east clockwise to the south side of the Lake) were: The West Palm Beach Canal; the Hillsboro Canal; the North New River Canal and the Miami Canal [5]. This is considered the Muck Canal Phase [1]. The Tamiami Trail was constructed and opened in 1928 which stretched across south Florida separating what would become Everglades National Park to the south from the rest of the Everglades to the north.

Severe drying of the Everglades due to the lowering of the Lake resulted in fires which consumed large areas of the peat soil. In addition, the occurrence of several deadly hurricanes crossing south Florida resulted in the U.S. Congress authorizing the Central and Southern Florida Project for Flood Control and Other Purposes (the C & SF Project). The construction of the C & SF Project resulted in the last and current phase called the Impoundment phase [1, 5]. The Eastern Perimeter Levee was built between 1952 and 1954 to protect the urbanized eastern coastal areas. This was followed by the construction of the Everglades Agricultural Area (EAA) between 1954 and 1959, adjacent to the south end of the Lake, involving addition of levees, control structures, pumping stations and canal improvements, to allow further agricultural development of the region of the former sawgrass plains. This region contained the thickest deposit of peat within the Everglades [5]. This was followed by the impoundment of the remaining Everglades north of the Tamiami Trail. During the years 1960 through 1963, three Water Conservation Areas (WCAs) were established with the construction of perimeter levees, complete with water control structures so that water could be moved between them [5]. Southeast of the EAA, WCA-1 was constructed and was ultimately designated as the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Further south and east of the EAA, WCA-2 was constructed and divided into WCA-2A and WCA-2B. The division was made to control the amount of water that would be allowed to seep into the Biscayne Aquifer, partially located under WCA-2B. Due south and west of the other two WCAs, the largest of the WCAs was constructed and designated WCA-3 which was also subdivided into WCA-3A and WCA-3B. Similar to WCA-2B, WCA-3B was located over a porous substrate which did not allow long-term water storage. Other modifications were made to deliver water to Everglades National Park [5].

1.1. Everglades peats

There are four major peats associated with the Everglades: Everglades peat; Loxahatchee peat, Okeechobee muck and Okeelanta peaty muck. Everglades peat is produced from partially decomposed sawgrass leaves and roots and makes up the bulk of the peat found within the EAA. Loxahatchee peat, formed from aquatic plants such as water lilies and forms the bottoms of sloughs whereas Everglades is the substrate of ridges within the ridge and slough landscape. The other two peats, considered mucks (Okeechobee and Okeelanta) are the result of overwash during high stages the Lake and contain a larger inorganic fraction (from 35 to 70%) than the other two peats (around 10%) [6]. The two mucks and the Everglades peats have been extensively utilized for agricultural purposes.

1.2. The Everglades Agricultural Area (EAA)

Most of the original Sawgrass Plains landscape (dominated by sawgrass, *Cladium jamaicense*), as well as the Custard Apple Swamp (dominated by pond apple, *Annona glabra*) was primarily converted to the Everglades Agricultural Area by the early 1960s. This region was deemed a prime agricultural region due to the thick organic soils present there [1, 6]. The custard apple mucks, about 7% of the EAA, are found adjacent to the southeastern shore of the Lake and were 2.8–3.8 m deep and about 60% organic matter [7]. These soils are now considered Typic Haplosaprists. The majority of the area (90%) is underlain with sawgrass peats which originally were highly organic, about 90% organic matter according to Baldwin and Hawker [6]. By the 1940s, these peats had decomposed, exhibiting an approximately half-meter thick surface layer of "black, finely fibrous, well decomposed organic material" [1, 6]. Subsidence over the next 30 years resulted in these soils being classified as the Montverde (sawgrass) muck series of Typic Medifibrists [8]. Currently, all the soils of the EAA are classified as Saprists which are the most decomposed suborder of Histosols [1, 9, 10]. The soils continue to subside, resulting in a continual transition from thicker to thinner soil series and ultimately may become mineral soils [11].

1.3. Everglades tree islands

Tree Islands cover a small part of the ridge and slough landscape but are unique features for maintaining biodiversity and play a significant role in the biogeochemical cycling of nutrients in the Everglades [12]. Tear-drop shaped tree islands are believed to have been shaped by flow and have a broader "head" region and with a "tail" pointed downstream. Tree island heads have the concentrations of soil phosphorus that are orders of magnitude higher than the sediments of the surrounding sloughs [13]. The peat of tree islands is called "Gandy peat" [1]. Many tree islands have been lost or severely degraded due to oxidation and fires caused by droughts and drainage due to altered hydroperiods [14, 15]. Severely degraded tree islands have lost much of their elevations such that trees are unable to grow on them because of frequent flooding. These tree islands typically have extensive areas of herbaceous plants and are now termed "ghost" tree islands, appearing similar to large ridges in the landscape. Most of the tree islands of WCA-2A are now considered ghost tree islands and their outlines can still be located on the landscape but they now host very few trees [16, 17].

2. Background

The basin in which the Everglades formed provided an adequate substrate while the subtropical nature of the climate of south Florida provided the appropriate environment for the formation of peat soils. This process began approximately five millennia ago and it is believed that sometime in the recent past, peat built up to create a maximum surface covering the historical Everglades basin. Peat accretion has been estimated to have been about 12 cm per century over the last millennium or so. Since anthropogenic drainage was initiated in the late 1800s, the organic peat has shrunk and been lost by subsidence, fire and oxidation, both bacterial and chemical [1]. Rates of subsidence exceeding 2.5 cm per year have been measured in the EAA [18, 19]. The degree of subsidence due to oxidation is highly dependent upon the depth of the water table below the surface of the peat [20, 21] and has been a controlling factor in carbon emissions from the Everglades. Closed chamber studies have been conducted in an attempt to quantify the carbon emissions from peat soils in the Everglades [22] and resulted in measured emissions from 0.4 to 2.67 $g/m^2/h$.

A number of studies have been conducted to determine the amount of peat remaining in the current Everglades footprint (the EAA, EPA and Everglades National Park). The USEPA's Regional Environmental Monitoring and Assessment Program or R-EMAP has measured ground depth and surface elevation [23–25]. The program has created maps that allow a comparison of the changes in elevation over the past 5 decades leading to the estimation of peat loss from the Everglades during that period. Our group has endeavored to utilize a Geographic Information System (GIS) by creating and analyzing raster grids of historical and current Everglades elevation data sets to determine the amount of peat and carbon lost within each region of the current Everglades and the EAA as well as on a tree island in WCA-2A. In addition, we have used historical data sets to determine the original peat volumes of the various predrainage landscapes of the Everglades and the existing peat volumes of the current regions of the Everglades.

The data sets used for the peat volumes analyses include: the historical surface of the predrainage Everglades determined from historical (mid-1800s through early 1900s) land and canal surveys across the landscape [26]; a current (2005) surface of the current Everglades created from a number of data sources [27]; historical surface of the predrainage EAA from historical land and canal surveys [28]; recent land surveys done specifically within the EAA [29]; a south Florida bedrock map from Parker and colleagues [30]; a tree island survey conducted in 1973 [31] and one from the same tree island conducted in 2009 [16].

2.1. Data sets

A number of sources were utilized to create the surfaces used in evaluating peat volumes:

1. The predrainage peat surface data used was created for hydrological models, specifically the Natural Systems Regional Simulation Model (NSRSM) created and used by the South Florida Water Management District to simulate the hydrologic flow of the predrainage system under various scenarios (**Figure 2**, left). The surface was created using data from more than 300 land (township) and canal survey notes from the mid-1800s through the early 1900s [26].
2. The current Everglades system data set is from the South Florida Topography Project [27] and is a combination of a number of data sets including LIDAR, Radar from the Shuttle Radar Topographic Mission, bathymetric surveys, photogrammetry, and measured spot elevations (**Figure 2**, right and **Table 1**).
3. The predrainage Everglades bedrock map is a digitized version of an Everglades bedrock contour map presented by Parker and colleagues [30] (**Figure 3**, left).

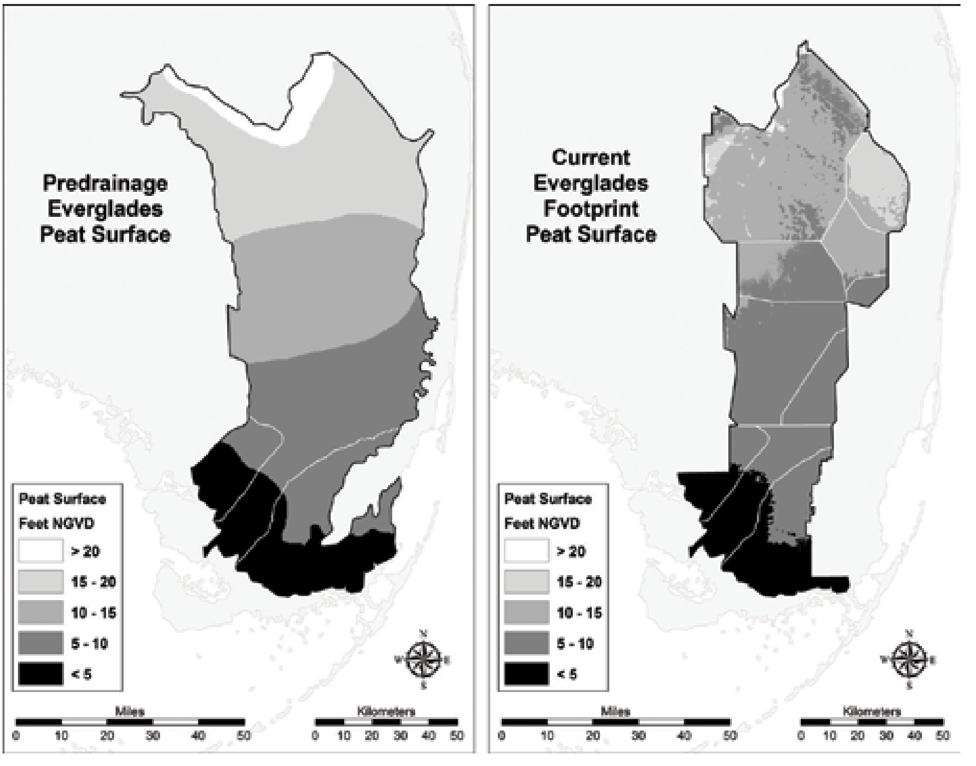

Figure 2. Maps of peat the peat surfaces used for the calculations reported by Hohner and Dreschel [2], derived from surface elevation data sets developed by Said and Brown [26], left and Holt and colleagues [27], right.

4. The current Everglades bedrock map was clipped from Data Set 3 above (**Figure 3**, right)
5. The 1973 tree island map was a digitized version of a survey map from the Central and Southern Florida Flood Control District, now known as the South Florida Water Management District [31].
6. The 2009 tree island survey was digitized from data reported by Ewe and colleagues [16].
7. One EAA predrainage map was created by clipping from the predrainage peat surface data from Data Set 1, above.
8. One EAA predrainage map was digitized using notes from a number of land surveys and canal surveys conducted in the early 1900s [28].
9. One EAA current surface was created by clipping from Data Set 2, above.
10. One EAA current surface was digitized from data presented by Snyder [29].
11. The EAA bedrock surface was created by clipping from Data Set 3, above.

In addition, spatially measured bulk density and peat carbon content point data sets from the USEPA R-EMAP were interpolated to create raster surfaces for the calculations of peat mass and carbon [23–25].

Data source	Data type
U.S. Army Corps of Engineers (USACE)	Terrestrial Light Detection and Ranging (LIDAR) Surveys
	Hydrographic, Structural and Channel Cross-section Surveys of the Okeechobee and the Atlantic Intercoastal Waterways
	Hydrographic Surveys of the St. Lucie Estuary, the Caloosahatchee Estuary and the Lake Okeechobee
Collier County	LIDAR Survey
International Hurricane Research Center (IHRS), Florida International University	LIDAR Survey
National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA)	Bathymetric Surveys of the Loxahatchee Estuary, the St. Lucie Estuary and the Lake Okeechobee
	Coastal Relief Model (CRM) Bathymetry of the Collier Shore, and the Charlotte Harbor to the Key West
Lee County	Photogrammetry
U.S. Geological Survey (USGS)	Measured Spot Elevations
	High Accuracy Elevation Dataset (HAED)
	National Elevation Dataset (NED)
South Florida Water Management District (SFWMD)	Coastal Bathymetry of the Naples Bay, and the southwest Florida to the Florida Bay
Shuttle Radar Topographic Mission (SRTM)	Radio Detection and Ranging (RADAR) of the Everglades Agricultural Area

After [33].

Table 1. Sources of data combined for the South Florida Topography Project (Current Elevation Data Set).

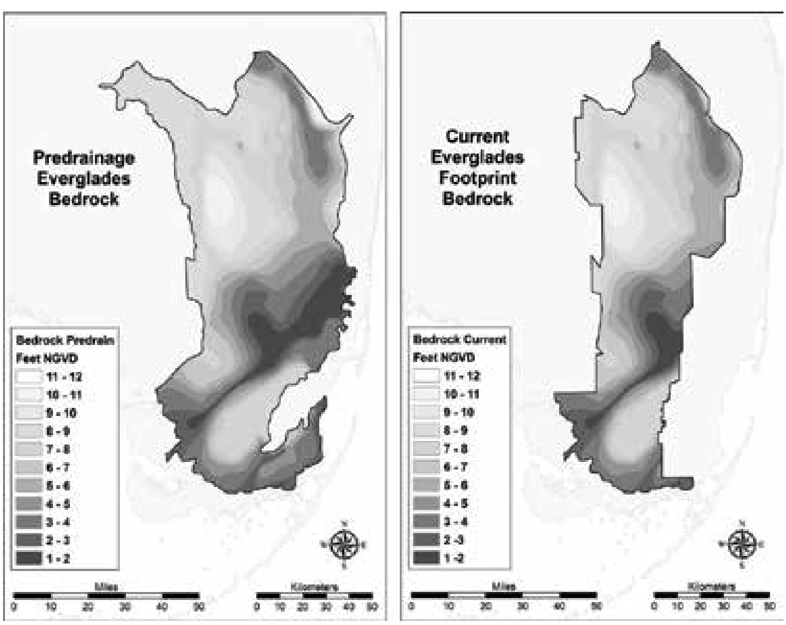

Figure 3. Maps of Everglades bedrock used for the calculations reported by Hohner and Dreschel [2], derived from a map presented by Parker and colleagues [30], left and the same surface clipped to the current Everglades footprint, right.

3. Approach and results

The availability of both the predrainage surface elevations and the current surface elevations made it possible to create GIS raster grids (305 × 305 m pixel size) from which the differences could be calculated, thus providing a means for calculating volume differences. Thus, for the initial calculations of peat loss, ArcGIS software's Raster Calculator function of the Spatial Analyst Tool [32] and a raster layer subtraction technique was used to determine the change in volume from predrainage to the present. This was the process used by Aich and Dreschel [33] following the correcting of the two surfaces to a common vertical datum (NAVD88). These volumes were converted to SI units and then used to calculate the mass of peat loss from each region by multiplying by a bulk density of 0.26 g cm^{-3} [34]. The mass of each region was then calculated using a carbon content of 51.8% [34] and the carbon dioxide released by multiplying the carbon by the molecular weight of carbon dioxide divided by the atomic mass of carbon (44/12). The results of these calculations are presented in **Table 2**.

For the calculation of peat volumes and loss in the EAA, two methods using different data sets were used in an attempt to confirm the numbers. See [28] for greater detail. For the first method, an early EAA (1915) surface elevation map (Data Set #4) was created using a subset of the data described for Data Set #1 and ordinary kriging and the current (2005) peat thickness map was created from measurements at 15 locations made by Snyder [29] and ordinary kriging. For the second method, the predrainage EAA surface was clipped from the map created by Said and Brown [26] which provided Data Set #1 and the current surface was clipped from the map created from the South Florida Topography Project [27] as well as the bedrock surface map from Parker et al. [30] which provided data set #3. All surfaces not in NAVD88 were corrected to that datum. For both methods, ArcGIS software's Map Calculator function of the Spatial Analysis Tool [32] and a raster layer subtraction technique was used to determine the differences between the surfaces. All values were converted to SI units for the calculation of peat volume (m^3), peat mass (MT = metric ton) and carbon mass from the past, present and the amount lost (**Table 3**).

For the calculation of peat loss from Dineen Island, a ghost tree island in WCA-2A, two data sources were available. A survey map from 1973 (Data Set #9) [31] was used to create a surface elevation map and for the most current surface, a survey conducted in 2009 (Data Set #10) [16] was used to create the surface elevation maps (**Figures 4** and **5**). Both surface elevation maps were created using ordinary kriging and elevation points collected during a number of transects made across the island [17] (**Figures 4** and **5**, [17]). The difference between the surfaces

Everglades region	WCA-1	WCA-2A	WCA-2B	WCA-3A	WCA-3B	ENP	EAA	Total
Volume of peat lost (m^3)	2.2×10^8	2.1×10^8	1.1×10^8	1.3×10^9	2.5×10^8	1.2×10^8	4.9×10^9	7.1×10^9
Average subsidence (m)	0.4	0.5	0.9	0.6	0.6	0.01	1.7	–

Table 2. Everglades peat loss and subsidence since the mid-1800s from [33].

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EAA analysis	Time period	Original peat volume (m^3)	Peat volume remaining (m^3)	Peat volume lost (m^3)	Average subsidence (m)	Peat mass lost (MT)	CO_2 lost (MT)	Average emission rate (g CO_2 m^{-2} h^{-1})
Method 1	1915–2003	6.5×10^9	2.0×10^9	4.5×10^9	1.6	2.5×10^8	4.9×10^8	0.22
Method 2	1880–2000	8.3×10^9	3.4×10^9	4.9×10^9	1.7	2.5×10^8	4.9×10^8	0.17

MT = metric ton.

Table 3. Results of the GIS analysis of the peats of the Everglades Agricultural Area [28].

were used to calculate the volume change in the head and near tail plus far tail of the tree island. The volumes were converted to SI units. Then, in combination with physical data from peat cores taken along the same transects in 2009, the calculation of the changes in peat mass, peat carbon and peat nutrients were performed (**Table 4**). Two possible explanations for why there was an increase in elevation on the small head are: 1. The two surveys did not overlay each other exactly and that the second survey captured the bedrock high or 2. Peat accretion due to the dominance of an exotic tree, Brazilian Pepper *(Schinus terebinthifolius)* accounted for an increase in soil elevation [17].

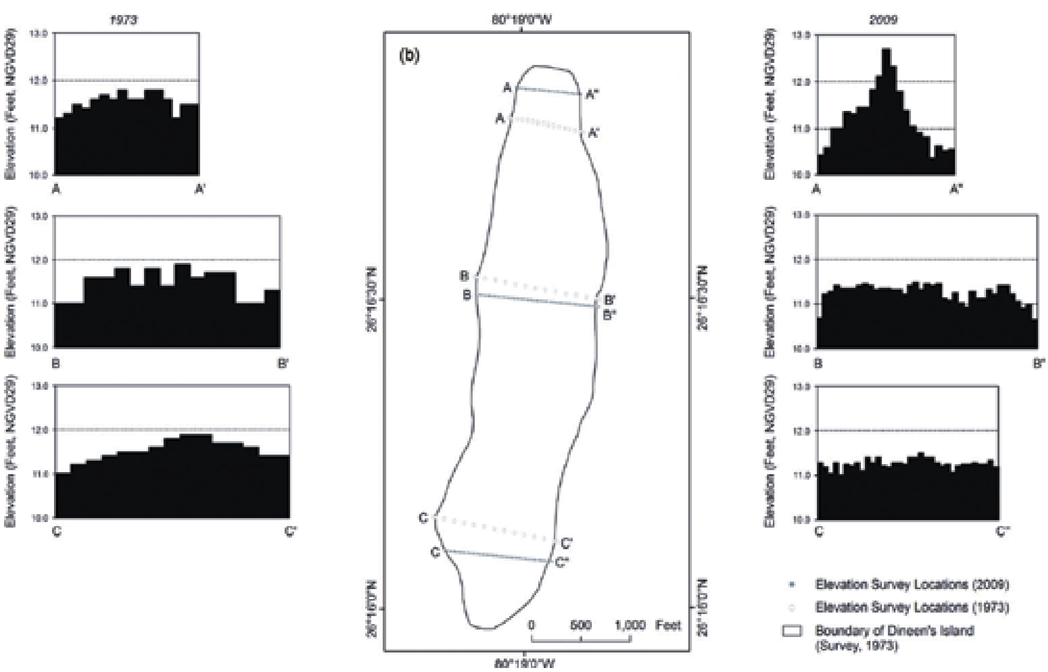

Figure 4. Topographic profiles of Dineen Island in 1973 and 2009 showing the change in the peat surface over 36 years. Modified from [17].

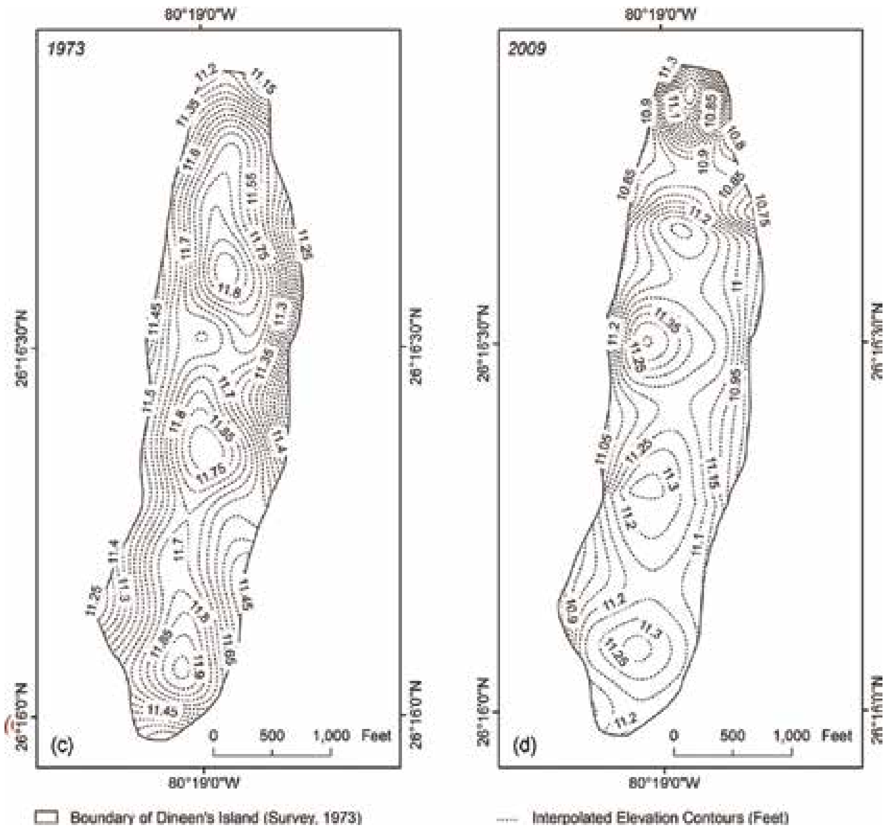

Figure 5. Interpolated contour maps of the peat surface of Dineen Island in 1973 (left) and 2009 (right). Modified from [17].

Hohner and Dreschel [2] utilized Data Sets #1, #2, and #3 to determine the volumes of the predrainage landscapes (**Figure 6**, left) and current regions (**Figure 6**, right) and the volume lost. These predrainage and current volumes were then combined with bulk density data from the USEPA R-EMAP [24] to calculate the corresponding masses and loss on ignition. The loss on ignition values were converted to bulk percent carbon using a conversion value of 0.51 [35] which was reported as the carbon content of the organic matter of typical peats. The results of those calculations are presented in **Table 5**. The current volumes were then compared to recent R-EMAP results [36] where 228 spatially-referenced peat depth measurements were

Dineen island analysis	Volume change (m^3)	Peat mass change (MT)	Carbon change (MT)	Total phosphorus change (MT)	Total nitrogen change (MT)
Head	5.6×10^2	57	25	0.8	1.6
Near and far tails	-7.3×10^4	-8.0×10^3	-3.6×10^3	−3.1	-2.1×10^2

Table 4. Results of the GIS analysis of the changes in peat on an Everglades tree island of WCA-2A between 1973 and 2009 [17].

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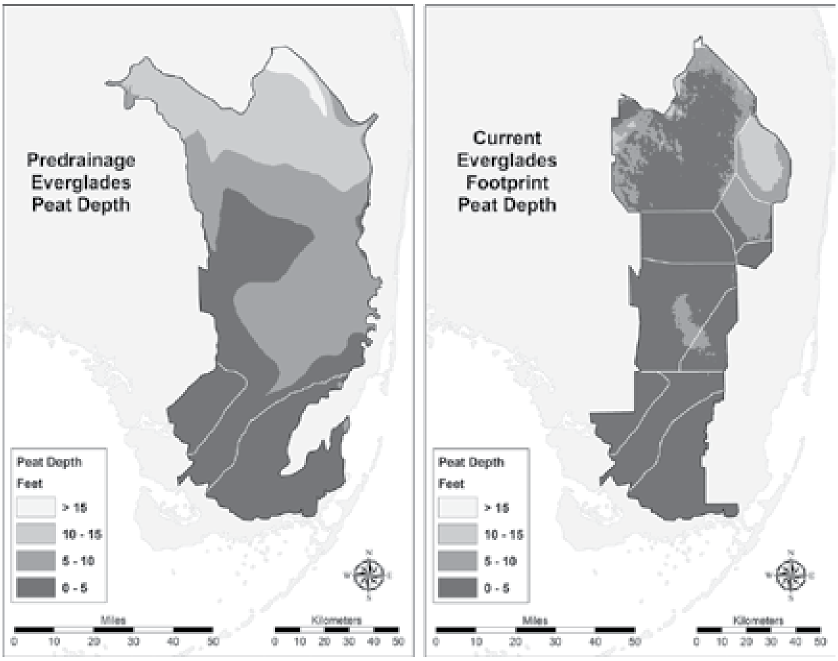

Figure 6. Maps of peat depth, derived from surface elevation data sets and the bedrock map from Parker and colleagues [30]. Left: predrainage peat depths using the predrainage surface developed by Said and Brown [26]. Right: current peat depths using the current surface from the South Florida Topography Project [27].

Region	Total area (km^2)	Predrainage peat volume (m^3)	Current peat volume (m^3)	Predrainage peat mass (MT)	Current peat mass (MT)	Predrainage peat carbon (MT)	Current peat carbon (MT)
WCA-1	5.6×10^2	2.0×10^9	1.8×10^9	1.4×10^8	1.2×10^8	6.5×10^7	5.6×10^7
WCA-2A	4.2×10^2	9.1×10^8	6.9×10^8	7.7×10^7	5.9×10^7	3.4×10^7	2.6×10^7
WCA-2B	1.1×10^2	2.2×10^8	1.1×10^8	3.0×10^7	1.6×10^7	1.0×10^7	5.5×10^6
WCA-3AN	7.2×10^2	8.5×10^8	2.2×10^8	1.3×10^8	3.0×10^7	4.5×10^7	1.1×10^7
WCA-3AS	1.3×10^3	1.8×10^9	1.1×10^9	2.5×10^8	1.1×10^8	7.8×10^7	4.7×10^7
WCA-3B	4.0×10^2	7.2×10^8	4.6×10^8	1.3×10^8	5.7×10^7	3.2×10^7	2.0×10^7
ENP Ochopee Marl Marsh	3.8×10^2	6.9×10^6	9.2×10^6	1.9×10^6	2.7×10^6	3.6×10^5	4.8×10^5
ENP Shark River Slough	7.7×10^2	3.5×10^8	2.8×10^8	6.3×10^7	5.2×10^7	1.8×10^7	1.4×10^7
ENP Eastern Marls & Taylor Slough	9.9×10^2	1.4×10^7	1.2×10^7	4.3×10^6	4.1×10^6	6.5×10^6	5.0×10^6
Total EPA	5.6×10^3	6.9×10^9	4.7×10^9	8.2×10^8	4.5×10^8	2.9×10^8	1.8×10^8

Region	Total area (km^2)	Predrainage peat volume (m^3)	Current peat volume (m^3)	Predrainage peat mass (MT)	Current peat mass (MT)	Predrainage peat carbon (MT)	Current peat carbon (MT)
Total EAA	2.6×10^3	8.3×10^9	3.5×10^9	1.0×10^9	5.6×10^8	4.0×10^8	1.6×10^8
Total EPA + EAA	8.2×10^3	1.5×10^{10}	8.2×10^9	1.9×10^9	1.0×10^9	6.8×10^8	3.4×10^8

Table 5. Results of the GIS analysis of the original and current volumes, masses and carbon of the peats of the current Everglades footprint [2].

made across the Everglades to calculate the regional volumes remaining. The results of the comparison showed that although regionally, current volumes differed somewhat between the two, the total volume of the current EPA was the same for both methods, 4.7×10^9 m^3 (see [36] and **Table 5**).

4. Discussion

The Everglades is one of the largest peatlands in the world, recognized internationally by being designated as a Wetland of International Importance (Ramsar Convention), an International Biosphere Reserve (UNESCO) and a World Heritage Site in Danger (UNESCO) [37]. However, for the past century and a quarter, anthropogenic modifications to the region have resulted in changes in the hydrology, chemistry and biology of the Everglades.

In particular, the Everglades experienced drying as a result of being hydrologically cut off from Lake Okeechobee in the late 1800s and early 1900s. This lead to years of excessive drying of the peatland resulting in biological peat oxidation and the occurrence of peat fires. Because of this drying, the Everglades has experienced wide-spread soil loss. The amount of peat oxidation is directly related to the depth of the water table below the peat. By far, the greatest amount of peat loss has occurred in the Everglades Agricultural Area due to controlling ground water levels to enable the growth of food crops.

The loss of the peat soils in the EPA is an impact that has affected aspects of hydrology, landscapes, habitats and atmospheric chemistry, namely the increase in carbon dioxide and other greenhouse gases. Thus, the quantification of peat soil loss is important in the evaluation of the ecological and societal impacts such as water storage and climate change.

Quantification of peat soil loss has been pursued in a number of studies [6, 8, 17–22, 24, 29, 36], but current GIS technologies have only been available recently to conduct the investigation of changes in surface elevation provided by data mining historical spatial data sets. The use of GIS in combination with spatial data sets for the determination of peat loss was demonstrated by the current study for several landscapes within the Everglades of Florida. Where spatial data sets are available, this technique appears to be a viable method of estimating the changes in soil surface and/or the underlying soil depth, even though there are many uncertainties in using historical data sets and limited point data in creating the surface elevation maps and raster grids. These limitations are discussed in detail in [2, 17, 28, 33].

The key findings from the analyses described here are:

1. Since the mid-1800s, the EPA and the EAA have experienced peat subsidence from much less than a meter to greater than 1.7 m depending upon the primary substrate of the region;
2. This subsidence has resulted in the loss of more than 10 billion cubic meters of peat from these regions;
3. Individual (ghost) tree islands have also experienced quantitatively similar peat subsidence in WCA-2A. We extrapolated this loss to all the ghost islands (total area about 22 times that of Dineen Island) [17];
4. The historical Everglades contained about 20 billion cubic meters of peat, massing approximately 2.6 billion metric tons;
5. The current EPA covers approximately half the area but has less than a quarter of the peat remaining (4.7 billion cubic meters) massing about 450 million metric tons.

We estimated that at least 1.3 billion metric tons of carbon dioxide have been emitted from the Everglades region since predrainage (1880) due to peat loss (**Table 6**). This is roughly one-quarter of the carbon dioxide emitted by the entire U.S. in 2015 (5,172,338,000 metric tons) [38]. Thus, the loss of peat carbon from the Everglades has had a significant impact on the global carbon balance.

The Central Everglades Planning Project (CEPP) [39] is a restoration project intended to fill canals and remove levees with the purpose of returning flows to specific regions of the Everglades. Although portions of the Everglades may be restored, the Everglades has lost half of the area and thus, it is impossible to fully restore it to predrainage conditions. If future restoration activities such as the CEPP are successful in keeping the remaining Everglades hydrated, further peat oxidation will be prevented and peat accretion may again be greater than loss.

Everglades region	Ghost tree islands of WCA-2A (1973–2009)	EAA (1880–2000)	WCA-1 (1885–2005)	WCA-2 (1885–2005)	WCA-3 (1885–2005)	ENP (1885–2005)	Total
Estimated carbon lost (MT)	7.9×10^4	2.4×10^8	9.0×10^6	1.3×10^7	7.7×10^7	4.0×10^6	3.4×10^8
Estimated CO_2 emitted (MT)	2.9×10^5	8.8×10^8	3.3×10^7	4.6×10^7	2.8×10^8	1.5×10^7	1.3×10^9

Table 6. Summary table of the estimated peat carbon lost from the current Everglades footprint and the estimated resulting carbon dioxide emissions.

Acknowledgements

We recognize the contributions of Fred H. Sklar, Susan Gray, Martha Nungesser, Kenneth Rutchey, Theodore Schall, Colin Saunders, Nenad Iricanin, Binhe Gu and Sharon Ewe. The 2009 ghost tree island surveys were conducted by Jennifer Vega, Kristin Vaughan, Russel Bahe, Colin Johnson, Robert Sekerka and Miriam Barranco, John Jones and Jamie Breig. This work has been fully funded by the South Florida Water Management District, West Palm Beach, Florida, USA.

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Section 2

Peat Characteristics and Horticultural Use

Chapter 4

The Status of Pachiterric Histosol Properties as Influenced by Different Land Use

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74151

Abstract

Soil drainage as well as soil cultivation and fertilization has considerable influence on the organic matter mineralization rate and changes in the profile structure. Our research suggested that quantitative and qualitative characteristics of peat soil are changing in response to the renaturalization processes and different management. The study set out to estimate chemical and physical properties of Pachiterric Histosol, qualitative and quantitative changes in carbon resulting from different management and renaturalization processes. Wetland and peatland soils are among the largest organic carbon stocks, and their use contributes to carbon emissions or accumulation processes. The focus of our work is research into the peculiarities of organic carbon accumulation and transformation as influenced by different land use of peat soil. Results on the chemical properties of Pachiterric Histosol showed the influence of management and renaturalization on mobile and by pyrophosphate solution extractable humic and fulvic acids and humification degree. We are also exploring the specificities of organic carbon variation in the context of peat renaturalization and are seeking to answer the question as how to optimize the use of peat soils and how to match up this with the renaturalization processes in order to reduce greenhouse gas emissions and contribute to organic carbon accumulation and conservation in the soil.

Keywords: Pachiterric Histosol, land use, soil profile, carbon, humification, humic acids

1. Introduction

Peat soils in the world: Soils are the largest pool of carbon in terrestrial ecosystems, globally containing more than two-thirds of the ecosystem's total carbon [1]. Organic soils (histosols) are an important reservoir of organic carbon (OC) [2]. Peatlands are an integral part of the global climate system. They occupy a relatively small fraction (approximately 3%) of the Earth's land area, but store about 30% of the world's soil carbon [3, 4]. Heightened attention is being devoted to their anthropogenic transformation changes in the physical and chemical properties caused by those processes [3, 5, 6]. Anthropogenic disturbance, primarily agriculture and forestry as well as drainage can disrupt the cycle of carbon and result in the changes in atmospheric gas emissions [3, 7]. Increasingly, more research is being carried out on the properties of peat soils worldwide [8–10]. **Figure 1** shows territories of peat in the world.

Peat soils in the Nordic-Baltic region: Relatively large territories of the Nordic-Baltic countries are covered by peat soil layers [13]. The Nordic and Baltic countries contain a large extent of peatland, which is characterized by a great diversity of peat accumulating ecosystems. Approximately, 45% of this peatland has been drained and emits about 25% of the total CO_2 emissions. The CO_2 emissions from the peatland in Iceland and Latvia are twice as large as those from all other sources combined, except land use; in Estonia, Lithuania and Finland 50%, in Sweden 25% and in Norway 15%. Just in Denmark and Greenland, the emissions from peat soils are below 10% of the total other CO_2 emissions [14]. Peatlands may thus play a vital role in national climate change mitigation policies.

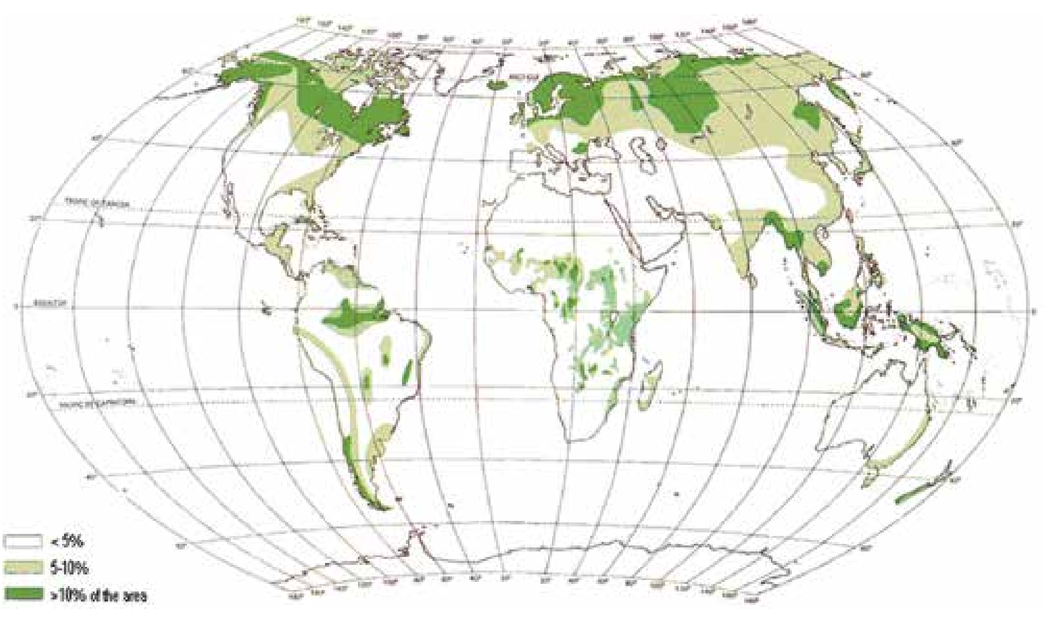


Figure 1. Peats in the world [11, 12].

Peat soils in Lithuania: Peat soils occupy approximately 9.5% of the Lithuanian soil cover [15]. Of these, about 44% is made up of marshes, 13%—high bogs, about 2%—intermediate type peat, and even 34%—other peaty mineral soils, and about 90% of all peatlands are drained or removed and are used for agriculture. There are approx. 40,000 bogs varying in size in Lithuania; low-lying bogs constitute nearly two-thirds of the peat soils [16]. According to various sources, their area totals 414,000–578,000 ha. Histosols occupy nearly 8% of the total area of Lithuania. Terric Histosol accounts for 44%, Fibric Histosol for 13%, Terric-Fibric Histosol for 2% and other Umbric mineral soils for 34% of the total Histosols. About 7% of Lithuania's Histosols have been little investigated so far, their types have not been identified. Specimens of the most common and typical Histosols occurring in Lithuania are provided in **Figures 2** and **3**.

Histosols with a peat layer depth of not less than 100 cm are attributed to deep peat soils, and those with a peat layer thickness not exceed 100 cm are attributed to shallow peat soils. The peat layer thickness of Histosols with a removed peat layer generally does not exceed 40–50 cm. The peat layer thickness of Umbric mineral soils does not exceed 40 cm. In drained Histosols, due to the mineralization of the upper peat layer, the peat layer thickness may decrease to 20 cm. The various types of Histosols differ in morphological and chemical properties.

Peat soils, especially those used for agricultural purposes, have been insufficiently studied so far. The soil drainage methods, soil cultivation, fertilization and crops exert considerable influence on the organic matter mineralization rate and changes in the soil profile structure. There is very little research evidence on the morphology of the peat soil profile, changes in organic matter forms, humification and carbon as influenced by drainage, agricultural use and renaturalization.

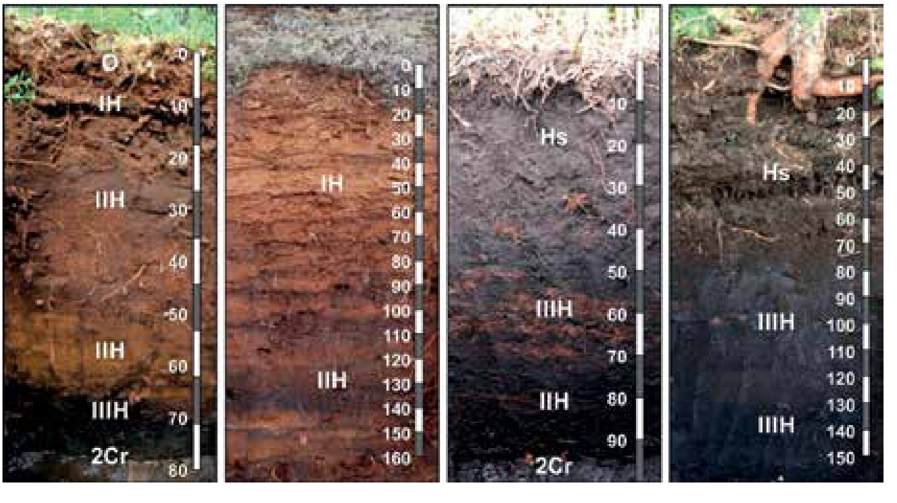


Figure 2. Profiles of Lithuanian Histosols: from left to right, 1 – Pachifibric Histosol (high moor shallow peat soil) – Siluva high bog, 55°32′22.27″N 23°17′50.48″E, 2 – Bathifibric Histosol (high moor deep peat soil) – Rekyva high bog, 55°50′27.54″N 23°18′13.67″E, 3 – Pachiterric-Fibric Histosol (transitional moor shallow peat soil) – Siluva peatland, 55°32′36.51″N 23°13′49.50″E, 4 – Bathiterric – Fibric Histosol (transitional moor deep peat soil) – Tytuvenai intermediate bog, 55°34′16.76″N 23°17′27.90″E (pictures by Dr J. Volungevičius).

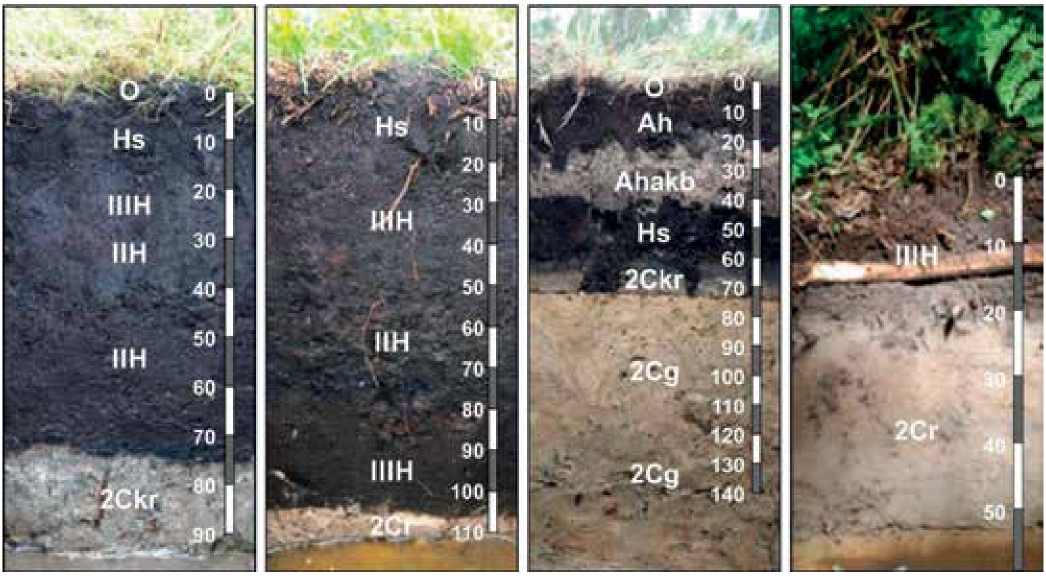


Figure 3. Profiles of Lithuanian Histosols: from left to right, 1 – Pachiterric Histosol (low moor shallow peat soil) – Radviliskis low bog, 55°49′43.15″N 23°28′36.03″E, 2 – Bathiterric Histosol (low moor deep peat soil) – Kabeliai peatland, 53°57′11.59″N 24°19′01.31″E, 3 – Removed Drainic Bathiterric Histosol – Radviliskis low bog, 55°48′51.15″N 23°29′22.43″E, 4 – Areni – Umbric Gleysol – the Curonian spit, 55°31′04.73″N 21°06′50.94″E. Pictures by J. Volungevičius.

Vegetation and peat soils: There is research evidence on the positive role of grasslands in the organic matter buildup. Perennial grasses can decrease organic matter decomposition, since they partly restore organic matter by leaving a large amount of plant debris such as roots and stubble. It is recommended establishing long-term grasslands, which, if appropriately managed, could produce an abundant biomass yield; however, organic matter transformation is influenced by the sward composition and management, as well as by soil conditions.

Plants are known to influence peatland carbon fluxes both (i) directly through respiration and (ii) by the production of litter and root exudates, which are then broken down by microbes within the peat matrix [17]. It has been documented that plant identity can influence the diversity of low molecular weight soil organic compounds and that plant species richness increases the richness of soil organic compounds, at least for low molecular weight organic compounds [18]. The fresh organic matter should be introduced in the soil, which would promote humus formation. Crops grown in a crop rotation determine the quantitative and qualitative composition of plant residues getting into the soil and significantly regulate soil microflora complex. Grasses and legumes are an important source of soil humic substances. They leave a large amount of roots in the soil, during the breakdown process of which soil humus substances are formed, of which the most valuable are humic acids. It was determined that about 49–50 dt of non-decomposed roots are left in 1 ha of the soil under clover [19].

Peat soil and land use: In order to elucidate which factors cause an increase or decrease in soil organic carbon after agricultural abandonment, it is necessary to integrate the data on the temporal dynamics of the plant community and soil organic carbon. According to the data of the Lithuanian Geological Survey (https://www.lgt.lt/epaslaugos/pages/trees/geolis.xhtml), about 90% of the wetlands are drained in Lithuania. Nearly 94% of the soils in low moor peat and peaty declensions were drained in Lithuania in the second half of the twentieth century. Draining of peat soils was conducted in order to adapt them for agricultural purposes [20]. However, there is very little published data on the changes in peat soils in response to different land use and renaturalization process. To date, there are few studies that have investigated peat soils, especially their use for agricultural purposes.

Peat soil organic carbon: Strack and Zuback [10] have documented that peatlands have a significant role in the global carbon cycle by storing from 469 to 486 Gt of carbon, emitting around 10% of the total global methane emissions and acting as great sources of organic carbon (particulate and dissolved) to downstream ecosystems. The change of land use and accompanying disturbance of peat soil can be the main cause of soil carbon loss, e.g. deforestation [21–23], cultivation [24] and cropping [25]. Labile soil organic matter is characterized by fast decomposition rates and short turnover times. It accounts for approximately 5% of soil organic matter, but is highly active because it is made up of readily decomposable compounds [25]. In sustainable agriculture, the management and enhancement of soil organic carbon are highly relevant. Soil organic matter is the source and sink of the atmospheric carbon dioxide and plays a major role in the global cycling of carbon. Soil organic carbon content can be measured by conventional techniques. The contents and storage of soil carbon and nitrogen are impacted by soil-forming and anthropogenic factors.

Anthropogenic activities such as fertilization and cropping systems play a significant role in the regulation of carbon and nitrogen amounts in agricultural soils and greenhouse gas emissions [26, 27]. Due to the human activities, the atmospheric carbon dioxide concentration is rapidly increasing, while the long-term storage capacity of terrestrial and ocean ecosystems is decreasing [28]. In order to understand the role of the soil in the global carbon dynamics, it is necessary to estimate soil carbon stocks. Recently, elevated attention has been paid to the role of soils in the global carbon cycle, where the world's soils contain roughly three times the carbon contained in the total world's vegetation and twice the amount of carbon as carbon dioxide in the earth's atmosphere [29], and thus the alterations in soil carbon content can influence the atmospheric composition [9].

Peat soil humic substances: The quantity and quality of SOM and its major component — humus — are influenced by management practices. From the agricultural point of view, the understanding of the behavior and the function of soil organic matter pools are important to the environmental sustainability [30, 31]. Humification of organic substrates is a complex biochemical process occurring with a direct participation of micro-organisms. Generally, only a small part, about 10–20% of organic matter present in the soil is subject to humification. The major part of organic residues (80–90%) mineralizes to simple compounds or forms less readily decomposed organic compounds (lignin type), that make up almost non-hydrolysable part of soil organic matter [19]. The remaining part of plant organic matter turns into humic substances. Plant biological properties have a great effect on humus formation. Organic matter composing plant residues take part in the biochemical transformation process. The final result of this is products of full mineralization $CO2$, $H2O$, low molecular weight organic compounds and high molecular weight compounds. Since the soil contains various enzymes, different reactions can take place simultaneously. Carbohydrates and amino acids are fully mineralized. Organic compounds more resistant to biological oxidation (oligosaccharides, polysaccharides and lignin) break down much more slowly.

In these soils, organic carbon is stored in the form of plant residues in various stages of decomposition, as well as in the form of humic compounds, which can be defined as a mixture of macromolecules of variable chemical composition, size and shape [32]. Humification processes result in an increase in the content of humic substances in organic soils. They are involved in sorption processes and form soluble and insoluble complexes with metallic ions in the soil [33]. Soil humic substances are the key constituents of the adsorptive complex that affects various soil characteristics.

Dissolved organic carbon concentrations of peat soil: A few studies have attempted to understand the dissolved organic carbon cycling in peatlands. It was found that the concentrations of dissolved organic carbon are controlled by the total carbon content of the peat soil [34], by availability of oxygen, by water table depth [35] and by the peat degradation status [36]. The concentrations of dissolved organic carbon responded to the environmental conditions, but only after a lag period of a few weeks [37]. Dissolved organic carbon concentrations vary with season and land use — this has been proved by investigations from two fens in Northeastern Germany over 2 years [38]. The alterations in soil organic carbon resulting from the management practices are difficult to identify because these changes are slow and relatively small compared to the extensive background of soil organic carbon, which vary both spatially and temporally [39]. The identification of some sensitive labile soil organic carbon fractions, such as water soluble organic carbon and readily mineralizable carbon contributes to clarification of soil organic carbon changes at early stages as affected by management.

Organic matter humification degree of peat: Although mires and peatlands form one of the largest reservoirs of refractory organic matter, few studies on the humification process for peat have been conducted [40, 41]. In scientific literature, there is little information about the degree of humification of soil organic matter in peat soils. Different methods and approaches are used for the assessment and determination of humification. For example, the ratio of the area under fluorescence emission per total C content was defined as the SOM humification index [42]. According to Bejger et al. [43], humification is understood as the transformation of macromorphologically identifiable organic matter into amorphous compounds, as a rule involving the changes that occur in vegetal residues or soil organic matter during the humification process. Also, the ratio among extractable carbon, humic acids carbon, fulvic acids carbon and total organic carbon is used to determine the degree of humification [44]. It is clear that the relative increase in the share of humic acids with respect to other humic substances is valuable from the agronomic and ecological viewpoint. In our work, we used the definition of Orlov [45], stating that the relative share of carbon of humic acids in the total organic carbon in the soil, expressed in %, is understood as the degree of humification.

The main task of this research was to study the chemical composition of Histosol, to identify the differences in the soil total carbon, dissolved organic carbon, humic substances, humification of organic matter of differently used peat soil a with removed and non-removed peat layer.

http://dx.doi.org/10.5772/intechopen.74151

2. Experimental site and conditions

History: The wetlands are surface areas of excess moisture, overgrown with specific vegetation, and covered with a layer of peat that is thicker than 30 cm; land areas where the peat layer is thinner are called waterlogged soils. There are about 40,000 wetlands of various sizes in Lithuania [16]. Their total area is 414,000–578,000 ha, and they represent 6–7% of the country's territory. The low moor peat lands are predominant, and they account for about 66% of all wetlands. The Radviliškis Experimental Station was established in 1936 with a view to investigating whether low moor peat soils could be used for agricultural purposes. The studies from other countries indicate that the most valuable plants in the low moor peat soils are perennial grasses. However, it was also necessary to study annual plants to select the right plant change in the crop rotation in the low moor peat soil. The Radviliškis low moor peat land was formed at the source of the Beržė River, the eastern edge of peat land borders the Radviliškis town (**Figure 4**), and covers an area of 1203 ha. Field experiments were conducted at the former Radviliškis Experimental Station of the Lithuanian Institute of Agriculture on a low moor peat (Pachiteric Histosol) with the removed and non-removed peat layer at an altitude of 120 m above the sea level (55°45′N, 23°30′E).

The general characteristics of peat soil profiles (I, II, III) are presented in **Table 1**.

Stages of the long-term investigations: Peat soils in the former Radviliškis Experimental Station were studied using different approaches. The study period was divided into four stages. In each of these stages, we focused on specific problems.

Stage I: In 1995, an experiment involving field and grassland plants was set up on a low-lying bog with a removed and non-removed peat layer at Lithuanian Institute of Agriculture's Radviliškis Experimental Station. In 1995–2001, the study involved the following treatments: unused peat soil; unfertilized perennial grasses; crop rotation field; red clover and timothy mixture; perennial grasses fertilized with NPK (**Table 2**).

In this experiment, the effects of different use of peat soil on its properties were compared.

Treatments of the experiment

Stage II: In 2001, the use of Histosol for agricultural purposes was discontinued. Stage I was completed. However, it was noticed that within 3–4 years after the discontinuation of grassland use, marked changes occurred in it: unsown forbes and various types of willows appeared, alterations occurred in the soil properties as well. The process of renaturalization started. Therefore, research was resumed in order to study the processes of renaturalization.

Stage III: In 2007, while conducting research within the framework of the project funded by the Lithuanian Science and Studies Board, the first marked changes were identified in the unused peat soil. The published data suggest, as well as our observations in the current study, that the changes in organic matter in peat soils are much more evident than those occurring in mineral soils. Therefore it was important to continue to monitor and evaluate the ongoing renaturalization processes, in particular in terms of the quantity and quality of organic matter, and to determine the quality indicators that had not been studied before.

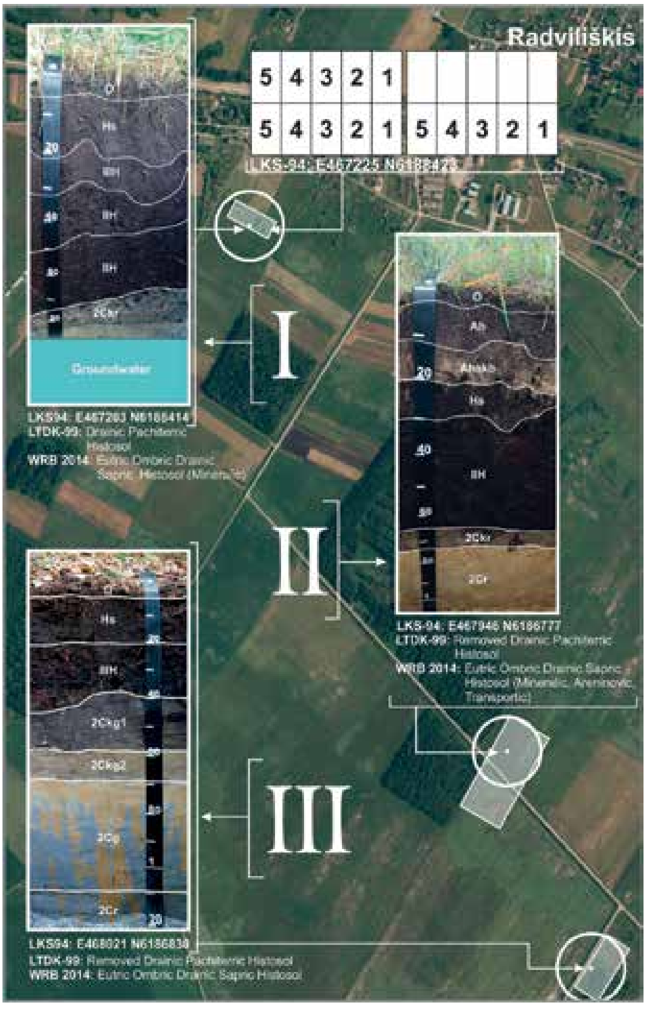


Figure 4. The scheme of the experimental site and sampling places: I – Drainic Pachiterric Histosol with a non-removed peat layer under renaturalization; II – Differently used removed Drainic Pachiterric Histosol; III – Differently used removed Drainic Pachiterric Histosol (source from information system of Lithuanian geological survey: Swamp and peat bogs of Lithuania; https://www.lgt.lt/epaslaugos/pages/trees/geolis.xhtml).

Stage IV: Since 2012 up to now. At this stage, we have accumulated the largest body of evidence from peat soil research, analyzed and summarized the data on the soil chemical composition from the renaturalization viewpoint and compared different land uses.

The treatments investigated at this stage of the long-term experiments in the soil with a non-removed peat layer were as follows: (i) unused peat soil; (ii) former unfertilized perennial grasses; (iii) former crop rotation (potatoes; winter rye and red clover) field; (iv) former red clover (Trifolium pratense L.) and timothy (*Phleum pratense* L.) mixture; (v) former perennial grasses fertilized with commercial NPK fertilizers. The treatments of peat soil with a removed peat layer were: (i) natural forest; (ii) arable crop rotation field and (iii) meadow.

Soil name according to LTDK-99	**I – Drainic Pachiterric Histosol with non-removed peat layer**		**II – Drainic Pachiterric Histosol with removed peat layer**		**III – Drainic Pachiterric Histosol with removed peat layer**	
Soil name according to WRB 2014	Rheic Drainic Fibric Histosol (Eutric)		Drainic Fibric Histosol (Areninovic, Eutric, Transportic)		Drainic Fibric Histosol (Eutric, Transportic)	
Coordinates: Longitude	E467203	E20°28′34.651″	E467946	E20°29′18.058″	E04968302	E23°29′39.02″
Latitude	N6188414	N55°50′24.572″	N6186777	N55°49′31.803″	N06186032	N55°48′26.37″
Altitude	119 m		117 m		116 m	
Climate: Precipitation	560 mm					
Average annual air temp.	+7.4°C					
Average annual soil temp.	+7.8°C					
Relief: Genetic group	Almost equal		Little wavy			
Genetic subgroup	Organogenic plain		Organogenic upland			
Land use	Perennial meadows				Forest	
Natural vegetation (trees)	—		—		*Betula pendula (Roth), Salix viminalis (L.), Salix cinerea (L.), Frangula alnus (Mill.), Sorbus aucuparia (L.), Padus avium (Mill.)*	
Natural vegetation (herbaceous)	*Elytrigia repens* (L.) Gould, *Cirsium arvense* (L.) Scop, *Urtica urens* (L.), *Taraxacum officinale* (L.) Weber ex F.H. Wigg, *Rumex crispus* (L.), *Aegopodium podagraria* (L.), *Stellaria palustris* (L.)		*Sinapis arvensis* (L.), *Elytrigia repens* (L.) Gould, *Taraxacum officinale* (L.) Weber ex F.H. Wigg, *Euphorbia cyparissias* (L.), *Hieracium pilosella* (L.), *Achillea millefolium* (L.), *Polygonum persicaria* S.F.Gray, *Equisetum arvense* (L.), *Viola arvensis* Murray.		*Phragmites communis (Trin.), Carex nigra (Reichard), Calamagrostis arundinaceae (Roth), Festuca gigantea (Vill.), Urtica dioica (L.), Glechoma hederacea (L.) Aegopodium podagraria (L.)*	
Soil surface coating	100%		70–80%		70–80%	
Soil-forming material	Low moor peat on the ground moraine		Low moor peat on sapropel and limnoglacial sand			
The beginning of carbonate occurring:	75 cm		65–74 cm, sapropel interlayer foams		40–70 cm, sapropel interlayer foams	
Depth of groundwater:	Min – 50 cm; max – 75 cm		−120 cm		−115 cm	
Effective soil depth	75 cm		65 cm		40 cm	
Anthropogenic effects:	Drained		Drained, removed peat layer			
Soil moisture:	Moist 0–50 cm; wet 50–120 cm		Dry 0–60 cm; moist 65–74 cm; wet 74–120 cm		Dry 0–40 cm; moist 40–110 cm; wet 110–120 cm	

Table 1. The general characteristics of three peat soil profiles.

Treatments				
UU	UF	CF	M	NPK
—	Sowing of perennial grasses	Potatoes	Sowing of red clover and timothy mixture	Sowing of perennial grasses
—	Perennial grasses 1st year of use	Winter rye	Mixture 1st year of use	Perennial grasses 1st year of use
—	Perennial grasses 2nd year of use	Sowing of red clover and timothy mixture	Mixture 2nd year of use	Perennial grasses 2nd year of use
—	Perennial grasses 3rd year of use	Mixture 1st year of use	Mixture 3rd year of use	Perennial grasses 3rd year of use
—	Perennial grasses 4th year of use	Mixture 2nd year of use	Mixture 4th year of use	Perennial grasses 4th year of use
—	Perennial grasses 5th year of use	Ryegrass	Mixture 5th year of use	Perennial grasses 5th year of use
—	Winter rye	Winter rye	Winter rye	Winter rye

Note: UU, unused peat soil; UF, unfertilized perennial grasses; CF, crop rotation field; M, red clover and timothy mixture; NPK, perennial grasses fertilized with NPK.

Table 2. The experimental design of differently used Histosol.

Thus, in the long-term research (1995–2017) we have attempted to study and build up a complete picture of the various changes that have occurred in the properties of Histosol over the period of more than two decades. Research done in other countries suggests that perennial grasses are the most profitable plants on low-lying bogs. However, our research was aimed to verify whether it is possible to grow various other plants, including annuals, and choose the right crop sequence in the rotation without damage to soil properties.

Methods of analyses: Soil samples for chemical analyses at stage I of the experiment were taken from 0 to 20 cm peat layer in 3 replicates. Prior to the chemical analyses, the samples were crushed and sieved through a 2-mm sieve, visible roots and plant residues were manually removed, and the samples were air-dried. For the analyses of humic substances aliquot of soil samples were further crushed and passed through a 0.25 mm sieve. Analyses were carried out at the Chemical Research Laboratory of Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry.

Soil pH was determined in 1 M KCl according to the standard ISO 10390:2005. Soil total nitrogen (Ntotal) was determined by the Kjeldahl method, and plant-available phosphorus (P_2O_5) and potassium (K_2O) were determined by the Egner-Riehm-Domingo method. The total content of potassium (K) was determined using an atomic absorptiometer AAnalyst 200 (Perken Elmer, USA) after the mineralization with sulfuric acid. Soil organic carbon content was determined by the Tyurin method modified by Nikitin in 1999 [46] using a photometric procedure at the wavelength of 590 nm and glucose as a standard after wet combustion, using the UV-VIS spectrophotometer Cary 50 (Varian, Netherlands) equipped with a computer program.

Mobile humic substances and humic acids were determined according to the method of Ponomareva and Plotnikova [47] using a soil: 0.1 M NaOH solution ratio of 1:5 for the extraction of mobile humic substances (**Figure 5**).

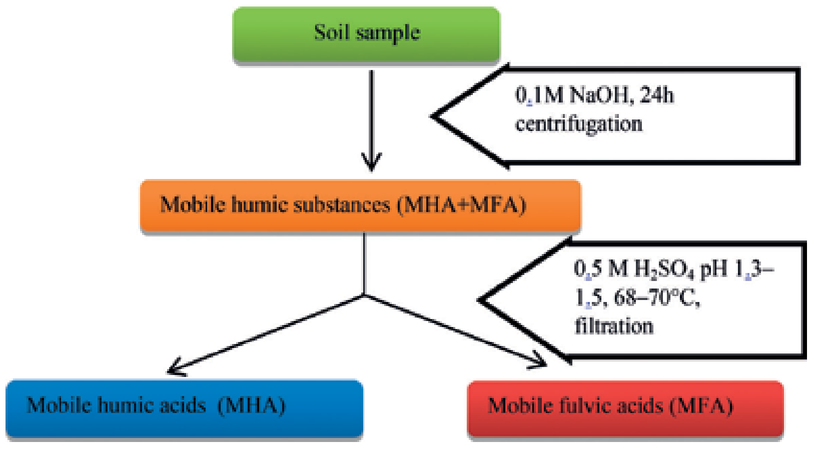


Figure 5. Determination of mobile humic substances according to the Ponomariova-Plotnikova-modified Tyurin method.

During stage I of the long-term soil investigations, humic substances were additionally extracted from the Histosol (0–20 cm) by the NaOH and sodium pyrophosphate +NaOH solution [46].

Water extractable organic carbon (WEOC) was determined using an ion chromatograph SKALAR (Skalar Analytical B.V., Netherlands). The soil samples were shaken with cold distilled water at soil: water ratio of 1:5 for 1 hour using a multi-functional orbital shaker PSU-20i (BioSan, Latvia). The extract was obtained after filtration through 0.45 μm cellulose filters. The automatic ion chromatographic measurement procedure is based on the following reactions: the sample is acidified under nitrogen using sulfuric acid solution. Labile organic carbon is released in the sample thanks to this reaction. In this process, organic carbon is oxidized to carbon dioxide. The amount of carbon dioxide is measured by infrared detection at 2–100 mg C L^{-1} range. The obtained results (mg C L^{-1}) are recalculated in g kg^{-1} soil.

For the determination of hot water extractable carbon (HWEOC), a suspension of soil:water (1:20) was prepared and boiled for 2 hours under reflux. Brown-yellow color extract was filtered through 0.45 μm cellulose filter. Carbon content in the extract was determined with an analyzer TOC 5050A (Shimadzu, Japan).

Soil particle size distribution was determined in the liquid dispersion using the light-scattering technique Mastersizer 2000 (Malvern Instruments, UK) which measures particles in a wide range from 2000 to 2.0 μm.

Statistical analyses: Experimental data were analyzed by the one-factor analysis of variance (SAS) and ANOVA.

3. Results and discussion

Profile I of Drainic Pachiterric Histosol (with non-removed peat layer) (**Figure 6**).

We determined that the most notable changes in soil characteristics are taking place in the upper layer of the peat soil profile. Organic matter transformation is taking place in this soil layer.

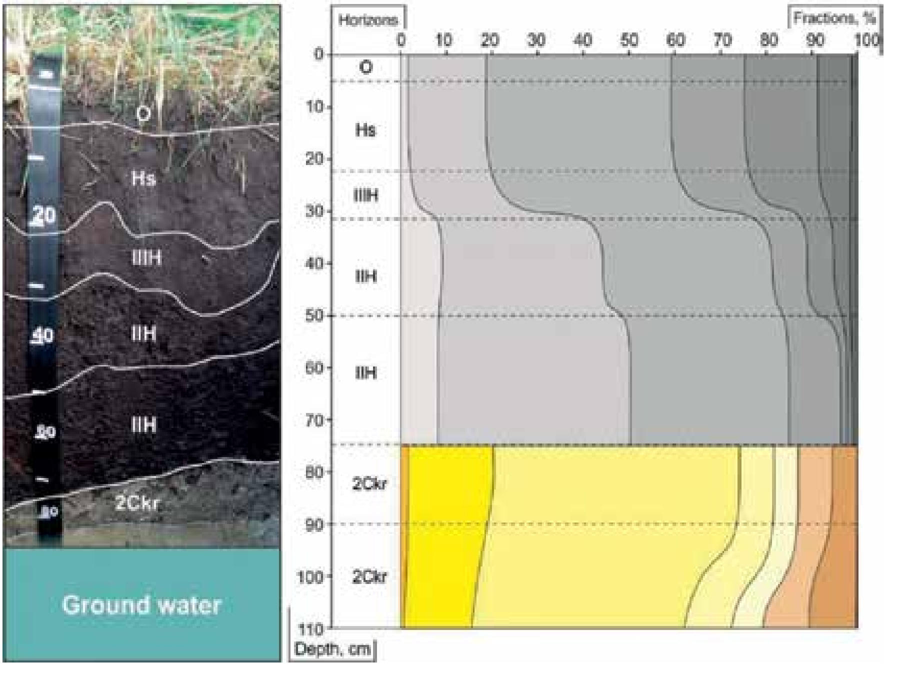


Figure 6. The textural composition of Drainic Pachiterric Histosol with a non-removed peat layer (according to WRB2014: Rheic Drainic Fibric Histosol (Eutric)).

The peat soil, the profile of which is given in **Figure 6**, was formed on Central Lithuanian ground moraine loam formations, which are found at a depth of 75 cm (2Ckr horizon), and they consist of carbonated skeleton moraine loam enriched with rocky stones. This horizon is waterlogged, and forms the basis for the formation of peat. The upper peat layer is drained, mineralized and, therefore, settled (up to 20 cm). Surface strongly mineralized Hs horizon formed after soil drainage and plowing, and the total thickness of the peat does not exceed 100 cm. This peat soil was not arable recently, therefore, the sod horizon enriched with organic matter began to form on its surface, and this is typical of soils that have long been present under the natural vegetation cover.

Profile II of Drainic Pachiterric Histosol (with non-removed peat layer, grassland) (**Figure 7**).

If the effect of human activity on the morphological and chemical characteristics of the peat soil profile is inherent only in the upper horizons (0–25, and partially 25–35 cm), meanwhile the peat soil, which profile is presented, is partly man-made due to intense anthropogenic activity. The basis of this peat soil is limnoglacial sand, whose fraction composition changes in depth. The amount of medium (500–250 μm) and small (250–100 μm) sand fraction is decreasing, and content of silt particles (53–2 μm) are increasing. The limnoglacial sand, covered with watertight sapropel at depths of 65–75 cm, creates favorable conditions for the formation of peat.

The upper layer of this peat soil was removed, and the naturally occurring medium mineralized peat remained only at 35–65 cm depth (horizon IIH). The horizon Hs formed after

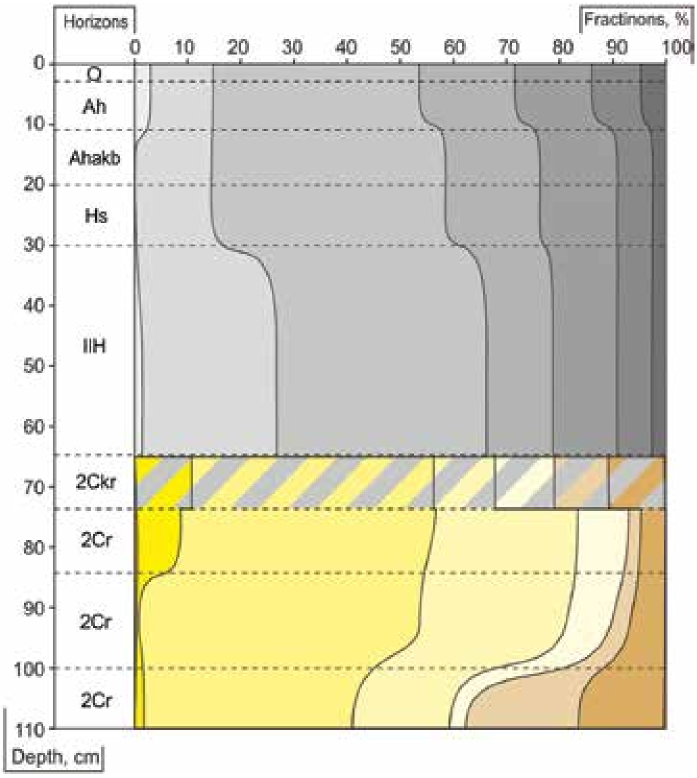
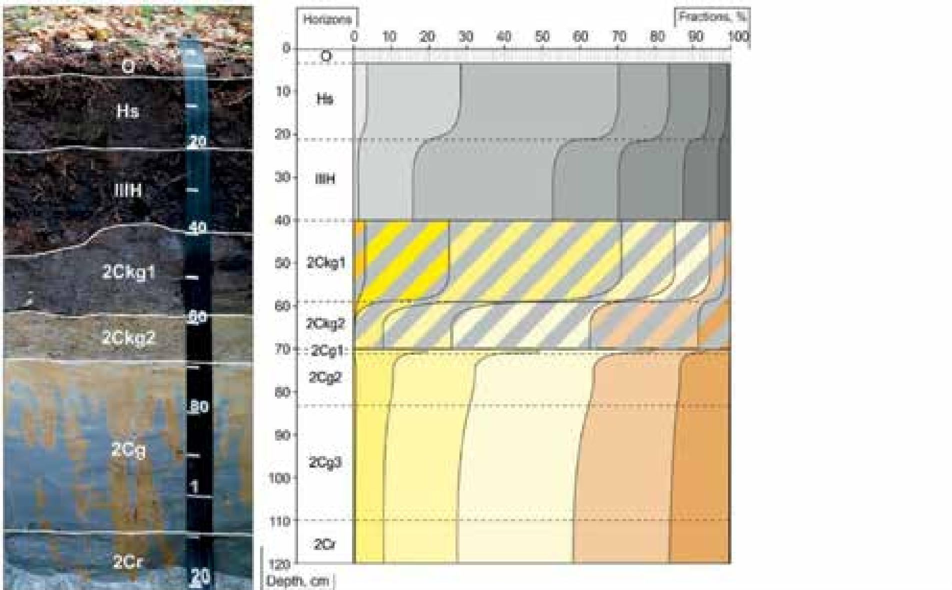


Figure 7. The textural composition of Drainic Pachiterric Histosol with a removed peat layer (according to WRB 2014: Removed Drainic Fibric Histosol (Areninovic, Eutric, Transportic)).

the drainage and exploitation of peat as a relic of the exhausted horizon. The anthropogenic Ahakb horizon was pushed/poured from the mixed mineral and organic soil when the surface and drainage system of the maintained peat bog were treated. Mineral humic Ah horizon was formed in the upper part of the removed peat profile after re-cultivation. The O horizon that formed above Ah horizon indicates that this anthropogenic peat does not undergo intense economic activity, and therefore the surface may be characterized by a weak sod formation process.

Profile III of Drainic Pachiterric Histosol (forest) (**Figure 8**).This Histosol has formed in the central part of the limnoglacial basin. Its ground surface is composed of limnoglacial sand, whose texture varies with depth. The content of medium (500–250 μm) and fine (250–100 μm) sand fractions is decreasing and the content of silt particles (53–2 μm) is negligibly increasing. Limnoglacial sand at the 40–70 cm depth is underlain by carbonated sapropel. This sapropel forms aquifuge, which creates conducive conditions to peat formation. As peat layer is removed in this Histosol, and according to the rules of peat bog exploitation, there has to be left about 50 cm peat, currently only 37 cm of the peat layer remains (in the 7–40 cm depth) and it consists of strongly decomposed peat (IIIH) and mineralized peat (Hs). Soil-forming ground surface texture of this Histosol is heterogeneous. This ground surface contains two



Fractions of soil forming materials	Particle sizes, μm (by FAO)							
	Sand					Silt		Clay
	Very coarse	Coarse	Medium	Fine	Very Fine	Coarse	Fine	
Mineral	2000-1000	1000-500	500-250	250-106	106-53	53-38	38-2	<2
Organomineral	2000-1000	1000-500	500-250	250-106	106-53	53-38	38-2	<2

Figure 8. The textural composition of Drainic Pachiterric Histosol with a removed peat layer (according to WRB 2014: Removed Drainic Fibric Histosol (Eutric, Transportic)).

horizons differing in genesis and four horizons differing in texture. The sand layer present at 84–120 cm depth (2Cg3–2Cr horizons) formed at a deeper place of the limnoglacial basin under the effect of less intensive movement of water mass. This is evidenced by an increase in silt (53–2 μm) content. With decreasing water mass, its movement exerted marked effect on the newly forming deposits: silt (53–2 μm) content decreased, while sand (500–53 μm) content increased. This effect is particularly evident at 70–72 cm depth of the profile. Sapropel started to form from the decomposed organic residues after the basin had drained. Silt particles (106–38 μm) and more decomposed organic matter predominate in sapropel present at 60–70 cm depth. Fine sand (250–106 μm) and higher decomposed organic matter content predominate in sapropel at the 40–60 cm. With increasing mineralization of peat horizons, the content of 1000–250 μm particles increases. Peat mineralization decreases with depth.

3.1. Chemical composition of Pachiterric Histosol

At stage I of the experiment, Pachiterric Histosol with non-removed peat layer had the higher N content (26.0–27.1 g kg-1), compared to peat with removed peat layer (16.1–18.7 g kg^{-1}), as well as P (**Tables 3** and **4**). In opposite, the highest ash content was determined in peat soil with removed peat layer (26.6–34.4%). Also, results of SOC and pH indicated different carbon amounts then peat soil layer was previously removed or non-removed (**Tables 3** and **4**).

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Pachiterric Histosol with non-removed peat layer	pH_{KCl}	Ash %	SOC g kg^{-1}	N	P	K	P_2O_5	K_2O
				Total			Mobile (A-L)	
				g kg^{-1}			mg kg^{-1}	
Unused peat soil	5.6	19.2	343.8	26.8	12.0	0.95	89	531
Former unfertilized perennial grasses	5.6	18.6	343.7	26.0	11.8	0.74	57	136
Former crop rotation field	5.5	18.3	338.8	26.4	12.9	0.81	129	525
Former red clover and timothy mixture	5.5	17.9	341.4	27.1	12.3	0.69	137	360
Former perennial grasses fertilized with commercial NPK	5.6	18.4	342.0	26.7	13.0	0.77	180	390

Table 3. Content of macroelements (0–20 cm) of Pachiterric Histosol with a non-removed peat layer. Stage I of the experiment. 1998–2001.

Pachiterric Histosol with a removed peat layer	pH_{KCl}	Ash %	SOC g kg^{-1}	N	P	K	P_2O_5	K_2O
				Total			Mobile (A-L)	
				g kg^{-1}			mg kg^{-1}	
Unused peat soil	6.3	28.6	330.2	16.6	0.83	0.90	110	314
Former unfertilized perennial grasses	6.5	34.4	324.3	16.1	0.51	0.79	79	225
Former crop rotation field	6.4	32.8	321.5	16.1	0.50	1.00	230	446
Former red clover and timothy mixture	6.2	30.9	328.8	16.8	0.45	0.88	188	331
Former perennial grasses fertilized with commercial NPK	6.2	26.6	332.3	18.7	0.47	0.85	165	338

Table 4. Content of macroelements (0–20 cm) of Pachiterric Histosol with a removed peat layer. Stage **I** of the experiment. 1998–2001.

Different factors cause an increase or decrease in SOC and humic substances. Soil organic carbon (SOC) stocks are expected to increase after conversion of cropland into grassland [48]. Shallow and conventional tillage, past cultivation affected peat properties [38, 49, 50]. The composition of humic substances of Pachiterric Histosol with a non-removed peat layer is presented in **Table 5**. Humic substances (humic acids and fulvic acids) are organic compounds of mineral soils and peats. Humic acids are more valuable. They are formed during chemical and physical transformations in soils and peats. The differently used peat soil had different contents of 0.1 M NaOH and pyrophosphate solution extractable humic acids (**Table 5**).The content of humic acids extracted by pyrophosphate solution was much higher than that extracted by 0.1 M NaOH solution. The soil of the crop rotation field had lower humic acids contents compared to the soil under grasses.

Peat humification degree is an indicator of processes of decomposition and humification of peat. Peat humification can be estimated in the field or in the laboratory conditions using a range of the methods including determination of chemical properties [40]. Humification degree (HD) by mobile humic acids (HA1) of Pachiterric Histosol with non-removed peat layer was higher (12.1–12.9) compared to peat with non-removed peat layer (7.8–8.7) (**Figures 9** and **10**).

Treatment	HA1 g kg^{-1}	MHS	HA_{pyr}	HS_{pyr}
Unused peat soil	47.1	89.3	47.1	132.4
Unfertilized perennial grasses	48.9	91.9	49.3	136.5
Crop rotation field	48.3	92.0	44.7	136.0
Red clover and timothy mixture	49.6	93.3	51.8	136.4
Perennial grasses fertilized with NPK	48.3	92.1	50.6	133.5

Note: HA1, mobile humic acids, extracted by 0.1 M NaOH; HA_{pyr}, humic acids in pyrophosphate solution; HS_{pyr}, humic substances extracted by pyrophosphate solution.

Table 5. Composition of humic substances in differently used Pachiterric Histosol (0–20 cm) with non-removed peat layer. Stage I of the experiment. 1998–2001.

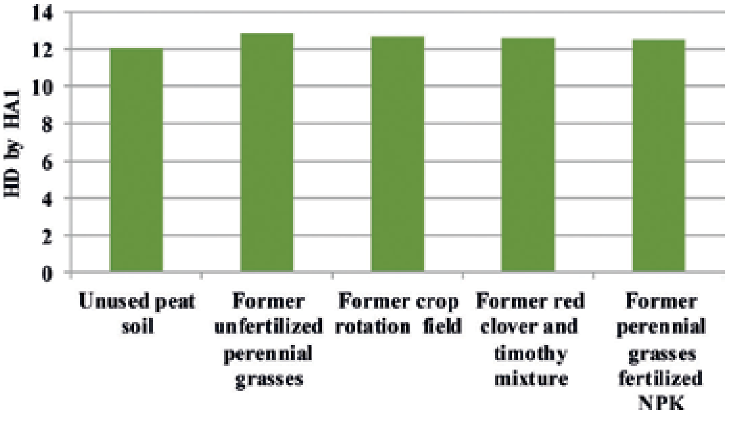

Figure 9. HD (%) according HA1 in differently used Pachiterric Histosol with non-removed peat layer (0–20 cm). Stage I of the experiments. 1998–2001.

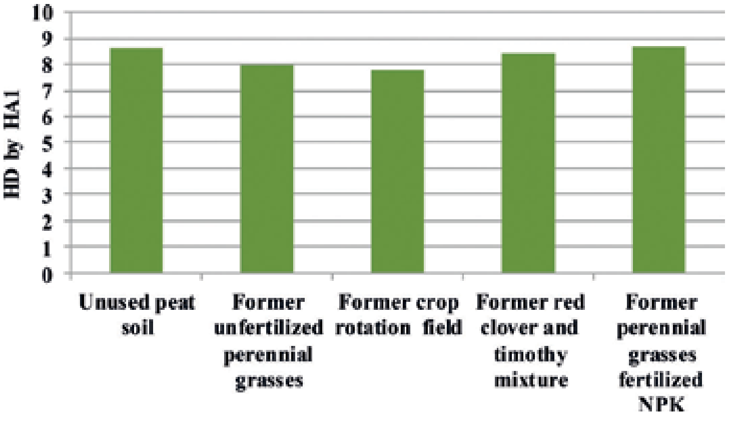

Figure 10. HD (%) according HA1 in differently used Pachiterric Histosol with removed peat layer (0–20 cm). Stage I of the experiments. 1998–2001.

HD (%) according to HA1 in differently used Pachiterric Histosol with a non-removed peat layer was higher, compared to the soil with a removed peat layer. In the unused peat soil, particularly in Pachiterric Histosol with a removed peat layer, under the effects of renaturalization, there was determined a markedly lower HD compared with that in the Pachiterric Histosol formerly used for agricultural purposes (**Figures 11** and **12**).

Humification degree (HD) by HA1 of Pachiterric Histosol with non-removed peat layer at stage IV of the experiments was higher (20.0–20.4) in peat soil under former grasses and legumes (**Figure 12**). HD in crop rotation field of peat with removed peat layer was similar to HD in peat soil with non-removed peat layer (**Figures 13** and **14**). In the long-time, semi-natural sward of peat soil with removed peat layer humification processes were more intensive: HD reached 76.3% (**Figure 14**).

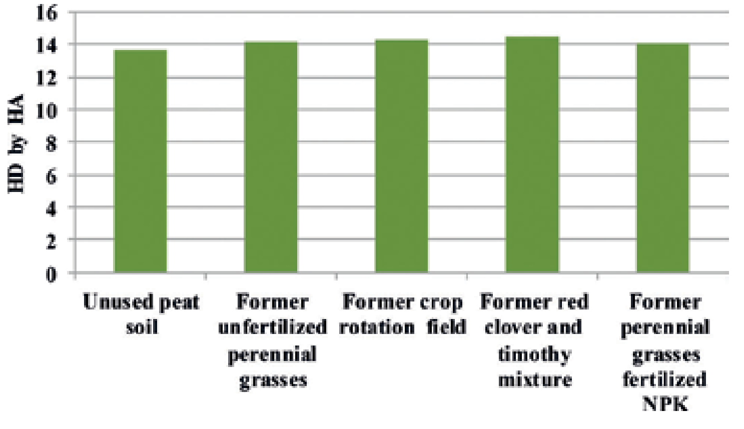

Figure 11. HD (%) according HApyr in differently used Pachiterric Histosol with non-removed peat layer (0–20 cm). Stage I of the experiments. 1998–2001.

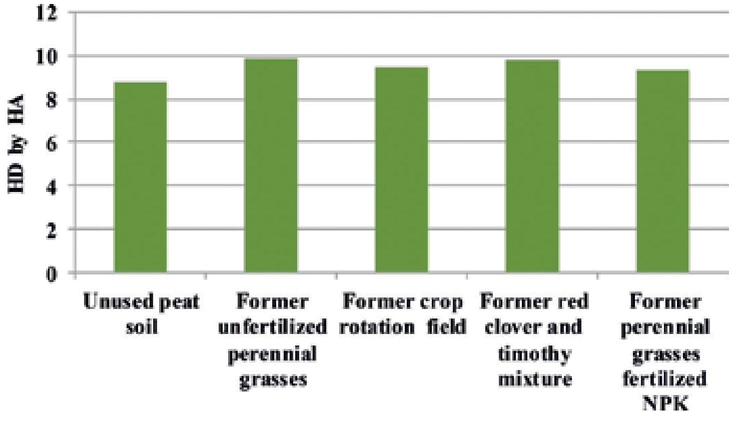

Figure 12. HD (%) according HApyr in differently used Pachiterric Histosol with removed peat layer (0–20 cm). Stage I of the experiments. 1998–2001.

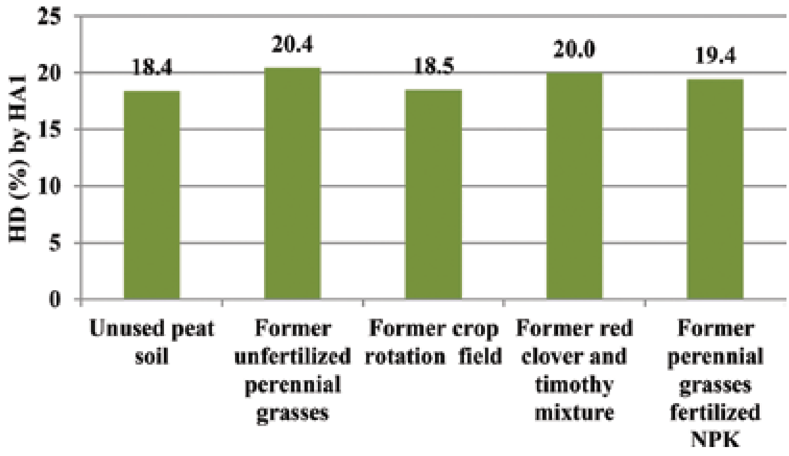

Figure 13. HD (%) by HA1 in differently used Pachiterric Histosol with non-removed peat layer (0–20 cm). Stage IV of the experiments. 2012–2014.

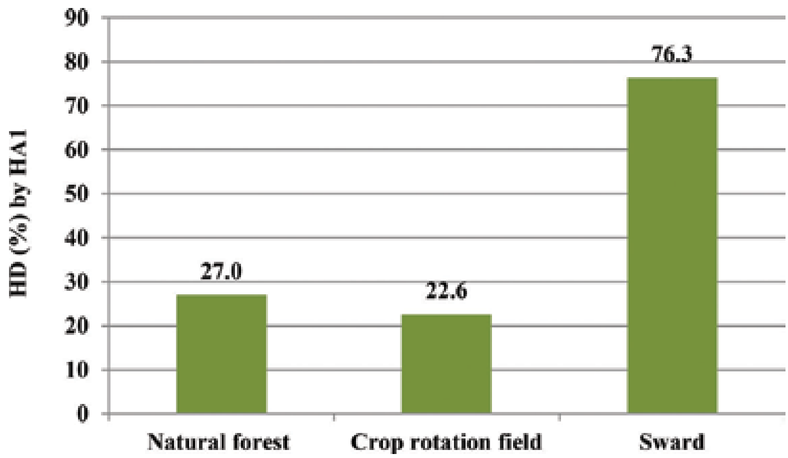

Figure 14. HD (%) by HA1 in differently used Pachiterric Histosol with removed peat layer (0–20 cm). Stage IV of the experiments. 2012–2014.

3.2. Macroelements of differently used Pachiterric Histosol

After more than 12 years, the soil under unfertilized grasses had the same content of N (26.0 g kg^{-1}), the content of N in other treatments decreased during this period. The peat soil under perennial grasses fertilized with mineral fertilizers had a higher mobile potassium (K_2O) content 495.7 mg kg^{-1}. The total potassium content was related to former fertilization (**Table 6**).

Labile carbon (WEOC and HWEOC amounts): According to data presented it the **Figure 13**, when organic carbon compounds reduce their solubility, mobility, decreasing WEOC content of Pachiteric Histosol, thus increases carbon stability of organic soil. Marked differences in WEOC contents in the 0–20 cm layer were determined between the Histosols with a removed and non-removed peat layer (**Figures 15** and **16**).The amount of labile WEOC ranged from

Pachiterric Histosol with non-removed peat layer	pH_{KCl}	Ash %	SOC g kg^{-1}	N	P	K	P_2O_5	K_2O
				Total			Mobile (A-L)	
				g kg^{-1}			mg kg^{-1}	
Unused peat soil	6.05	15.9	406	25.8	1.39	1.07	79.04	351.6
Former unfertilized perennial grasses	6.00	15.5	416	26.0	1.46	1.04	61.55	364.4
Former crop rotation field	6.09	15.4	423	24.1	1.46	1.33	106.42	420.1
Former red clover and timothy mixture	6.02	15.6	415	18.8	1.12	1.15	83.21	387.8
Former perennial grasses fertilized with commercial NPK	6.08	16.0	435	24.2	1.11	1.22	75.01	495.7
$LSD_{0.05}$	0.072	0.38	12.3	2.49	0.173	0.242	9.973	80.32

Table 6. Content of macroelements (0–20 cm) of Pachiterric Histosol with a non-removed peat layer. Stage IV of the experiment. Average data of 2012–2014.

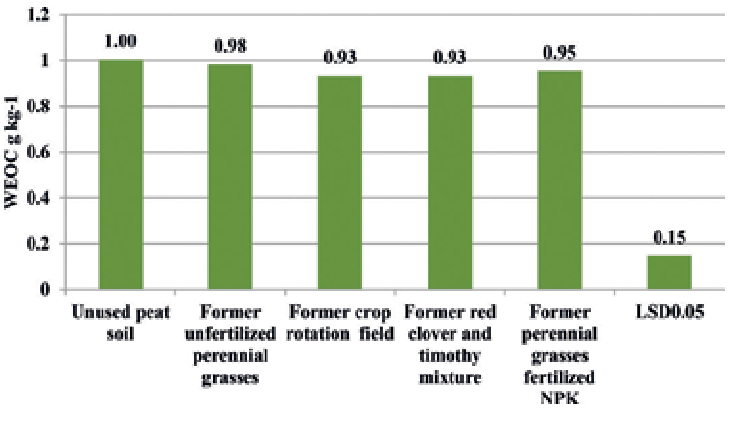

Figure 15. WEOC (g kg^{-1}) in differently used Pachiterric Histosol with non-removed peat layer, of the long-term experiment (IV stage of the experiment).

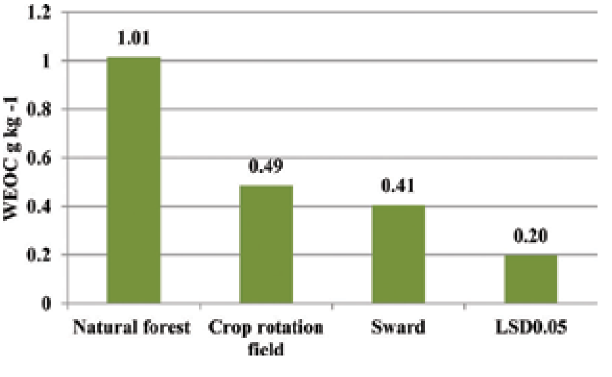

Figure 16. WEOC (g kg^{-1}) in differently used Pachiterric Histosol with removed peat layer, of the long-term experiment (IV stage of the experiments).

0.93 to 1.0 g kg^{-1} in peat soil with non-removed peat layer and from 0.41 to 1.01 g kg^{-1} in this soil with removed peat layer. In the soil of former perennial grasses and crop rotation, field significantly less WEOC was found compared to at all unused soil (1.00 g kg^{-1}).

Due to peat soil cultivation and mineralization, organic acids form organo-mineral compounds and reduce their mobility and solubility, which in turn, decreases soil WEOC content. In natural forest, there were established higher (1.01 g kg^{-1}) amounts of labile carbon compared with other land use. It is related both to the organic matter as well as total carbon accumulation in the forest floor.

The amount of labile carbon (HWEOC) was higher compared to WEOC and ranged from 13.9 to 14.8 g kg^{-1} in Pachiteric Histosol with non-removed peat layer (**Figure 17**). The higher (14.8 g kg^{-1}) amount of HWEOC was found in unused peat soil and former red clover and timothy mixture field. The soil of former perennial grasses was found significantly less of HWEOC (13.9 g kg^{-1}).

The soil of unused peat with the greatest share of dissolved organic carbon had the highest lability and the lowest stability of carbon compounds. The highest accumulation of soil organic carbon but the lowest relative share of WEOC was in the peat of former red clover and timothy mixture former perennial grasses fertilized with commercial NPK respectively, which shows that the most favorable processes for carbon stabilization and conservation are taking place there.

In summary: Peat soils, particularly those used for agricultural purposes, have been insufficiently studied so far. There is especially little research on the morphology of peat soil profile and organic matter changes after drainage and during the renaturalization process. Soil drainage as well as soil cultivation and fertilization has considerable influence on the organic matter

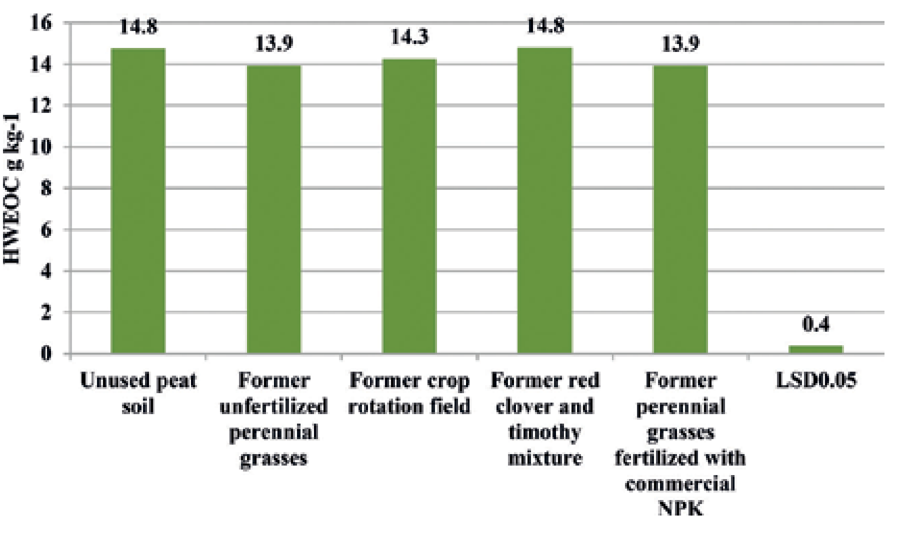

Figure 17. HWEOC (g kg^{-1}) in differently used Pachiterric Histosol with non-removed peat layer, of the long-term experiment (IV stage of the experiment).

http://dx.doi.org/10.5772/intechopen.74151

mineralization rate and changes in the profile structure. Our research suggested that quantitative and qualitative characteristics of peat soil are changing in response to the renaturalization processes and different management. The study set out to estimate chemical and physical properties of Pachiterric Histosol, qualitative and quantitative changes in carbon resulting from different management and renaturalization processes. Wetland and peatland soils are among the largest organic carbon stocks, and their use contributes to carbon emissions or accumulation processes. The focus of our work is research into the peculiarities of organic carbon accumulation and transformation as influenced by different land use of peat soil. Results on the chemical properties of Pachiterric Histosol showed the influence of management and renaturalization on mobile and by pyrophosphate solution extractable humic and fulvic acids and humification degree. We are also exploring the specificities of organic carbon variation in the context of peat renaturalization and are seeking to answer the question as how to optimize the use of peat soils and how to match up this with the renaturalization processes in order to reduce greenhouse gas emissions and contribute to organic carbon accumulation and conservation in the soil.

Acknowledgements

The paper presents part of research findings, obtained through the project "The influence of long-term, contrasting intensity resource management on the soils of different genesis and on other components of agro-ecosystems (SIT-9/2015)" funded by Research Council of Lithuania.

Conflict of interest

No conflict of interest is declared.

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Chapter 5

Peat Use in Horticulture

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79171

Abstract

Peat is a spongy substance which is an effect of incomplete decomposition of plant residues in different stages of decomposition. Between the several organic matters which are used as substrate for horticultural plants cultivation in soilless conditions, peat is the unabandonable ingredient for mixtures for commercial production of plants. Peat is used in horticulture as a component of garden plant substrates, in agriculture for the production of garden soil and as an organic fertilizer, and in balneology as a material for baths and wraps. The use of peat for agriculture and horticulture is determined by the following quality parameters: the degree of decomposition, ash content, pH, the presence of carbonates, the density of the solid phase, bulk density, and porosity. As an organic material, the peat forms in the acidic, waterlogged, and sterile conditions of fens and bogs. The conditions seem like the development of mosses. The plants do not compose as they die. Instead of this, the organic matter is laid down and accumulates in a slow time as peat due to the oxygen deficiency in the bog. This makes peat a highly productive growing medium. In the present novel review, we discuss the peat use in horticulture.

Keywords: plant, horticulture, growth, medium, peat

1. Introduction

The crops under systems of modern cultivation which is dealing with soilless culture consume substrates in organic and inorganic forms for nutrition of nutrient solutions. In general for the greenhouse plants, this system is used to maximize the productivity of crops and utilizing from all inputs in an efficient way for commercial production. In precious crop production, soilless culture systems in greenhouses are advised as alternative system to conventional production. For controlled conditions in the growth field, this conservated system is used. Due to this system, horticultural plants are increased by yield in soilless culture compared to culture of conventional soil. For increasing development of plants, the artificial system supports plants via mechanical instruments [1].

To gain much quality and more productivity in crops, ornamental and greenhouse plants, peat is used for a fast production. In some areas, the soils are not convenient for intensive production of plants, and due to this, container media are used in agriculture of greenhouse. The common media used for the systems in Northwest Europe and Israel are peat [2, 3].

Peat is based on organically decomposed matter and mostly plant originated. It composes from accumulation of nutrient and oxygen imperfection, acidity and waterlogging conditions. Also peat is composed from mosses, shrubs, small trees, and herbs in low temperatures like subarctic and boreal regions which reduce the decomposition ratio [4]. In the humid tropical conditions, the peat is composed from the trees of rainforest [5].

Peat has important functions for plant. It keeps water and nutrients, and gives them steadily to plants. It has air pockets or pores to supply oxygen to plant roots and allow for drainage. It is slight, clean, sterile, and does not include foreign material. Peat is one of the most important growing medium that is safe and cost-effective used in the production of horticulture plants. It is valuable for horticulture plants, because the peat has a good capacity to hold air and water in high quantities of available formed plant nutrients. The plant growth is supported by peat via providing appropriate conditions. The peat is a very clean medium that has no weeds or pathogens inside and also has comfortable storage conditions and very economical to buy. The peat also enables the media for several applications with its low pH and nutrient content. It has an important structural characteristic that is long constant even under intensive use and it is biodegradable [6]. Peat has perfect powers of absorption that absorbs water up to approximately 20 times its own dry weight, and can also pull oil [7]. It can be used as a very good heat insulator for dry peat. It can pick up various chemicals such as nutrients and pollutants. It is a perfect growth substrate for greenhouse crops, trees or vegetable seedlings, and potted ornamental plants. Also, it can improve garden soils [7].

The fields of usage of peat are as follows: (1) it is used for energy like fuel heat production and electricity for industrial or residential or other aims; (2) used for agricultural or horticultural aims like compost content or growth medium; and (3) used also for chemical and organic products like activated carbon, medicinal products like antibiotics, or therapeutic applications like baths of peat [8].

2. Historical use of peat in horticulture

Peat is an organic sheet composed in watery ecosystems where the local vegetation is being decayed. Peat lands are among the few available ecosystems that produce long-term energy [7]. For a long time, peat has been used for as absorbing urine in stables or as a great and dirty fuel. However, the most common use of peat has been for agriculture, pasture, and forestry [7].

Peat for fuel has been extracted in Europe since time immemorial, and the systematic industrialized extraction of peat for commercial purposes dates back to the thirteenth century; the peat is extracted for the purpose of fuel usage but in the last quarter of nineteenth century, this trend has declined by leaving its place to coal. And then, the initial form of peat was the peat moss litter. It is composed from white peat which is used to bedding for cattle and horses. Next form of peat in industry was active carbon which is sourced by black peat. The only active carbon factory which uses the peat as raw matter is The Purit (Norit) factory and is a part of the Cabot Corporation, nowadays. The other form of peat is potting soil and garden peat. This is also a common process in production of peat which has started in the late 1890s. In the history, there are two production types in peat factories such as peat cardboard and clothing. Allagnou from France was founded a factory to produce fibers from peat in 1884. Also, felt is made from this fiber matter. Due to low quality of products, the numbers of customers of Allagnou's were declined and the factory was closed. Another Frenchman, Beraud, took over the machinery and tried elsewhere in the country, but also met with little success. After 1992, the extraction of peat in The Netherlands was stopped due to usage of peat lands for energy and industrial production purposes. Nevertheless, the production and extraction of peat continues still in some part of the world for horticultural purposes in Europe, and it is a big player in the growth media and composting fields [9].

Lawrence and Newell were the creators of standardized growing media for commercial purpose in 1930, UK [2]. A mixture called "John Innes" includes some blends of loam, sand, and peat. Somehow, the quality of loam was hard to determine and the cost of transport of heavy mixtures was very high and this situation made an obstacle for growing horticultural industry [10].

At the beginning of 1950s due to widening of crop production in greenhouses and containerized nursery, there have been many studies and researches started to find and develop components for container-grown plant substrates. In the middle of twentieth century, for producing the containerized crops, the producers started to use sand, mined soil, and Canadian Sphagnum peat in the US mined soil [11]. With the developing technology, the producers started to use drip irrigation system with the combination of liquid fertilizer which made the producing, harvesting, and transport much more cheaper and easier and then, this business became a profitable way. In the US, the optimum soilless component was determined as bark and peat for crops growing in short or long periods in 1950s [12].

In UK, the usage of peat proportion in media was declined in 10 years duration [13], but it was really slow that there is approximately 3 million m^3 peat usage still continuing. The several obstacles like cost, quality and technical problems provide high proportion usage of peat in media [14].

With the increasing amount of soilless cultures in the world in the last years, the general forms of peats were started to use as peat-lite and bark and wood chips mixture for growing media in the container systems [1].

When we look at the historical dimension of growing media development, as an example, in Germany, it has been used in many different steps like below. Initially, in 1950s, the gardening soil has been used by horticulturists and there has been several components like their composted organic waste and mineral soil used in these mixtures. Also, in the plants with the bare roots or ball rooted plants, the mixtures were commonly used. Clay has been added in the mixture of peat culture substrates in 1950s and also the mixture developed alone without adding clay. The distribution of these substrates took place in1960s and the main component of in these growing media becomes peat. For the vegetable production in the West Europe, the rock wool becomes popular and distributed in the late of 1970s. The comfort of the usage of rock wool cubes and slabs provides producing private mixtures with better properties for plant species between the 1980s and 1990s. Approximately, the annual usage of peat in media now is between 77 and 80% in the Europe industry of horticulture [15].

3. Advantages of peat as growing media in horticulture

A suitable substrate is required for plant seed germination and emergence. This medium allows for the optimal development of plants in pot [16–18].

Different media are used in plant cultivation. These are organic matters like several origins of compost, chips of woods, barks and fibers from coconuts, agro industrial by-products, peat, dehydrated moss, and inorganic materials such as rock wool, vermiculite, and perlite [18–20]. Especially, peat has optimal quality features and it is the most used substrate in seedbed for seedling. In general, the tree and underglass cultivation and container shrubs use the greenhouse potting or nursery soil as growing media and peat becomes a substrate [21].

The growing media must provide oxygen and water supports for plant growth and efficient supply of continuous water system without cutting the oxygen to the plant roots. For a good rooting substrate in propagation, the most appropriate conditions should carry the convenient amounts of air and water and pH for nutrient uptake [22].

The peat becomes the main component for containerized mixture in commercial production and also very good component for vegetable and ornamental growing media when compared with all other organic materials for horticultural crops due to its several physical properties like high porosity and water holding capacity (WHC), slow degradation ratio, and low bulk density, and also good chemical properties like high cation exchange capacity (CEC) [23].

Now, more than a half century, the peat has been used for a substrate of horticulture due to its appropriate conditions like low nutrient status and pH. The reason is that the producers the needed dosages of nutrients for each plant's requirement. Moreover, peat provides a balanced aeration to roots and water with its high water holding capacity and aeration properties, that is why, peat substrates do not require precise irrigation schedule. According to data, peat use by sector in UK is 32% for container nursery stock (280,000 m^3), mushrooms 30% (260,000 m^3) bedding plants 16% (143,000 m^3) and other sectors such as pot plants, vegetable transplants, glasshouse salads, and bulbs follow. Smaller amounts of peat are also used for soft fruit and cut flower production. A very important characteristic of peat is that not many changes occur during the storage period. This fact is very important for growing media. An experiment which took place in Nottingham Trend University investigated changes in organic growing

http://dx.doi.org/10.5772/intechopen.79171

media during storage [24]. Alternative substrates such as paper and timber waste, bark, and wood fires have a high percentage of cellulose and hemicellulose. Due to the action of microorganisms, structural collapse may occur. Another problem that may appear is the development of molds or microbial organisms and the utilization of nutrients, especially nitrogen. Coir is another alternative substrate that can be used without these problems. Coir, like peat, has a high percentage of lignin; so, it is quite resistant to microbial degradation, but in order to use other substrates, certain measures should be taken. It is essential to have a very careful composting procedure for materials such as bark and timber by-products [25].

4. Peat physical properties

Peat is used extensively as an appropriate media for big quantities of vegetables because of its favorable physical properties, slow degradation rate, and relatively high CEC [23]. The positive effect of the physical properties in peat medium is the continued long period. The physical properties of peat include total porosity, pore sizes, water retention, bulk density, etc. In a media, high ratio retention of easily available water and providing good aeration for respiration of roots are considered the most important physical properties that needed to promote optimal plant and seedling growth. The deficiency of oxygen in a growth media with low aeration pores weakens root enlargement when low gas exchange occurs and consequently slows down plant growth. Aeration porosity for horticultural use should be ideally of minimum 20–25% [22, 26]. The desired value is up to 45% in warm greenhouse conditions because of increased oxygen requirement of the roots and also the rise in carbon dioxide production [27].

The physical properties of peat are related to source and degree of decomposition of the peat-forming vegetation. Generally, peat is an organic material with low bulk density, particle density, and too high porosity [28]. Particle density is relatively low, usually ranging from 1.0 to 1.6 [29]. The bulk density of the peat commonly used varies from mostly 0.05 to 0.200 g cm^{-3}. It can also increase to 0.500 g cm^{-3} depending on the types of plant residues and their decomposition. The total porosity in the peat reaches up to 80–90% and even a bit more due to dominantly low bulk density values despite less particle density. As the peat particle size distribution increases, water retention capacity decreases and the aeration volume increases. The water retention capacity at 1 kPa in peat is about 45–55% as the volume, while more decompose peat retains higher water 4–8 fold on the dry weight [30]. Aeration volume and water amount hindered at several tensions are the function of total porosity and the distribution of pore sizes of the media for plant growth. The total porosity of a growth media is the sum of the macro-, meso-, micro-, and spaces of ultramicropores [31]. The aeration and drainage is supplied when the macropores are larger than 100 μm in diameter, the mesopores are 100–30 μm in diameter for water conductivity, and the micropores are 30–3 μm in diameter to supply retention of water. The water in the ultramicropores with less than 3 μm diameter is not useful for plants. The results of many studies showed that peat provided high macropore volumes (45–50%) and also greater water volumes (40–45%) at low tensions (<1 kPa) [31–34]. Moreover, the mixed mediums containing peat have more water holding capacity in the root zone and create a more aerated environment.

5. Peat chemical properties

In general, approximately 80–90% of a fresh peat sample is composed of water and the remaining of solid material. The solid material has most of the components as organic and only 2–10% as inorganic.

6. Peat organic properties

The vegetative part of peat, and to less extent the microbial sources, includes organic residues [35, 36]. Due to complex chemical structure of peat, it contains very huge organic compounds. Additionally, there are several types of peat from bog to bog. Also, chemical composition may show changes with depth in the same bog. The organic composition of peat is effected by the peat position of decomposition, drastically. The elemental composition of peat change is given in table below as decomposition function. The microbial degradation of vegetative material in peat leads to 10% increase in the carbon content of peat from 50% at H1–H3 to 60% at H8–H10. The oxygen decrease in peat leads to 10% decrease via ascending humification approximately 43% at H1–H3 and 33% at H8–H10. N (nitrogen) and S (sulfur) have little increase, while H (hydrogen) is static, roughly.

Each element percentage in **Table 1** is taken from the dried organic material part of sample, and while the decomposition is proceeding, inclusion of several organic materials reduces [37]. In the highly decomposed peats, the microorganisms in the soil degrade the materials into hemicellulose and cellulose. The degraded matters like hemicellulose and cellulose is shown at H9–H10. The degradation occurs slowly in some high-resistant materials such as lignin, and at the end, these materials stay as decomposed in significant amounts. In the process of humification, the degradation occurs, and it is not only loss of matters. Humic acids and bitumen ratios are increasing as seen in **Table 2**. Humic acid constitutes approximately 60% of organic material. In **Table 2**, also ascending N compound amounts from microbial sources are shown.

Although the humification level is not effective, the derived plant matter from peat has some effects on chemical property. The effect on peat of plant is shown in **Table 3**.

Element	H 1 to H 3	H 4 to H 7	H 8 to H 10
Carbon (%)	48-53	56-58	59-63
Hydrogen (%)	5 0-6 1	5 5-6 1	5 1-6 1
Oxygen (%)	40-46	34-39	31-34
Nıtrogen (%)	0 5-1 0	0 8-1 1	0 9-1 9
Sulphur (%)	0 1-0 2	0 1-0 3	0 2-0 5

Table 1. The function of humification in peat elemental composition percentage [35].

http://dx.doi.org/10.5772/intechopen.79171

Organic material	H 1 to H 2	H 5 to H 6	H 9 to H 10
Cellulose (%)	15-20	5-15	-
Hemicellulose (%)	15-30	10-25	0-1
Lignin (%)	5-40	5-30	5-20
Humic acids (%)	0-5	20-30	50-60
Bitumens (%)	1-10	5-15	5-20
Nitrogen compounds (%)	3-14	5-20	5-25

Table 2. Percentage of different organic material components in peat of several humification degrees on dry basis [37].

	Sedges		Mosses		Forest	
	Plant	Peat	Plant	Peat	Plant[a]	Peat
Ether-soluble	1-3	1-3	1-5	2-6	4	3
Water-soluble	3-13	2-3	4-8	ND[b]	15	N[b]
Hemicelluloses	12-31	0	21-25	12-19	17	3
Lignins[c]	21-42	38-46	7-12	25-52	30	61
Proteins[d]	4-15	22-23	4-6	5-6	3	14
Ash	3-5	10-13	3-4	1-2	5	4
Total	93-98	88-91	73-86	73-87	90	90

Note: (a) Oak leaves, (b) ND not determined, (c) including humic acids, (d) assuming all nitrogen present to be protein (i) bitumens.

Table 3. Comparison of peat plants and peat soils (%, dry basis) [35].

The dissolved part of peat includes bitumens that are soluble in hot and nonpolar organic solvents.

The ascending amount of bitumens and ascending decomposition of peat is shown below **Table 3**.

The main carbohydrates in peat are pectin, cellulose, chitin, and lignin which are explained in detail below [35].

- Pectin is an extraction from peat using hot water and has a 1, 4-α bonding linkage and a galacturonic acid unit linear chain as shown in **Figure 1**.

- Hemicelluloses are composing the biggest part of peat. The original source of hemicelluloses is taken from plant or microbial sources. Hemicellulose has between 200 and 300 sugar units which compose long chains of glucose, fructose, mannose, galactose, rhamnose, arabinose, xylose, galacturonic acid, and glucuronic acid. Water is not used as a solvent for cellulose. Cellulose is a linear polymer of glucose and contains approximately 10,000 sugar units bonded with 1,4-P linkages, shown below in **Figure 2**.
- Chitin is a linear polymer of N-acetylglucosamine and is determined in the cell walls of fungi as shown below in **Figure 3**.

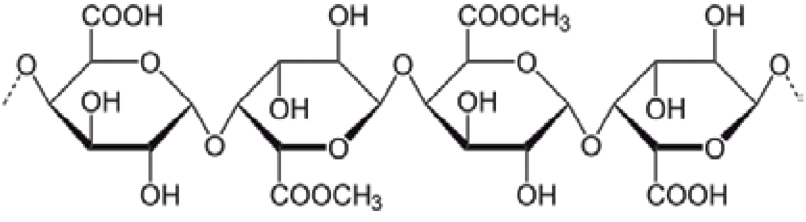

Figure 1. Pectin chemical structure [35].

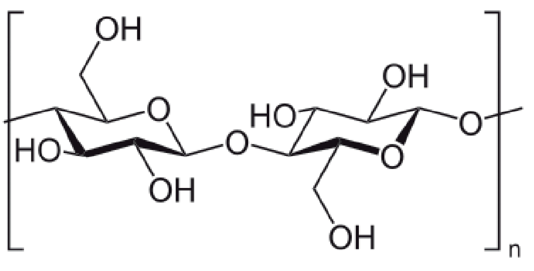

Figure 2. Cellulose chemical structure [37].

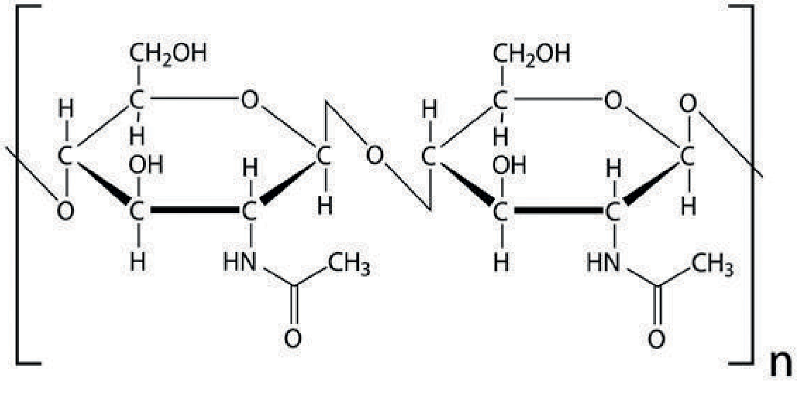

Figure 3. Chitin chemical structure [36].

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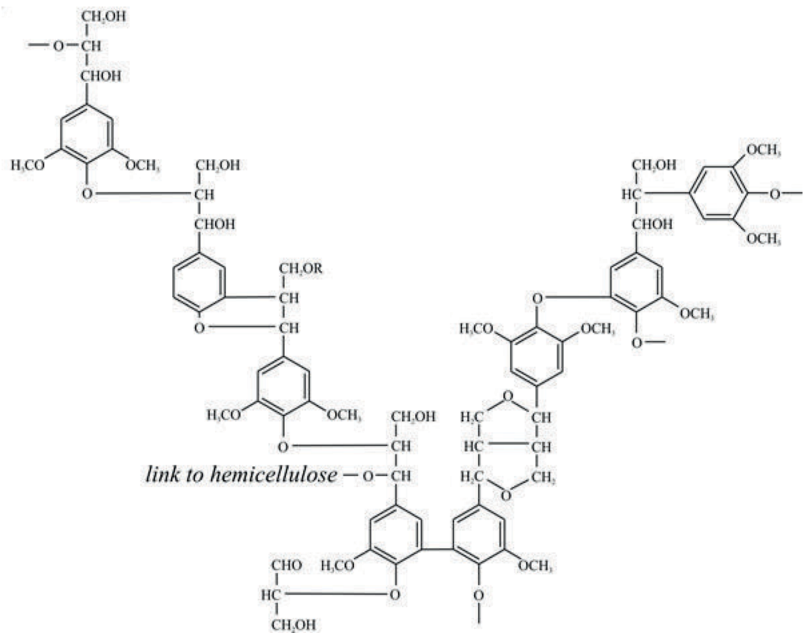

Figure 4. Lignin chemical structure [36].

- The main part of the structure of lignin is shown below in **Figure 4** and called as phenol, composed a chain of n-propyl in para position and a group of methoxyl in one or two ortho positions. The parts of lignin are arc linked in different ways to compose a structure of macromolecular complex. The main aim of lignin is to protect the plant from biological attack by microorganisms. The decomposition degree effects the proportion of lignin in an ascending way about the decay resistance of lignin.

7. Peat as a substrate in horticulture

The destiny of the nursery and greenhouse production is related with the growing media quality. In the production of media for plant growth, there have been used several combinations of inorganic and organic components. The peat is used not only for greenhouse and nursery production but also for gardening at home (**Figure 5**). In the history, the most used organic material was peat which is extracted from peat lands from decomposed plant matters that have poor drainage.

In vegetable growing, it is aimed that the product is productive, high in quality, and healthy in terms of human nutrition. In order to achieve these goals, factors such as the selection of appropriate varieties, the use of quality seeds, and the cultivation of healthy and quality seedlings are important. The medium in which seedlings are growing is important in healthy

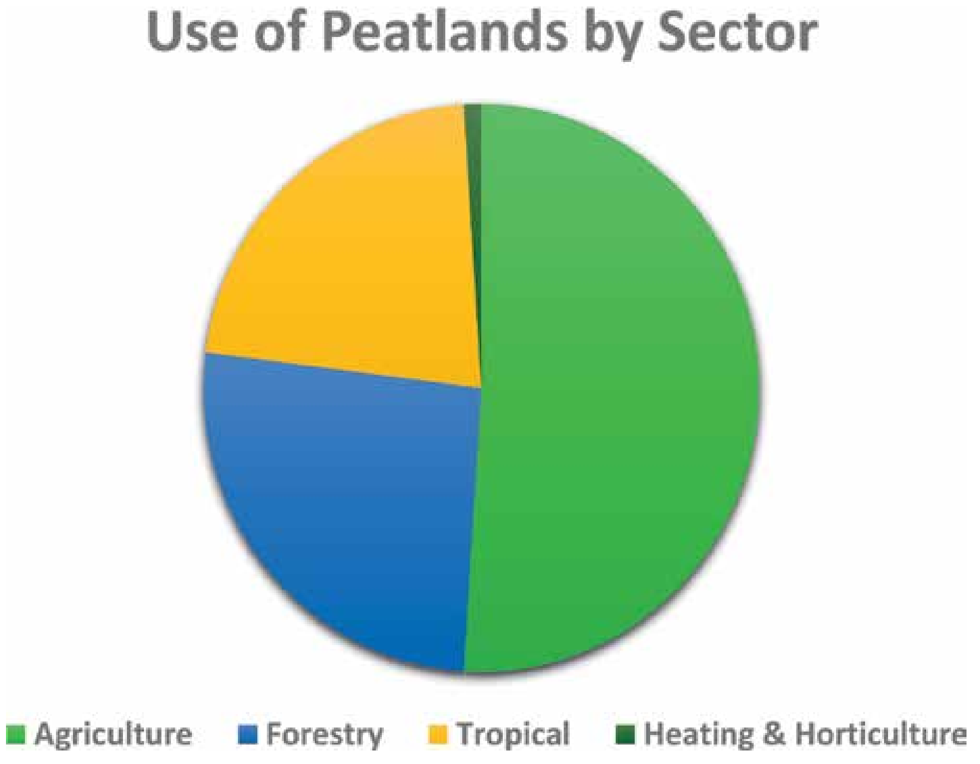

Figure 5. Use of peat lands by sector (https://www.gardenmyths.com/peat-peatmoss-true-story/).

and high-quality seedling production. Costs must be low for these used mediums to be advantageous to manufacturers. Mediums are used for seedling growing, seed germination, emergence rate, rate of growth, and quality of the seedlings. When seedlings are grown in unsuitable mediums, they may experience problems with germination and increase seedling cost with inadequate germination. In addition, since the seedlings are late planting, the growing period is delayed, the harvest is delayed, the yield decreases, and seedling deaths occur after planting and during planting. For all these reasons, it is necessary to pay attention to the selection of the environment to grow seedlings. Many different mediums and mixtures of them have been used in growing seedlings in recent years, especially peat. Mostly, peat is used in seedling cultivation in Turkey [38].

In extensive agriculture for a fast production and increasing the profits of sales, ornamental plant nursery production can be the best example which commonly uses the nonrenewable resources. According to imperfect management applications, the green industry is seen as a polluting industry. But the most spread media for ornamental growth in Mediterranean is peat due to its better chemical and physical characteristics [39].

The peat is an unabandonable substrate in horticultural industry till now, and environmental impact will prove the usage of peat will continue in the sector due to its high demand and need [40].

In the horticulture industry, the peat has three different forms that are commonly used as peat humus, moss peat, and reed-sedge. The moss peat is generally taken from sphagnum moss. The minimum decomposed type of peat is called as peat moss which is light tan to brown in color, is lightweight as 6.5 lbs/yd3, has high moisture and holding capacity and acidic conditions between pH 3.8 and 4.3, and due to these properties, it has a clear and proper fluffed structure. Peat moss is a common sample on a volume basis as an example 50% peat moss:50% perlite, vol:vol. There are significant differences between sphagnum moss and peat moss due to sphagnum moss's live portion or young residue of the plant. In plant shipment, to line hanging baskets, and in propagation, the most used matter is sphagnum and there are some efficient substances in sphagnum to inhibit the fungi growth related with damping off. The most common peat form in Florida is the reed-sedge peat which is extracted from reeds, sedges, cattails, marsh grasses, and other associated swamp plants. In common, the reed sedge and hypnum moss are used to derive peat humus which provides a better level of decomposition and has generally dark brown to black color and a low capacity of moisture retention. In seedling production in containers, peat is also a major constituent for substrate. The greenhouse growth transplants are the crucial parameter for optimizing the production systems and directly affect the production phase in the field [41]. The greenhouse growth transplants have many good properties like early production, robust, uniform growth, and healthy root systems [42].

The most common applied method is the use of transplants in small cell production using peat-based media [43].

In horticultural production of fruity vegetables like cucumber and bean, the preferred medium is solid substrate all over the world. The EU, US, and Canada used solid substrates for the estimation of growth of approximately 95% of greenhouse vegetables to be produced [44]. Rock wool (RC) and peat are the main components that are used in solid substrate cultivation, conventionally [2, 45–47].

There have been several studies conducted on pepper growth with soilless substrate on the parameters such as growth, quality, and quantity after studies on tomato. The media for pepper growth were several such as perlite, soil, sand, peat, and pumice. The effects of media components on the yield, weight of pepper fruit, ascorbic acid values, and total soluble solids were studied. When all media were compared, the peat was found to be the most efficient for plant growth with higher ascorbic acid content, total soluble solids, fruit number per plant, and yield on pepper. The potassium ratio was found higher in peat when compared with the other media [48], and it is reported that this higher potassium rate can increase the vitamin C in plants [49]. When a comparison was made between only-peat substrate and peat-perlite and peat-zeolite substrates, the biggest leaf area was determined in seedling growth in only-peat substrate; however, the dry material content was not much in leaves when compared with the peat-perlite and peat-zeolite substrates [1].

In the EU, the reported total amount and ratio of peat in media for plant growth is 25,990,000 m^3 equaling 75.1%. The main reason for this high percentage is long experience of countries on peat production and their high resources. The usage ratios of peat by country are as follows: 99% in Estonia, 99% in Lithuania, 92% in Latvia, 88% in Finland, 87% in Ireland, 87% in Denmark, 87% in Sweden, and 81% in Germany [50].

8. Disadvantages of peat

In the recent decades, the decreasing usage of peats brought the ascending prices and costs and also produced some hesitations if it will have an impact on environmental problems. Indeed, the mining of peat from very high fragile ecosystems may cause a potential degradation of natural habitats of biodiversity and living organisms. For wild animals and plants habitat, peat has a crucial importance to develop the quality of groundwater, and furthermore, it preserves the CO_2 sinks. So the intensive use of peat in horticulture industry may cause the release of CO_2 from these ecosystems as it is a nonrenewable source. Due to this, global warming may increase and a global movement should be started to success a sustainable peat and an intelligent wetland usage. The growing requirement and need of soilless media for horticultural industry causes to find new media for plant growth from organic wastes instead of peat as a nonrenewable source and its ascending concerns for environment. During the last years, there has been an increased concern about the use of peat. Many peat bogs are characterized as special areas of conservation. The number of license for peat extraction has decreased in order to protect environmentally significant peat bogs. Pressure of environmental groups has increased in order to reduce the use of peat by growers. Government has set as target that 40% of the total market demands, for growing substrates and soil improvements, should not be covered with peat-reduced or peat-free products, by 2004. In 1999, 36% of the market was covered by peat alternatives. Some of peat alternatives may include wood residues, forest harvest materials, urban wastes, composts, and other industrial wastes. Scientists have made several experiments to test peat alternative substrates [1].

Scientists all over the world examine the potential peat alternative substrates and the disadvantages that may have, when compared to peat. Evaluation of water and nutritional consumption is very important for peat alternatives. The use of peat alternatives is going to expand in many different horticultural sectors. An experiment which took place in Chile tested the use of vegetable wastes with melon as a substrate [51]. The compost of vegetable waste was compared to coir and rock wool as far as it concerns yield and quality of melons. The vegetable had satisfactory results only when it was leached prior use, otherwise high pH and salinity occurred.

Since the pressure for adopting new growing media alternative to peat is steadily increased, it is almost sure that sooner or later the use of peat alternatives is going to increase. Some supermarkets have given instructions to the growers that in order to keep buying from them, they should limit the use of peat. The reduction of peat use may increase the cost of horticultural production. In order to further decrease the peat in horticulture, further research is required for disease, nutrition and water management, and storage characteristics. Finally, further research could be done so as to determine the optimum substrate for each plant. One of the main issues of peat is wetting again the medium when it becomes dried. Because of that, synthetic agents are used in general in peat-based media to fix the problem [52].

9. Conclusion

Container-grown plant substrate mixtures are very important for the production of nursery and greenhouse plants. There have been several studies conducted on horticulture plants with soilless substrate on the parameters such as growth, quality, and quantity. Peat has been used for successful cultivation of different vegetables and ornamental crops in soilless culture since the early 1900s. Peat has important functions for plant. It keeps water and nutrients and gives them steadily to plants. It has air pockets or pores to supply oxygen to plant roots and to allow for drainage. Because of the several disadvantages, the use of peat alternatives is going to expand in many different horticultural sectors.

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Section 3

Peatland in Geotechnical Engineering and Hydrology

Physical and Geotechnical Properties of Tropical Peat and Its Stabilization

Prabir K. Kolay and Siti Noor Linda Taib

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74173

Abstract

The chapter presents the physical and engineering properties of tropical peat treated with various types of stabilizers. Quick lime (QL), fly ash (FA), and ordinary Portland cement (OPC) were used as stabilizers. The amounts of QL, FA, and OPC added with the peat samples are in the range of 2–8, 5–20, and 5–20%, respectively. Various physical or index and engineering tests have been conducted to characterize the peat samples. Unconfined compressive strength (UCS) tests were conducted on original and treated peat samples cured for 7, 14, and 28 days. The results show that the UCS value increases with the increase of all stabilizers used and with curing period. The UCS tests were also conducted on the peat samples with the combination of QL and FA to study the combined effects of the stabilizers. The present study established different correlations between physical and engineering properties of original peat and UCS results on treated peat samples with different types of stabilizers. Geotechnical engineers can refer to these correlations to determine the bearing capacity of treated peat. In addition, scanning electron microscope (SEM) studies were conducted on original and treated peat samples to investigate the microstructure of the samples.

Keywords: tropical peat, characterization, stabilization

1. Introduction

Peat or organic soil is highly heterogeneous formed due to the decomposition of organic matter such as plant remains, leaves, trunks, roots, and so on. Peat can be found anywhere in the world except in barren and arctic regions which cover about 5–8% of land area [1]. Tropical peats cover about 8–11% of the area in Malaysia, Indonesia, Brazil, Uganda, Zambia, Zambia, Venezuela, and Zaire. The department of irrigation and drainage in Sarawak mentioned that there are about 2.7 million hectares of peat land in Malaysia (i.e., 8% of the total land area). Among them, about 1.66 million hectares, that is, 63%, are located in deltas and coastal plains of Sarawak. Most of the year, this peat land area is waterlogged [2]. Peat has typical characteristics, which include high natural moisture content, high compressibility and water-holding capacity, low specific gravity, low bearing capacity, and medium-to-low permeability [3].

Hence, characterization and improvement of peat is necessary to construct any type of infrastructure on it. This is a major problem for infrastructure development as the geotechnical properties of peat soils are lower than mineral soils. However, due to rapid industrialization and population growth, it has become necessary to have infrastructure facilities and road construction everywhere, including in the peat land area. Prior case histories show that several construction methods such as the displacement method, the replacement method, the stage loading and surface reinforcement method, the pile-supported embankment method, the light weight fill raft method, the deep in-situ chemical stabilization method, and the thermal pre-compression method have been employed in Sarawak [4, 5]. It is observed that some of the projects were technically successful, while others had excessive settlement and failure problems after completion of the project.

Another major problem in Sarawak is the large quantity of fly ash (FA) production from coal-fired thermal power plants. The burning of coal resulted in over 4.2–13 million tons of coal ash as a by-product from 2000 to 2005 in Malaysia mostly disposed into ash pond or lagoon, which is a challenge for the environment [6, 7]. Therefore, it is necessary to increase the use of this FA in order to avoid increasing disposal costs and environmental impact. Due to its pozzolanic nature, fly ash can be effectively used in a variety of construction applications. However, there is a legitimate concern with respect to the potential release of toxic contaminants associated with the use of such wastes. Hence, it is believed that small percentages of fly ash (FA) can be used with peat for stabilization purposes in civil engineering applications. However, Kolay and Singh [7] discussed the impacts of toxic contaminants on the environment. Also FA uses in soil treatment, as conditioners or filler material for low-lying wastelands, in refuse dumps reclamation, and construction or geotechnical secondary raw materials [8, 9] has increased their potential geo-environmental impact. Therefore, the use of FA provides economic benefits by reducing disposal costs and negative environmental effects through engineering applications.

The stabilization of clay and soft soils has been studied by several researchers using cement [10–17]; fly ash [18–21]; and lime [22–25]. Few researchers focused on the stabilization of mineral soil such as clay, silty clay, and dispersive soil by different types of stabilizers. However, geotechnical engineers do face challenges due to inadequate basic tropical peat soil data for construction projects. There are only a few studies [11, 26–29] that have discussed the stabilization of highly organic soil or peat soil. It is difficult to determine the physical or index properties of peat soils due to high water content and variability. Aminur et al. [2] provided a comparison result of physical and geotechnical properties of organic and peat soils. Correlations between various index properties are also useful for peat soil when compared with mineral soils. Previous researchers established the relationship between physical and geotechnical properties with different types of peats [11, 30]. The morphological properties of clay, silty clay, and organic soil have been discussed by several researchers [2, 31]. Most of the researchers focused on soft clay for morphological microstructure investigation and very few studies are available on peat [2, 24, 32].

As FA is a recent issue in Malaysia, there are limited studies available on waste FA utilization. Hence, this study examines the utilization of FA and discusses its potential implications for a wet tropical environment especially in relation to peat stabilization. Therefore, the present study focused on the utilization of the waste FA along with quick lime (QL) and ordinary Portland cement (OPC) for peat stabilization purposes. Furthermore, a few correlations were established from physical and geotechnical properties of the original peat. Geotechnical engineers can use these correlations to determine properties of peat, where geotechnical data are not available.

2. Experimental procedure

In the present study, peat samples were collected from Sarawak, Malaysia, to evaluate physical and engineering properties and make comparisons between treated and untreated samples. The peats were sun dried, sieved through specific sieves, then oven dried at 60°C, and used for different physical and engineering property tests. Commercially available OPC and QL and locally available FA were used as stabilizers. The mixing of the peat and stabilizers can be accomplished using different types of modern equipment in the real field.

The moisture contents of the peat samples were measured by drying the sample in an oven at 105°C for 24 h according to BS 1377 [33]. The degree of decomposition is usually assessed using the Von Post scale, where there is 10 degree of humification (from H1 to H10) in the Von Post system. The peat sample was squeezed in the hand to perform the degree of decomposition test. The color and fluid that is released between the fingers is observed and the pressed residue remains in hand after squeezing is measured as the degree of decomposition. The loss on ignition (LOI) tests were carried out as a percentage of oven-dried mass according to ASTM D2974 [34]. The LOI method was used to determine the organic content (OC) of the peat samples.

The specific gravity (G_s) of the peat samples was determined in accordance with BS 1377 [33]. For accuracy, the average G_s value was obtained from the result of three tests. The fiber content (FC) was measured according to ASTM D1997–91 [35]. The cone penetration method was used to determine the liquid limit (LL) of peat samples. The LL tests were conducted as per the guidelines of BS1377 [33]. The pH tests were conducted in accordance with BS 1377 [33].

Standard Proctor tests were conducted according to BS 1377 [33] to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the peat samples. The unconfined compressive strength (UCS) tests were conducted to determine the shear strength parameters of the peat and stabilizers. The UCS tests were performed according to the guidelines provided in ASTM D2166 [36]. Sample sizes of 50 mm in diameter and 100 mm in height were used in this study. The UCS tests were conducted after the curing period of 7, 14, and 28 days. Due to heterogeneity of peat and FA sample, a minimum of three samples were tested with each percentage of stabilizer and average result is presented. SEM micrographs were conducted to study the morphology of peat, FA and treated peat samples. The SEM tests were performed by using the instrument JEOL, Japan, with model number JSM-6701F.

3. Results and discussion

Table 1 shows the physical and engineering properties of the various peat samples collected from Sarawak, Malaysia. The chemical composition of FA is shown in **Table 2**. The results show that the FA used in this study falls in the category of Class F ash according to ASTM C 618 [37].

3.1. Physical and engineering properties

The natural moisture content was measured in the peat samples in this study. Generally, peats have high natural water content. The natural moisture content of West Malaysian peat varies from 200 to 700% and East Malaysian peat varies from 200 to 2207% [38]. The natural moisture content of peat samples is presented in **Table 1**. **Table 1** shows that the moisture contents of the peat soil samples are very high; this may be attributed to the fact that peat soils have high FC and hence it is able to absorb more water. The degree of decomposition is usually assessed by

Properties	**Sample**				
	M_1	**M_2**	**M_3**	**M_4**	**M_5**
Moisture content (%)	587.20	620.20	496.30	360.70	605.60
Degree of decomposition	H4	H3	H5	H6	H7
Fiber content (%)	65.93	65.00	62.50	61.40	31.98
Loss on ignition (%)	96.12	85.67	78.75	67.88	44.74
Organic content (%)	95.96	85.10	77.90	66.60	42.53
Liquid limit (%)	150.00	78.00	75.00	73.00	69.00
Specific gravity (G_s)	1.17	1.45	1.78	1.64	1.82
pH	3.85	4.05	4.53	5.15	6.18
UCS (kPa)	28.56	31.28	40.38	38.3	43.28

Table 1. Physical and engineering properties of peat samples.

Oxide	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**SO_3**	**TiO_2**	**LOI**
(%)	59.40	24.40	7.60	1.71	2.22	0.23	3.91	0.23	0.17	0.15	0.85

Table 2. Chemical composition of FA.

Von Post scale and there is 10° of humification (from H1 to H10) in the Von Post system. The results show that all samples fall into the category of H3–H7, according to the Von Post scale.

The FC of different peat samples is also presented in **Table 1**. The results show that sample M_1 has higher FC than the other samples and sample M_5 has lowest FC. This may be attributed to the fact that the M_5 sample was more decomposed than the other samples. It is also observed that M_1–M_4 samples fall within the hemic peat soil group and M_5 sample falls within the sapric peat soil group [39]. The results of LOI and OC show that the sample M_4 and the sample M_5 have lower than 75% OC and so can be categorized as highly organic. The remaining samples can be categorized as peat soil. This may be attributed to the fact that the M_5 sample has lower FC and the M_1 sample has higher FC than the other samples.

The cone penetration method was used to determine the LL of the peat samples. The results show that LL value is higher for the M_1 sample as this sample contains more FC and therefore it has high water absorption capacity. Cheng et al. [40] also stated that organic contents are the primary contributors in increasing Atterberg limits and compressibility. The G_s results of the peat samples are also presented in **Table 1**. It can be seen that sample M_5 has a higher G_s value due to its lower FC value. Den Haan [41] also observed that the specific gravity in organic or peat is affected by the organic constituents of cellulose and lignin which have lower G_s values. Typical G_s values of the peat in West Malaysia are in the range of 1.38–1.70 and East Malaysia are of 1.07–1.63 [38].

The pH results show that the M_1 sample has a lower pH value than other peat samples and sample M_5 has a higher pH value. In present study, standard Proctor tests were performed to determine the compaction characteristics of the peat soil samples. The compaction results of the peat soil samples are also presented in **Figure 1**.

Sample M_5 shows an MDD value of 8.47 kN/m^3 and an OMC value of 55.50%. It can also be observed that this is the maximum dry density and minimum moisture content as compared to the other samples. This may be attributed to the fact that sample M_5 has lower FC and as a result it has lower water absorption capacity and higher dry density than the other samples.

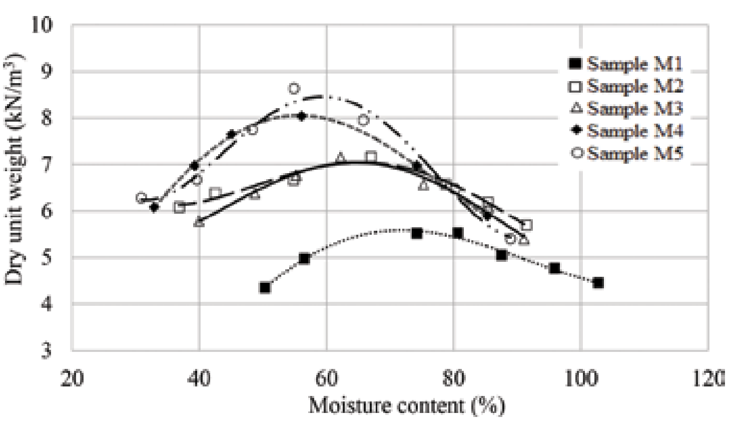

Figure 1. Compaction characteristics of peat samples.

3.2. Engineering properties of stabilized peat

The UCS tests were conducted on the original peat and treated samples with different percentages of stabilizers. The sample M_1 was chosen for the UCS tests in this study as it was the worst among all the samples. The UCS results obtained from QL, FA, and OPC stabilizers are shown in **Figure 2**. The results show that the UCS value increases with the increase of FA and curing period. The results increased up to 6% of QL with the curing period and decreased beyond this percentage. A similar trend of UCS results of lime-treated peat soil samples was reported by Kok and Kassim [22] and Aminur et al. [23]. The results also show that the UCS value increased with the increases of the OPC percentage and the curing period. The increase in strength is much more predominant with a higher percentage (20%) of OPC added to the untreated peat samples. It can be attributed to the formation of calcium silicate hydrate (CSH). The pozzolanic reactions that initiate during the curing process, which lead to calcium silicate hydrate cementitious product formation, are as follows.

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO)_2(SiO_2)_4(H_2O) + 3Ca(OH)_2 \quad (1)$$

The hydration process begins in the mixer and continues until it reaches its ultimate strength. The hydration also depends on the quality and quantities of the cementitious materials as well as the environmental temperature and the sample's moisture. Furthermore, organic matters vary significantly in their chemical composition. Organic matters also significantly influence the soil reactivity [42]. The major components of the organic matter in peat include humic acid, fulvic acid, lignin, and molecular weight.

Class F FA is not a self-cementing material; therefore, a set of UCS tests was also undertaken with the combination of QL and FA. The UCS results obtained from laboratory experiments are shown in **Figure 2**. The results show that UCS increases with the increase of QL and FA and also with the curing period. The maximum strength was obtained from 28 days of the curing period. After the addition of 6% QL, the UCS value decreases up to 28 days of the curing period and after this successively increases. This may be attributed to the fact that the reaction rate of QL and FA with peat is very slow and the CSH formation take place after

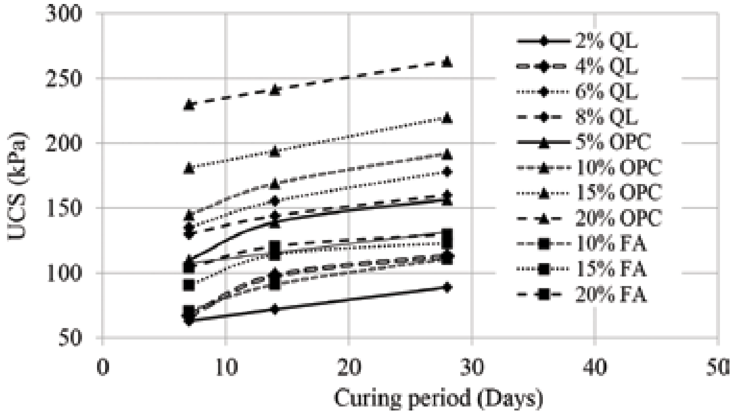

Figure 2. UCS values of treated peat with QL, FA, and OPC after 7, 14, and 28 days curing periods.

certain curing time. The results also show that approximately 70% of UCS was obtained from the combination of 6% QL and 20% FA when compared with 20% OPC. Similar results from FA- and QL-treated peat have been observed by Kolay et al. [43]. Silica and alumina present in fly ash and clay minerals greatly increased pH, which make them available for reaction with the calcium from lime and fly ash to form cementitious hydrates, calcium aluminate hydrate (CAH), and CSH. However, the formation of these calcium aluminosilicate hydrates is mainly responsible for the high strength. A wide variety of hydrate forms could be generated, depending on the quantity and type of lime or FA, soil characteristics, curing time, and temperature.

3.3. Correlation between physical and engineering properties

As the correlation between physical and engineering properties is very useful to determine any unknown properties of peat, various correlations were established in this study. The correlations of the basic physical and geotechnical properties are shown in **Figures 3** and **4**. **Figure 3** shows that MDD decreases with the increases of liquid limit (LL) and optimum moisture contents (OMC). This may be attributed to the fact that higher FC had higher water absorption capacity; as a result, MDD decreased with the increases of LL and OMC. The correlations are presented in **Figure 3**. The results show that the data are too scanty as only five samples were investigated in this study. However, the authors have established these relationships only to study the fundamental behavior of the peat rather than real-field applications.

The correlations between FC, $G_{s,}$ and OC are shown in **Figure 4**. The figure shows that the value of FC increases with the increase of OC. The correlation in **Figure 4** shows that the R^2 value is 0.984. **Figure 4** also shows the correlation between G_s and OC where G_s decreased with the increase of the OC value. This may be attributed to the fact that higher OC had higher FC and consequently density was lower. Den Haan [41] stated that peat contains higher organic substances and hence the physical properties of the peat may be affected by the organic substances. Previous researchers also observed a similar trend between G_s and OC relation [41].

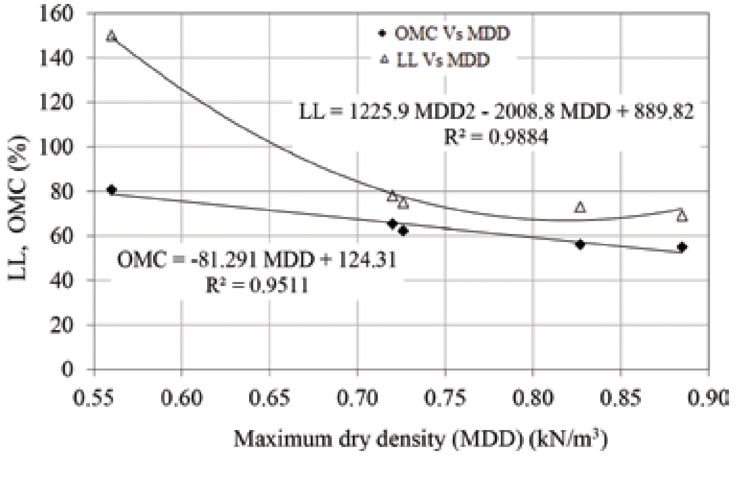

Figure 3. Correlation between LL, OMC, and MDD of the peat.

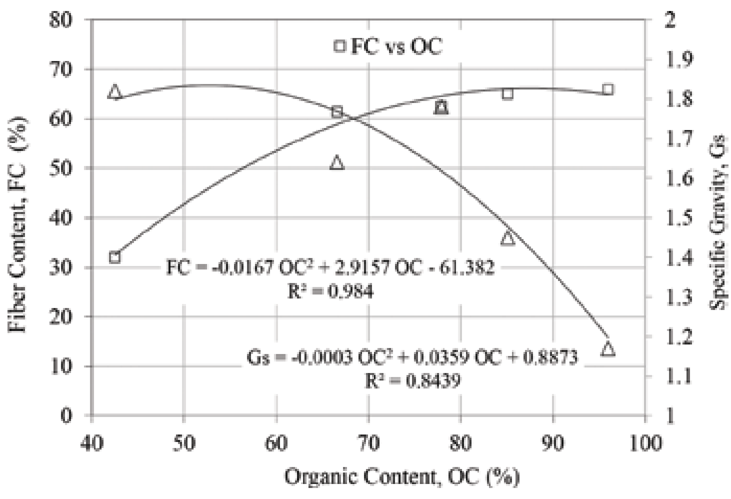

Figure 4. Correlation between FC, $G_{s,}$ and OC of the peat.

The correlations between UCS values for 28 days of the curing period and different percentages of stabilizers were established. **Figure 2** shows that UCS value increased with the increases of FA and QL percentages. Geotechnical engineers can refer to these correlations in order to comprehend the ultimate strength of treated peat where the geotechnical data are not readily available. The relationships between UCS and stabilizers are shown in Eqs. (2–4). The R^2 values for FA- and OPC-treated peat soil are 0.88 and 0.99, respectively.

$$UCS = 1.14 \times FA\ (\%) + 99.66 \quad (2)$$

$$UCS = 1.58 \times OPC\ (\%) + 219.13 \quad (3)$$

$$UCS = 1.98 \times FA\ (\%) + 123.67\ (20\%FA\ \text{and}\ 6\%QL) \quad (4)$$

3.4. Morphological characteristics

The SEM tests were conducted on peat, FA, and stabilized peat samples to investigate the microstructure. Aminur et al. [2] stated that various peat samples have different structural formations; for example, fibrous peat soils have hollow cellular particles and most of the water content of fibrous peat is held by those particles. Cheng et al. [40] also discussed the microstructure of the peat. Mesri and Ajlouni [1] also observed that peat particles can be bend, permeable and compressible and consist of fibers, fragments of long streams, and thin leaves.

Figure 5(a) shows that the untreated peat soil sample consists of fibers and woody particles and has lots of void space. **Figure 5(b)** shows the FA mainly consists of spherical particles with

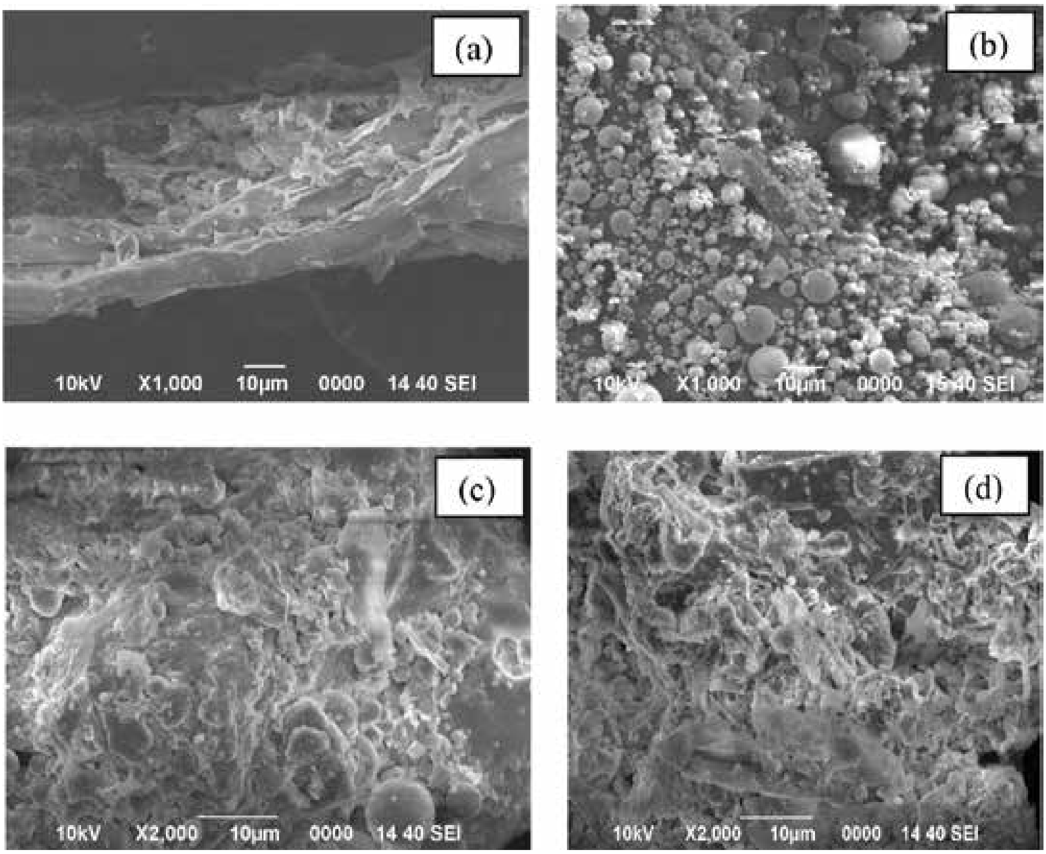

Figure 5. SEM images of (a) peat, (b) FA, (c) peat + FA, (d) peat + OPC.

some irregular shapes. **Figure 5(c)** and **(d)** shows that the internal formation of FA- and OPC-treated peat was changed significantly due to new mineralogical formation.

It is also observed that FA-treated peat soil particles are strongly bonded and have increased shear strength. It also observed from the UCS results that the shear strength increases with the addition of stabilizer and over the course of curing periods. Therefore, the internal mineralogical formation improved when compared with untreated samples. The results show that the mineralogical internal formations of FA-treated peat were also improved. The needle-like particles were formed and the particles are tightly packed and strongly bonded in OPC-treated peat sample. This may be due to the fact that the CSH formation with OPC had significantly improved. Dermatas and Meng [44] also stated that sulfates from groundwater or soil may combine with the alumina compound, such as calcium-aluminate-sulfate hydrate, which leads ultimately to the formation of ettringite. However, the contribution of ettringite and the other cementitious treatment products to the resulting strength increases. As a result, shear strength of the peat soil can be improved by using waste FA and OPC and also a combination of FA + QL stabilizer.

4. Conclusions

The present study investigates the effects of different types of stabilizers on tropical peat samples. Laboratory experimental results show that M_4 and M_5 samples are organic soils and the remaining samples are peat. According to the ASTM standard and based on the Von Post scale, it can be observed that the M_2 sample is sapric, the M_5 sample is fibric, and the remaining samples are hemic peat. The UCS values of treated peat increased with the increment of stabilizer and curing period. Comparing the performance of the stabilizers, OPC is the best stabilizer, although moderate shear strength is achieved from FA + QL stabilizer which is also cheaper than OPC stabilizer. Relationships between physical and geotechnical properties were established in this study to investigate fundamental behavior rather than field applications of peat. However, more data is required for establishing strong relationships between physical and engineering properties for real-field applications. The SEM results show that untreated peat samples contain with fibers and are more porous than treated peat samples. In the case of untreated FA samples, the FA particles are spherical, broken, and some are of irregular shapes. The needle-like particles were also observed in the OPC-treated peat samples and the particles are also tightly packed and strongly bonded compared to the FA-treated peat samples. The study shows that the geotechnical properties of peat can be improved by using QL, FA, and OPC. Therefore, geotechnical engineers can use waste FA and commercially available QL and OPC for peat stabilization purposes.

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Chapter 7

Mass Stabilization as a Ground Improvement Method for Soft Peaty

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Piispanen Pyry

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74144

Abstract

Construction of road embankments or other infrastructures on soft peat is a challenge. The main problems are high compressibility and rather low undrained shear strength of peat. Mass stabilization provides a solution to improve the properties of a peaty subgrade. Mass stabilization is a ground improvement method, where hardened soil mass is created by adding binder into soil and by controlled in situ mixing. Mass stabilization poses an alternative solution for conventional mass replacement or other techniques, which leave peat in place. The chapter deals with mass stabilization of soft peat soil. Specific attention is paid to design, research and construction considerations, and experience obtained during last three decades. Peat properties before and after stabilization, design methods including pre-testing, stabilization technique and machinery, quality control methods and practices, binder technology, long-term performance of mass stabilized peat, environmental effects, feasibility, applications, and limitations are all presented and discussed in this chapter. The long-term observations (during the last 25 years) have shown that the strength of stabilized peat has continued to increase in average 1.6 times from the strength of 30 days. Therefore, mass stabilization has proven to be a flexible ground improvement method for peat layers with maximum thickness of 8 m.

Keywords: peat, soil properties, mass stabilization, deep mixing, ground improvement, design, execution, long-term performance

1. Introduction

Design and construction of road embankments on soft, compressible, peaty and organic soils is a demanding task for the geotechnical engineer. The primary challenges include the high compressibility of the peat deposit together with very low undrained shear strength [1, 2]. Traditionally, there are three common solutions for foundation engineering in peat areas:

1. Total removal of peat and replacement with imported, inorganic aggregate fill.
2. Leaving peat in place and using soil improvement methods.
3. Transfer load through the peat layer via piles or columns to lower, load-bearing soil layers.

A visual concept of the various methods available is presented in **Table 1**. Improvement method (a), mass replacement of the peat units with inorganic, compacted fill material, is not treated in detail in this document. Methods that leave the peat in place, presented as method (b) in **Table 1**, can be generally divided into four groups of techniques in which the peat layer is used as a load-bearing layer. Those techniques are (1) pre-compression, (2) reinforcement, (3) load modification, and (4) deep stabilization (deep mixing). Piling, which is presented as method (c) in **Table 1**, is not considered a peat treatment methodology because the entire embankment load is transferred to underlying bearing units, and thus no load is applied to the untreated or treated peat.

(a) Mass replacement	Excavation and replacement
	Mass exchange by squeezing
	Deep compaction
(b) Pre-compression	Preloading
	Surcharging
	Staged construction
Reinforcement	Synthetic georeinforcements
	Geocell mattress
	Timber grillage
Load modification	Lightweight fill (LWA, EPS, …)
	Counter berm
	Profile lowering
Deep stabilization	For the whole peat layer (**Figure 1a**)
(deep mixing)	To a given depth (**Figure 1b**)
	Combination of mass and column stabilization (**Figure 1c**)
(c) Piles	Piles and concrete slab (concrete or steel piles)
	Pile caps and georeinforcement (concrete or steel piles)
	Wooden piles and georeinforcement
Columns	Stone columns

(a) Peat replacement techniques, (b) peat left in place techniques, and (c) embankment load on supporting piles or columns.

Table 1. Ground improvement technologies at peat areas.

Deep stabilization (deep mixing) methodologies encompass a number of methods applied to stabilize peat masses in situ. Of these, the mass stabilization method is one of the commonly applied methods. Mass stabilization is taken to mean a ground improvement method in which added binder is mechanically mixed into the soil mass to harden and improve its engineering characteristics. The mass stabilization method presented in this paper was invented in Finland in the early 1990s and subsequently has been utilized in more than 30 countries. Mass stabilization reduces settlement, improves bearing capacity and stability, and supports slopes and excavations in soft soils. To achieve all of these targets in diverse applications, a significant amount of academic and industrial research, knowledge, and experience concerning stabilization of peat has been analyzed and subsequent collected into manuals and various other publications. Most completed stabilization projects have been successful; however, some negative outcomes have also been observed. Case studies of failures have been highly instructive also and have demonstrated the limitations of the method and highlighted areas requiring additional development.

Mass stabilization may be applied to a broad range of geotechnical engineering projects, including roads (illustrated in **Figure 1**), streets, railroads, municipal engineering, harbors,

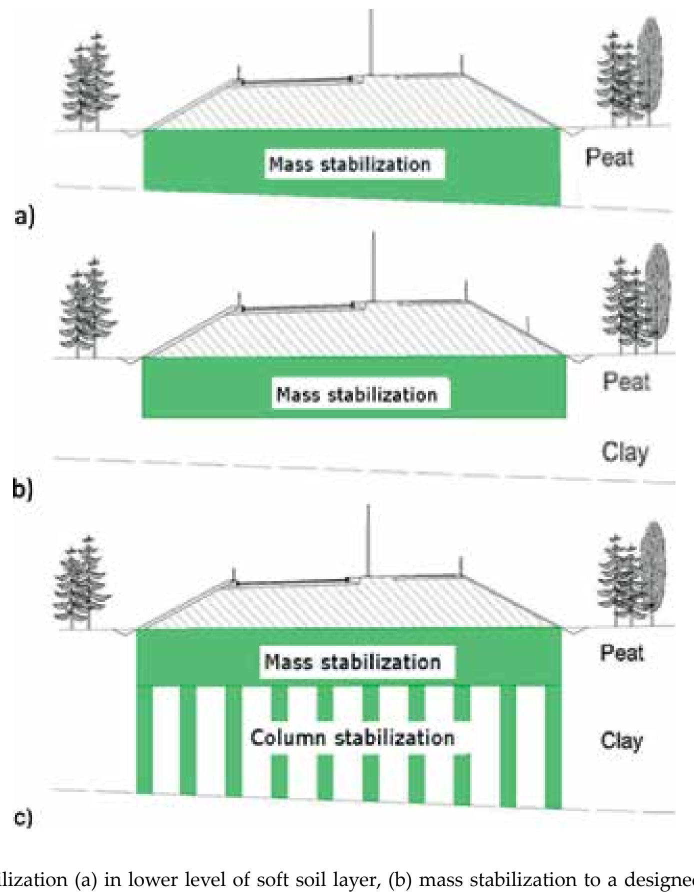

Figure 1. Mass stabilization (a) in lower level of soft soil layer, (b) mass stabilization to a designed target depth, and (c) combination of mass stabilization and column stabilization [3].

landscaping sites, flood protection, industrial sites, and commercial areas. Simple machinery (excavator with mixing tool, binder feeder, binder tank) and fast production rate allows for cost-effective application in comparison with traditional methodology. Additionally, environmental considerations favor the use of mass stabilization, because in situ techniques diminish the need to excavate and transport the peat, thus reducing carbon emissions from the peat deposit. The in situ technique binds the embedded carbon dioxide within the peat unit and reduces the production of methane and nitrous oxides. While the technique allows to keep drainage at high level (peat is not drying), the carbon dioxide equivalent release will stay low. The laboratory tests of Duggan et al. with stabilized peat indicate that stabilized peat not only holds its carbon but also the binder used seemed to uptake CO_2 both from the atmosphere and the peat [4]. These carbon emission reduction factors are expected to be significantly greater than the CO_2 emissions associated with the production of binder materials.

The intent of this chapter is to promote and encourage the use of mass stabilization techniques to improve peaty soils by highlighting project experiences and positive outcomes observed over several decades. These experiences have developed confidence in this cost-efficient and environmentally friendly method.

2. Engineering properties of peat

2.1. Classification of peats

Peat consists of organic material in various degrees of decomposition; it may contain residual vegetation or be wholly decomposed and amorphous. Peatlands occur throughout the world in environments in which vegetation does not fully decay, because the conditions are acidic or anaerobic. The partly decayed material accumulates and retains water, creating peatland areas [5]. Finland has the highest proportional area of peatlands (33.5%) in the world [6], which measured mean peat thickness of 1.4 m [7]. The deepest peatlands are situated in Southern Finland, where peatlands have typical depth of 4–6 m [8].

Von Post developed a classification system for peats in 1922, based on the degree of decomposition and including 10 separate categories [9]. In recent years, simpler classification systems, which refer on the structure of the peat, have been created by Radforth [10] and Landva [11]. These systems are generally considered to be more useful in geotechnical engineering, because they related mechanical properties to the structure. The recent European Standard SFS-EN ISO 14688-1 specifies that peat deposits can be classified based on the degree of decomposition. The classification test is comparatively crude, utilizing a visual-manual classification via a hand squeezing test. Peat is classified into three categories in SFS-EN ISO 14688-1 standard [12]: (1) fibrous, (2) pseudo-fibrous, and (3) amorphous.

Stratigraphically, peat layers are most often the uppermost soil layer [5]. Fibrous peat forms the uppermost layer, and the peat mass typically transitions toward the completely amorphous phase in the lowest part of deposit [2, 13]. The measured pH value for Finnish peats varies between 3.7 and 5.8, for example [13, 14].

2.2. Sampling and testing

Peat presents a challenge for testing because it is difficult to obtain representative, undisturbed samples for testing. Often larger samples are used and testing methods are adapted to accept the larger specimen size; examples of modified test protocols include the Rowe cell test [15] for oedometer (settlement) testing and large shear box test [13] for shear strength evaluation. Traditional difficulties in sampling and testing explain the comparatively limited engineering data available for peats. Additionally, peat units are heterogeneous due to their history and evolution and known variation in structure as noted above; as a result, peat layers typically exhibit clear and significant anisotropy. For example, Helenelund [16] reported that compression strength is approximately equal in the vertical and horizontal direction, but the tensile strength was clearly larger (nearly five times) for horizontal direction. Additionally, Ahonen [15] reported for fibrous Veittoistensuo intact peat samples that tested in horizontal friction angle was 17° and vertical 20° degree. The corresponding cohesion values were 7 and 0 kPa, respectively, for Veittostensuo fibrous peat. Fibrous peat also exhibits some degree of tensile strength.

2.3. Water content

Peat water content is typically high and varies considerably; common water content values of Finnish peat vary between 500 and 2000%. Typically, fibrous peats have higher water content than amorphous peats [1, 2]. In Finnish peats, the observed values for Leteensuo peat [13] varied between 300 and 1000% for pseudo-fibrous and 400–650% for amorphous peat. Ronkainen [17] reports that the mean water content for Finnish peats is 710% and median 673% (N = 172). Consistency limits (Atterberg limits) can be defined for amorphous peat, but not for fibrous [17].

2.4. Density

The in situ bulk density of natural peats varies depending on its water content. For amorphous peat, bulk density can be up to 1200 kg/m^3, while for an unsaturated fibrous peat including wood debris, density may be as low as 600 kg/m^3. The density is higher if inorganic minerals are present. The specific density is typically between 1.5 and 1.8 kN/m^3 [2]. According to Ronkainen [17], the unit weight of mean and median is 10.3 kN/m^3 (N = 159).

2.5. Permeability

The permeability of peat depends on its morphology and may vary significantly. The permeability of an unloaded peat lies typically between 10^{-4} and 10^{-7} m/s [17]. When peat is loaded and has compressed, its permeability decreases. Carlsten [18] reported values around 10^{-8} m/s for compression degree of 60%, and Munro [19] reported values as low as 10^{-11} m/s. Deformation properties of natural peat are a very important consideration because the primary consolidation of peat is significant and permeability changes rapidly with consolidation. The secondary compression of peats is essentially linear and progresses indefinitely, but in any case rate of compression decreases over time and will reach an end state at an indeterminate point after loading [20]. Jelisic [21] observed in laboratory conditions that approximately 90% of primary compression occurred during first 1–2 hours, with measured vertical compressive strain of approximately 60% under 80 kPa vertical load. Carlsten [5] observed a connection between water content, loading level, and deformation. Van den Haan and Kruse [22] cited the isotache model (originally developed by Leroueil et al. [23]) as a reliable method to evaluate settlements including both primary and secondary phases. The isotache model depends on the OCR and density of the peat.

2.6. Influence of mineral content

In addition to the influence of water content and degree of decomposition, measured strength parameters depend also on the mineral content of the peat. In general, increasing water content and degree of decomposition tend to reduce the strength characteristics of a peat, while increasing inorganic mineral content has the opposite effect and tends to lead toward increased strength [24].

2.7. Undrained shear strength

The undrained shear strength of normally consolidated fibrous peat may range between 6 and 7 kPa [19]. Forsman [25] reported that in Leteensuo-swamp the undrained shear strengths defined with vane test have varied between 5 and 30 kPa, with majority of results occurring between 10 and 15 kPa. In peat material, the strength is not usually increasing as a function of depth as is common for clays, because self-weight is so small. It is possible that the strength is actually decreasing in deeper layers, where the more amorphous peats are laying [19, 26].

3. The effect of mass stabilization on peat properties

The goal of the mass stabilization is to improve the geotechnical engineering performance of a soft subgrade (e.g. peat) by using an admixed binder agent. Mass stabilization significantly alters the geotechnical characteristics of soils and particularly peats. The target shear strength in mass stabilization generally varies between 40 and 70 kPa, being rarely more than 100 kPa. Many factors, such as peat properties, binder recipe (type and quantity), curing time, temperature, preloading level, and time, affect the result of the mass stabilization process and its rate of change. Mass stabilization changes the index properties of peat (i.e., water content, bulk density, pH, etc.), its strength and deformation properties, and water permeability [3]. **Figure 2** illustrates the effect of mass stabilization on the unconfined compressive strength and deformation.

Veittostensuo-swamp is located in South-Eastern Finland, and its characteristics are generally considered to be broadly reflective of typical Finnish peats. Veittostensuo was the first mass stabilized peat area, which was studied carefully, and therefore a significant body of research exists. These studies have informed the development of the mass stabilization process, binders, and quantities. The following paragraphs present selected results from the Veittostensuo peat stabilization studies.

The data obtained from Veittostensuo test studies include several laboratory test series, for example [15, 28], to develop binder material, addition rate, and results of field tests series, for example [24]. The strength in the field was defined using various sounding methods; more

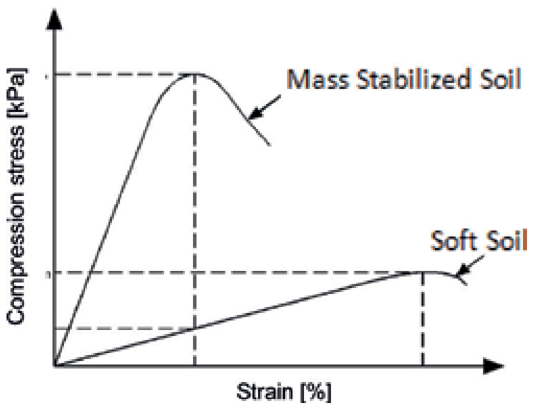

Figure 2. The impact of mass stabilization on strength and stiffness of soft soil [27].

details are presented in Section 8 and by Piispanen [24]. The thickness of peat varied between 2.2 and 3.5 m, with the fibrous upper part comprising the upper 1.2–2.4 m thick layer [28].

3.1. Initial neutralizing effects

Stabilization proceeds such that the binder agent first neutralizes the soil, and thereafter, additional binder introduced creates the desired stabilization effects. Janz and Johansson [29] and Babasaki et al. [30] have suggested that there is a minimum threshold value for binder agent, after which the strengthening reactions start. It is understood that initial addition of an alkaline binder first neutralizes the soil, and only after this buffering process can binding begin. In previous Veittostensuo case studies, the amount of binder utilized has clearly exceeded the minimum threshold value and the stabilization has succeeded.

3.2. Long-term pH trends

During stabilization of the soil units, the pH value of stabilized peat increased from the mean initial value of 4.6–12.5 during the first year. The long-term pH values have decreased to an average pH of 11.5 [24]. The value after the first year is still clearly high enough to demonstrate that the hardening is permanent. The reason for decrease in pH is thought to be the result of inflowing water from the non-stabilized part of the swamp and corresponding increase of water content. This conclusion is supported by observed decrease in water content during the stabilization process and subsequent increase in time elapsed after stabilization. In this case, the measured water content of peat decreased from original values of 1170–1670% (note that the amorphous peat had higher values) to approximately 170% after 1 year and subsequently increasing to average value 270% after a period of 23 years [24]. While the peat is assumed to be fully saturated, the increase was thought to mean that the peat is swelling and taking in additional water. Settlement monitoring has revealed, however, that settlement continued from first year to 23 years, and measured strength has increased, thus implying that no swelling has occurred. Therefore, it is considered more likely that during the stabilization process the water content has decreased sufficiently that the soil is only partly saturated because at least some of the pore water has been bound to the dry solid binder during the stabilization chemical

Property	(a) Intact peat	(b) Age 1 day to 1 year	(c) Age 1–23 years
pH	4.5–4.7 [33]	(1) 12.5–12.8(2) 12.2–13.2 [24]	(1) 11.3–12.2(2) 11.7–12.3 [24]
W (w-%)	1170–1470 [15]	(1) 160–210(2) 110–190 [24](1) 170–200(2) 100–190 [34]	(1) 230–370(2) 200–260 [24]
Unit weight (kN/m^3)	7.9–16.3 [33]	10.4–15 [31](1) 11.3–12.3(2) 10.9–2.7 [34]	–
Specific weight (t/m^3) [33]	1.66–1.69	–	–
Void ratio, e (−) [15]	18.3–22.2	–	–
Permeability, k (m/s) [24]	10^{-5}	10^{-6}–10^{-8}	–
Compression index C_c (−) stress level 40–80 kPa [15]	7.5–9.3	0.11–0.13*	–
Efficient cohesion c′ (CIDC, kPa, strain 15%)	1–6 [15]	(1) 30–512(2) 54–100 [15](1) 46–84(2) 37–49 [34]	–
Effective friction angle φ′ (CIDC, °, strain 15%)	19–20 [15]	(1) 21–22(2) 22–35 [15](1) 29–30(2) 37–41 [34]	–
Undrained shear strength (kPa)	7–20(vane test) [28]	(1) 50–100(2) 70–150 (vane test) [31]	(1) 70–100(2) 50–150 (vane test) [33]
Elastic modulus E_d (CIDC, kPa), strain 1.5%	1000–1900 [15]*	(1) 5100–8000(2) 7200–12,200 [15](1) 1700–7900 [34]	–
Bulk modulus K_d (CIDC, kPa) [15]	–	(1) 8000–11,500(2) 9500–17,800	–
Poisson's ratio ν′	0.36–0.4 [33]	(1) 0.1–0.21(2) 0.1–0.20 [15]	–
Compression modulus, M [15] stress level 40–80 kPa (kPa)	100*	(1) 4300(2) 4000	–
Coefficient of consolidation, c_v stress level 10–80 kPa (m^2/a)	0.9–19.3 [15]	(1) 640–3300 (Taylor) [15]	–
Coefficient of creep, C_α stress level 40–80 kPa	0.44–0.55 [15] oedometer	0.013field [24]	0.037field [24]
Thermal conductivity (W/mK)	0.39 [32]	0.20–0.57 [32]	–

*The presented values are the minimum and maximum values of laboratory tests for fibrous, amorphous intact peat and stabilized peat.

(1) Binder mixture of Finnstabi (including gypsum) and rapid cement 50% + 50%, 250 kg/m^3.

(2) Binder mixture of rapid cement and blast furnace slag 50% + 50%, 300 kg/m^3.

Table 2. The literature values of properties of non-stabilized (a) and stabilized (b, c) peat including references (Veittostensuo, Finland).

reaction. The dry mixing process also adds some air to the soil via the use of compressed air injected in to the mass [31]. In any event, observations of the peat units over the long term indicate that the saturation degree of the stabilized peat increases slowly over the long term.

3.3. Binders

Ahonen [15] used two different binders in his preliminary laboratory tests: (1) a mixture of Finnstabi® (including gypsum) and rapid cement mixed in the ratio of 50%/50%, addition rate of 250 kg/m^3 and (2) mixture of rapid cement and blast furnace slag mixed in the ratio of 50%/50%, addition rate of 300 kg/m^3. These same binders and amounts were chosen for the execution. The target shear strength for the peat was 50 kPa [28].

3.4. Deformation and strength properties

Ahonen [15] performed the oedometer test with Rowe cell (ϕ = 254 mm). The tests were started right after stabilization, and it was observed that in the beginning peat compressed 12–17% with the first loading step of 5 kPa. When the binding process started, the settlements practically ended, starting only after the loading exceeded 80–160 kPa, resembling the behavior of clays with pre-consolidation pressure. For intact peat, it is impossible and useless to define pre-consolidation pressure, because primary consolidation starts immediately after application of load. The deformation parameters decreased such that, for example, the compression index for stabilized peat was less than 10 times smaller than that of intact peat. The consolidation rate (coefficient of consolidation) on the other hand increased significantly [15]. Additionally, it is important to observe that post-stabilization creep rate was effectively zero.

Mass stabilization brought remarkable increase in both effective and undrained strength values [24, 31] although not as significant as were the increase in deformation properties [31]..

The field studies of Huttunen et al. [32] utilizing a thermal needle probe showed that thermal conductivity of the stabilized peat after 1 year varied between 0.20 and 0.57 W/mK, and the average was nearly the same as for intact peat 0.39 W/mK. This result means that stabilized peat, like intact peat, forms a thermal insulation.

In situ saturation degree of stabilized soil varies over long period, depending on the water absorption capacity and the permeability of the stabilized soil [31]. Incomplete saturation produces matrix suction, which leads to an increase in the undrained strength.

Table 2 presents observed geotechnical properties of peat in Veittostensuo case also as a function of time. The presented values are the minimum and maximum values of laboratory tests for fibrous, amorphous intact peat and stabilized peat. Estimated values have been defined from the test result diagrams; therefore, they are not exact values, rather giving a magnitude of the property. The mass stabilization mixed the peat layers therefore the values of fibrous or amorphous peat has not been specified in **Table 2**.

4. Mass stabilization applications and technique

4.1. Applications

Mass stabilization can be used in versatile applications as a ground improvement method and as a processing method for low-quality soils. Applications include [3]:

- roads, streets, and railways;
- municipal engineering;
- harbors and sea routes (fairways);
- landscaping sites (e.g. parks);
- environmental protection structures;
- industrial and commercial areas;
- housing construction areas; and
- flood protection.

Mass stabilization can be executed in the following ways [3]:

- Full penetration depth through the whole thickness of soft soil layers (**Figure 1a**).
- Partial penetration to a given depth (i.e. a "floating" structure, **Figure 1b**).
- Optimized as a combination structure—mass stabilization on top of column stabilization (**Figure 1c**)

In full depth mass stabilization, an almost non-settling ground improvement result can be achieved. In the case of partial mass stabilization to a given design depth, compressible soil layers are left under the stabilized zone. In this case, settlements will occur, yet the load induced by the embankment is distributed via mass stabilized layer to the lower layers, thus evening out the settlements and reducing differential settlements. The stress caused by the new structures affects the magnitude of these settlements. Settlements may be significant, if the applied stresses exceed the pre-consolidation stress of the lower soil layers.

Column stabilization carried out under mass stabilization reduces the settlements of the soft soil layers underneath mass stabilization. Additionally, this method improves the stability of the embankment by impeding the formation of a slip surface. Most commonly, the combination of mass and column stabilization is used in cases when peat or mud constitutes the uppermost soil layer, because the column stabilization method alone would not provide sufficiently strong columns for the upper part. Mass stabilization can also be used as a working platform for stabilization machinery in the areas with particularly weak subgrade conditions.

4.2. Technique

The principle of the mass stabilization method is presented in **Figure 3** and field photographs of mass stabilization implementation in **Figure 4b**. With the current equipment, the mixing tool attached to an excavator allows the execution of stabilization to depth of 7–8 m under favorable conditions. The optimal stabilization depth is typically in the range of approximately 3–5 m. However, thinner layers can also be mass stabilized. Commonly used mixing tools are presented in **Figure 4a**.

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In the "Nordic stabilization method," mass stabilization is carried out by using the dry technique, i.e. addition of dry binder or binder mixture. Wet mixing technique (alt. "slurry"), in which the binder is premixed with water before pumping and mixing to soil layer, can be used as well. It is noted in any case that the "wet method" requires an alternative type and design of feeder than the "dry method" and additionally demands significantly higher binder addition rate. This article deals only with mass stabilization with dry method.

The soft soil layer is commonly mixed to "pre-homogenize" the unit prior to injection of the binder. This process is intended to create a uniform pre-stabilization soil mass and thus a predictable and consistent result. A pressure feeder injects the binding agent (one or two binders, or a binder mixture) through the hose of the mixing tool. The rotating drums mix the binding agent into the ground and homogenize simultaneously the mixed mass. Mixing is executed by moving the mixer unit vertically and laterally from the surface to the desired depth. The reach of an excavator determines the progress of stabilization work. The work area is commonly divided into blocks, or areas, of equal size depending on the site geometry. Typically, the size of a block is between 3 and 5 m^2 and the work proceeds from block to block. The working capacity of a mass stabilization system depends on the soil material, but in general it varies between 50 and 200 m^3 of stabilized soil per hour and per mass stabilization unit [3].

To account for and counteract the natural loosening of the soil mass produced by mixing and air injection, a preloading embankment of 0.5–1 m height is constructed above the stabilized soil to promote hardening of the mass stabilized soil beneath the ground surface. The preloading embankment can be raised in stages after some hardening has happened to achieve a target final design level. However, regardless of site leveling objectives, experience indicates that the preloading embankment is indispensable to ensure the consolidation of the stabilized material during the hardening process (cf. curing of cement). The target strength of the mass stabilization is typically achieved in a period of 1–3 months [3].

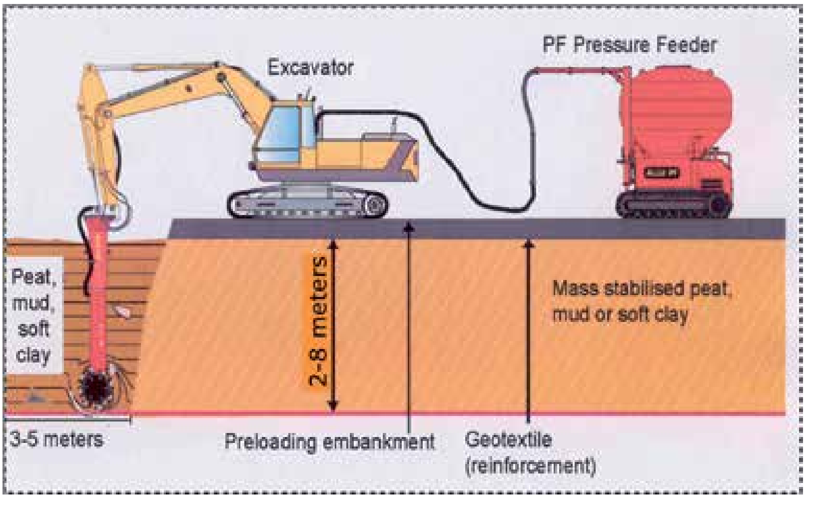

Figure 3. Mass stabilization equipment. Elements, such as a mixing unit, pressure feeder, and the control and data collecting unit, are attached to the excavator ([35], modified).

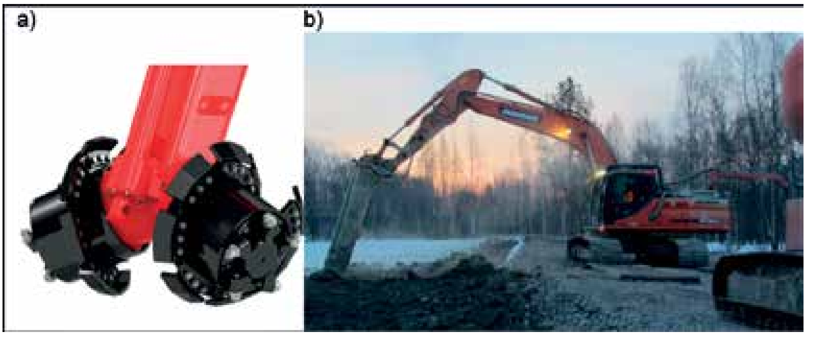

Figure 4. Mass stabilization mixing tool (a) [36]. Mass stabilization work ongoing at temperature −12°C (b) [photo Heikki Hämäläinen].

5. Mass stabilization binders

5.1. Binders

All mass stabilization projects utilize a binder, or chemical stabilizing agent, that reacts with the peat mass to change its strength and deformation properties. During the mixing and curing process, other soil properties, such as water content, degree of saturation, and permeability, are also altered [33]. As a result of the ground investigation and laboratory testing programmes, the quantity and quality of the binder are optimized to achieve target properties with minimal investment.

The chemical reactions involved in the hydration of different types of cement or lime and processes involved in soil stabilization using a variety of binders have been described and discussed thoroughly, for example in the thesis of Åhnberg [31]. The reactions generated when mixing various binders with soil vary by process, intensity, and duration, but in general, exhibit many similar characteristics. Hydration process will start after the binder is mixed in to the soil. Fly ash and slag can need a binder activator. Åhnberg indicates that some reactions may involve directly starting cementation. Some other may lead to further reactions with the soil and its minerals [31].

Up to approximately 70% of the unit price of mass stabilization can be dependent on the price of binder. Cement is the most commonly used binder in mass stabilization. Alternative solutions like industrial by-products are favored since cement is relatively expensive and it has considerably high carbon footprint [27]. The replacement of cement with binders based on industrial by-products (e.g. fly ash, oil shale ash, furnace slag powder, and gypsum) in the stabilization of peat has been studied widely both in the laboratory and in the field. The aim of using industrial by-products is to produce a positive impact on the technical and environmental quality of the stabilized masses, as well as to diminish the cost of the binder mixture. The environmental acceptability is evaluated by testing leaching of contaminants from the stabilized material in the laboratory. The results of the tests provide good reasons for the use of fly ash-based binders in the mass stabilization of peat [3, 37].

There are some general guidelines for the correct binder solution to a given peat stabilization project, based on laboratory tests and field stabilization. In the guidebook EuroSoilStab

[38] cement, cement+gypsum or cement + furnace slag are presented as generally suitable for stabilization of Nordic peat units. Additionally, cement + oil shale ash has proven to be a very effective binder mixture for Baltic peat [24]. Huttunen and Kujala observed in their feasibility study that fibrous peat is easier to stabilize than amorphous and that the parent plant type significantly influences the stabilization process [34]. Later, more comprehensive research has indicated that peat is a complex material and these arguments may be oversimplified.

In general, it is possible to mix the treated peat layer with various subcomponents such as additional aggregate materials, for example, sand or clay, in addition to the binder materials. Prior to the actual stabilization, these components are spread on the harrowed peat surface to be premixed with excavator to peat layer and mass stabilized. These components are then admixed into the soil either during pre-homogenization or mixing. That procedure improves the final result of mass stabilization [3].

In Finland, an environmental permit is needed for the use of by-product or waste material-based binders such as fly ash in mass stabilization, in the event that the product is not commonly utilized as a binder product and CE-marked or otherwise authorized for this use by a regulatory authority. Waste materials carry a high disposal tax (70 €/t as of 1.1.2016 in Finland) in the event that they are not utilized; as such, the producers of these types of waste materials are motivated to offer their material as stabilization binder [27].

In response to industry demand, in 2006, the Finnish Ministry of the Environment has prepared the "Government Decree on the recovery of certain waste in earth construction." The objective of this decree is to promote the recovery of waste by specifying conditions, which, if complied with, mean that the use of waste referred to in this decree in earth construction will not require an environmental permit in accordance with the Environmental Protection Act (527/2014). A new version of this decree is expected to become valid 2018, and more materials and applications (like use as a stabilization binder) are included in the new version [39].

5.2. Stabilization tests

Stabilization laboratory tests are used to define the technically and financially most competitive options, of which is then chosen the most suitable solution for the site in question [38, 40]. Sometimes, for example with contaminated soils, environmental qualification properties also affect the choice. The objective of the research is to ascertain the quality properties of the final product and to select the most applicable binder and the optimal binder amount.

The determination of the material properties to be achieved through stabilization process is carried out with sufficient accuracy to allow development of reliable geotechnical dimensioning (stability and settlement) and plans. For the needs of the design, it is important to know material variations in the area of concern and their impact on the results of stabilization and the speed of strength development [3].

After mixing binder into the peat in the laboratory, the stabilized mass in the cylinders is preloaded with a vertical load (usually 18 kPa). Under the loading, the stabilized peat compresses substantially over the curing period, particularly during the early stages of curing. The mass compacts and water exits from it due to the compression. The effect of preloading on the achieved strength is significant. Based on previous experiences, the achieved strength of preloaded specimens has a much better equivalence to the stabilization strengths measured in actual site conditions, as opposed to the strength of specimens when preloading has not been applied [3]. The tests also give approximate knowledge concerning the anticipated magnitude of compression of the stabilized peat layer. By varying the magnitude of the preload used in the laboratory tests, it is also possible to estimate the effect that a possible preloading embankment could have on the strength development or settlement behavior of the stabilized peat. The properties to be defined from the laboratory-made hardened specimens shall at the very least include the compressive strength and Young's modulus E (E_{50}) from unconfined compression tests [3, 40].

In demanding sites, it is recommended that the strength parameters and deformation properties of the stabilized soil should be determined using triaxial shear tests. The triaxial test enables better imitation of the prevailing load conditions and deformations taking place in the ground than the unconfined compression test [3, 40].

The strength of a laboratory-made stabilized test sample is usually higher than the strength of a corresponding material from the field, and thus a correction factor may be applied. This factor $\tau_{field}/\tau_{laboratory}$ is based on experience, and if there is no earlier experience, it can be necessary to perform test stabilization.

At present, there are no EN standards for the stabilization tests, but some national guidelines exist (e.g. in Finland [40] and in Sweden [41]), and in addition, an unofficial European guideline for stabilization in EuroSoilStab guidebook has been published [38].

6. Stages of project and execution

6.1. Project

The main stages of a mass stabilization project are as follows [3, 38, 42]:

- collecting initial information and data;
- feasibility study;
- initial site investigations and design including initial stabilization tests in laboratory;
- dimensioning and actual stabilization tests in laboratory;
- design, technical drawings, work specifications, quality assurance plan;
- competitive bidding;
- stabilization works and quality control; and
- follow-up quality control and reporting

The first, preliminary evaluation of the applicability of mass stabilization as a soil improvement solution at a given site can normally be done with comparatively incomplete initial data, assuming there exist previous experiences of deep stabilization from the area in question [3, 40].

The more unfamiliar the ground conditions are, the more initial data are needed for even the preliminary technical and economical evaluation. The important part of the "feasibility study" is to find out whether the site is suitable for mass stabilization work. In this phase, the following issues need to be investigated [3]:

- rocky fill layers, previous failures, etc.
- hard soil layers in the zone to be stabilized,
- pipelines, underground cables, etc.,
- existing structures (e.g. piles, timber grillage, etc.),
- climate condition (flood, drought, frost, etc.),
- accessibility of the site (roads for transportation of machinery and binders), and
- geographical location (distances, interest of contractors).

Geotechnical design and analysis sets the target strength for the mass stabilized layer, and the binder recipe is developed in order to comply with the strength requirements. In the case of "demanding" soils, where it is challenging to achieve satisfactory hardening of the stabilized layer, the target strength is established on the level which can be obtained with the use of a reasonable binder amount (e.g. the target that may be achieved with a reasonable price per cubic meter of mass stabilized soil). The design calculations commonly carried out in the process of designing a mass stabilized structure include stability and settlement calculations. In stability calculations, the mass stabilized layer is assumed to be an elastoplastic soil layer and the uncertainties of the results of the homogenization must be taken into consideration. The settlement of a mass stabilized layer has to be calculated at least in two phases—during hardening under the compaction embankment and after hardening under the final embankment [3].

6.2. Execution

Mass stabilization is executed according to plans, which might be updated and/or complemented during the progress of work. Mass stabilization projects require creation of a target-specific work organization plan, which describes how the work should be carried out in practice and how the contractor should demonstrate the obligatory quality assurance and quality control tasks. Stabilization work can be roughly divided into the following stages in the procedure where the mass stabilization equipment is working on the compaction embankment [3]:

1. Topsoil removal.
2. Removal of objects that disturb stabilization works and leveling of the area.
3. Marking of stabilization areas and blocks.
4. Ground level measurements.
5. Stabilization work (=mixing binders with sub soil).
6. Construction of compaction embankment.

7. Quality control of the stabilized layer.
8. Quality control and follow-up of the stabilized area.

In some cases, the procedure is altered, and the working platform is constructed straight against cleared subsoil and the stabilization machine is working over platform mixing the platform material to the subsoil before adding and mixing of the binder agent.

The following preliminary works are required to be done at the area to be stabilized: harrowing and clearing of trees, bushes, stubs, and roots and removal of fills, structures, or materials that would make the stabilization works either difficult or impossible to execute. The drainage of the area has also to be arranged in the cases where there is open water over subsoil [3].

The location of the stabilization grid is set out before the launch of stabilization. Before the production of the actual stabilization takes place, it is possible to execute a trial area. Trial stabilization makes it possible to check the designed binder and binder amount so that the required design strength can be reached. Usually, the actual production stabilization is started directly after the trial phase is done. Since every stabilization project is unique, stabilization work always needs to be designed on a case-by-case basis [3, 40].

During the binder feeding and mixing, the stabilized soil layer becomes loosened. The compacting embankment is normally constructed over blocks after binder injection and mixing to ensure compaction and consolidation of the stabilized layer and to enable the excavator to move on into the site (**Figures 3** and **4b**). This also allows for a faster start of reactions in binder and the removal of surplus air and water from the mass stabilized structure. In cases, when column stabilization is made under peat layer before mass stabilization of the peat layer (**Figure 1c**), the working platform is constructed straight against harrowed subsoil surface before column and mass stabilization. After column stabilization, the platform material is mixed to subsoil during or before binder injection and mixing and, after mixing, a primary compaction embankment has been constructed over blocks. The thickness of the primary compaction embankment is normally 0.5–1 m [3].

The following standpoints relating to the equipment and the construction site should be considered while the stabilization work is underway [3, 40]:

- weather conditions/temperature;
- the room reserved for the equipment at the site;
- changes in the ground conditions;
- how the binder(s) will be delivered and stored at the site; and
- preliminary curing of the layer to be stabilized how it affects the progression of the work.

Executing the stabilization in winter conditions is possible, but very harsh cold delays the curing process. In Finland, mass stabilization has been carried out even in the really low temperatures of −20 to −30 °C, but this is generally not recommended. If the ground is frozen, it might be necessary to use a drop hammer to enable excavation works. This will reduce work efficiency and make the hardening time longer.

6.3. Quality control QC/QA

Mass stabilization design documentation sets objectives and requirements for binder, stabilization work, and the final structure. The contractor keeps a record of fulfilling the objectives and requirements concerning stabilization work. The quality of stabilized layer is compared to the requirements set by the design [3, 35, 39]. The extent and methods of performance testing of QC/QA shall be defined in the plans and specifications for each individual case. Each mass stabilization project requires a target-specific site organization plan, which describes how the contractor should implement stabilization works and perform QC/QA to ensure adherence to design standards. The setup plan of the site is founded on work specifications that can be complemented by the contractor concerning, for example their own QC actions [3, 42–44].

Quality control done by the contractor happens alongside the mass stabilization work. Usually, this includes monitoring the quality of the soil that is being stabilized, for example the water content, observation of the site conditions compared to those described in the plans, monitoring the quality and the quality fluctuations of the stabilized masses, measuring the amount of binder addition, following the progress of hardening process, and ensuring the homogeneity and compression strength of the final product. Early results of QC allow the remaining stabilization works to be adjusted to fulfill the design objectives. The QA program concentrates on the strength properties and homogeneity of the stabilized soil. Normally, an external quality assurance inspector is employed for the duration of the implementation works of QA to ensure independent results [3, 43, 44].

Various QA methods have been experimented since the first applications of mass stabilization. Many of the methods established in use have been designed fundamentally for the Nordic column stabilization method but have proven to be appropriate for the mass stabilization also. Most of them are presented in **Table 3**. Heterogeneity is common and typical for mass stabilized soil due to variability in the mixing process and in the soil. Therefore, it is necessary to carry out a sufficient number of QA tests. In order to determine shear strength, a minimum of approximately 10 representative soundings (e.g. column penetrometer) should be performed and at least three vane shear tests should be carried out from a given subarea (**Figure 5**). At a given subarea, the binder recipe is held constant and the size of the area is limited (control includes geology, soil properties, dimensions of stabilized area, etc.), and in a larger project, there can be dozens of subareas. Statistical methods should be implemented for evaluation of soil parameters from individual tests (**Figure 6**) [43].

7. Settlements

Settlements within the mass stabilized layer occur in four stages [3, 40, 45] (the phases of mass stabilization settlement are presented in **Figure 7** and an example settlement of Case Veittostensuo in **Figure 8**):

QA methods	Method description	Area and type of the tip
Column penetrometer	Static/dynamic penetration	A = 100 cm^2, ϕ = 375 mm (wings)
Vane penetrometer	Vane rotation	ϕ = 130 or 160 mm, H = 0.5 × ϕ
Combined static-dynamic penetration test	Static/dynamic penetration with rotation	A = 50 cm^2 for stab. soil
CPT sounding	Static penetration	ϕ ≈ 36 mm, A = 10 cm^2

Table 3. Verification techniques for determination the quality of mass stabilized soil (modified based on [43]).

Figure 5. Column (A) and vane penetrometer (B) for columns [40]. The dimensions of the tip A are presented in the standard EN14679 [42] and in mass stabilization handbook [3] and of tip B in handbook.

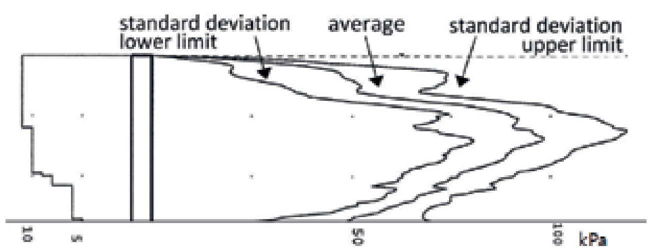

Figure 6. Principle of column penetrometer results from mass stabilized soil layer (z ≈ 2.5 m). On the left is the quantity of the soundings and on the right is presented average shear strength and standard deviation [43].

1. During stabilization work: Dry binder is supplied into the ground with the help of compressed air. It is mixed with the soil using a rotating mixing tool. This often causes some "loosening" of the stabilized soil and causes some raising of the stabilized layer surface.

2. Under the compaction embankment: The largest settlement in a mass stabilized layer happens during the initial compaction of the compaction embankment. A typical compaction embankment height is from 0.5 to 1 m. The embankment is left on place during the curing time to act as a load to the structure.

3. Under the final embankment: The actual embankment is constructed over the compaction embankment. The compaction embankment material can be replaced if considered necessary. Settlement plates are suggested to be used to check the progress of the compaction of the mass stabilized layer before the final embankment is put in place.

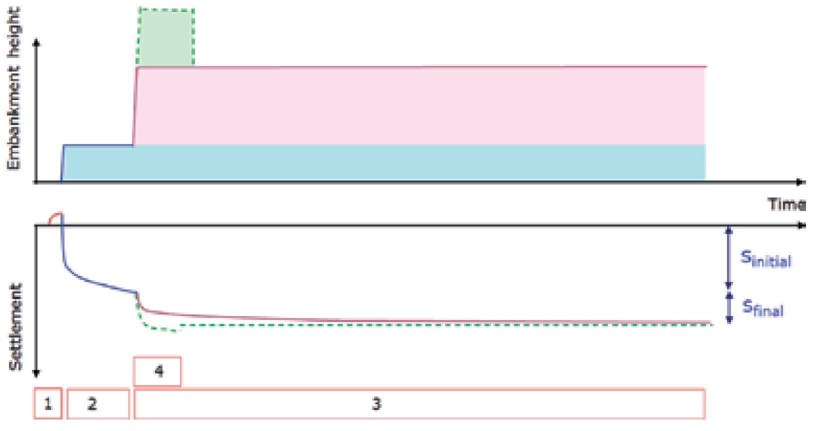

Figure 7. Phases of settlement in mass stabilized layer and settlement time diagram [45].

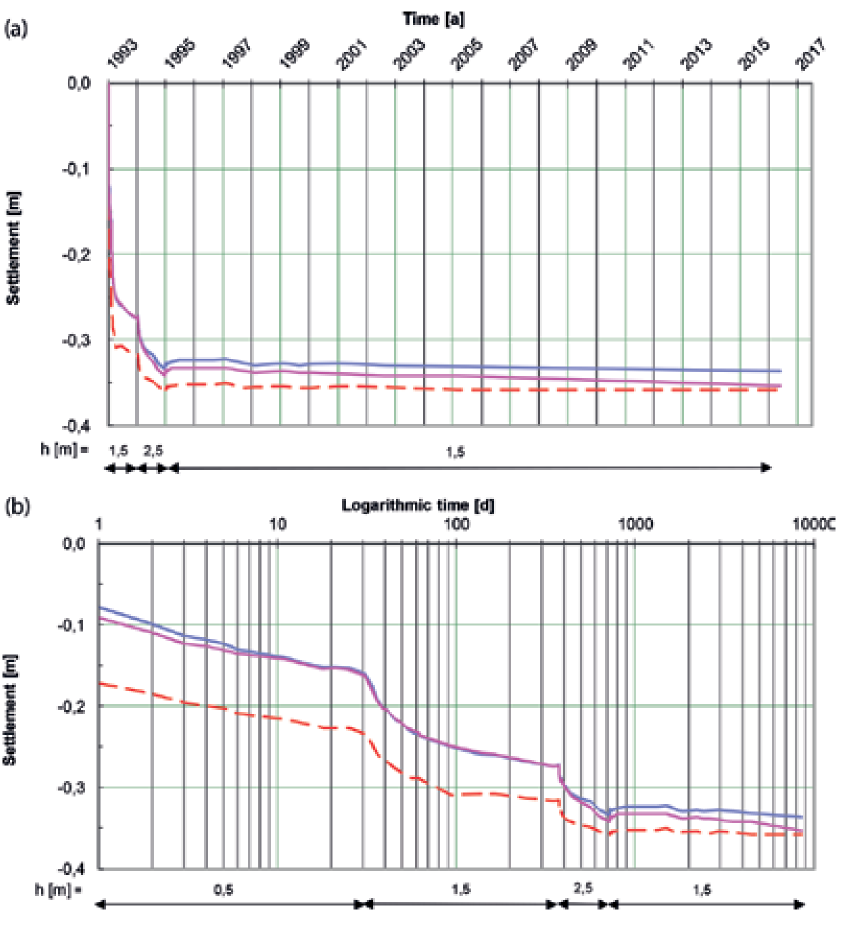

Figure 8. Case Veittostensuo, Finland. Measured settlement of embankment over mass and column stabilized soil (mass stabilized peat and column stabilized clay layer). The thickness of the embankment "h" is presented under the figure. At the horizontal axis, the time in linear (a) and logarithmic (b) scale [24] is presented.

4. Under the preloading embankment: Preloading embankment can be used to create a load equal to the final embankment load or an additional load (surcharge, overloading) on top of the stabilized soil. This is usually the case when settlements happening during the operating life of the structure should be as small as possible. If there are non-stabilized settling layers left under the mass stabilized layer, their settlement must be minimized with preloading or the long-term settlements will continue. When peat is the soil being stabilized, it is usually necessary to use a preloading embankment.

8. Long-term behavior of mass stabilized peat

Behavior of mass stabilized peat in the long term is a point of great importance. From the engineering perspective, long-term behavior consists of settlements, stability, and bearing capacity of the mass stabilized peat layer. The main property affecting these properties is the long-term development of the strength of the layer. No negative behavior should be observed if the design strength is exceeded during the whole lifespan of the mass stabilized peat layer [24].

The strengthening of the mass stabilized soil is mainly based on reaction product bonds between soil particles. Strength commonly increases in time as long as there are reactions taking place in the mass stabilized layer. The rate of the reactions and their associated strength increase are dependent on the binder and treated subgrade type. Åhnberg [31] proposed that hydraulic binders (e.g. cement) tend to have faster strength increase in the short term than pozzolanic binders (e.g. lime). It was also found that pozzolanic binders have better long-term strength increase, which lead to approximately same strength increase between hydraulic and pozzolanic binders within 1 year from the mass stabilization.

Janz and Johansson [29] proposed that the reaction products can break down rather quickly in certain environments. Peat mass stabilization is often exposed to chemical and physical attacks, such as frost damage, lime leaching, and sulfate attack (delayed ettringite formation). Especially when the "Nordic stabilization method" technique is used, the binder amount and achieved strength are relatively low compared to, for example column stabilization. This theoretically exposes mass stabilized peat layer to a greater risk of strength reduction in the long term.

Piispanen [24] has studied the long-term behavior of 6.5–23 years old Finnish and Estonian mass stabilized peat layers using in situ testing. The study focused on defining the development of strength, index properties (e.g. water content, pH), and settlements from the moment of stabilization to the present time.

Piispanen's study [24] considered that a total of 18 stabilized sections were studied, each differing according to binder or subgrade type and properties. Investigations were completed primarily performing in situ soundings and sampling. New soundings were compared to the previous quality control soundings, which had commonly been performed 30 days from the mass stabilization (measured strength/30-day strength ratio). Mass stabilization depths were divided into 0.5 m depth ranges for assessment. Mean and dispersion values were calculated at every depth interval and the values of similar depth intervals were compared at different times to evaluate the long-term strength increase. The results of the study are presented in **Figure 9** and **Table 4**.

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There are settlement measuring results from mass stabilization cases, but the long period settlement measuring data is not as extensive. In the case of Veittostensuo, there are settlement observations from a period of 23 years. These measured results are presented in **Figure 8**. Settlement parameters are determined on the basis of the results presented in **Table 2**. The majority of the settlement has taken place during 2–3 months under the compaction embankment and final embankment. After the surcharge with preloading embankment, the settlement has been minor [24].

In the case of Veittostensuo, water content and pH of the mass stabilized layer were analyzed from the samples taken and compared to the previous results, if possible (**Table 2**). It was noticed that the water content had almost doubled from the samples taken after 1 year from the mass stabilization compared to the samples taken after 23 years. Additionally, the pH value had decreased approximately one unit on a same time range, but remained high (>11). Regardless of these results, the strength of the mass stabilized material had increased throughout the mass stabilized peat [24].

The study [24] concluded that the long-term behavior of peat mass stabilization is from an engineering perspective positive and controlled as the strength of the mass stabilized peat commonly increases in time, and the material tends to be robust for changes of the index properties.

9. Cases

During the past decades, mass stabilization method has become popular as a ground improvement method and as a way of handling soft excavated or dredged soils in Nordic countries, in European countries, in the Far East, Australia, as well as in North and South America. Mass stabilization has been used as an in situ ground improvement method in versatile applica-

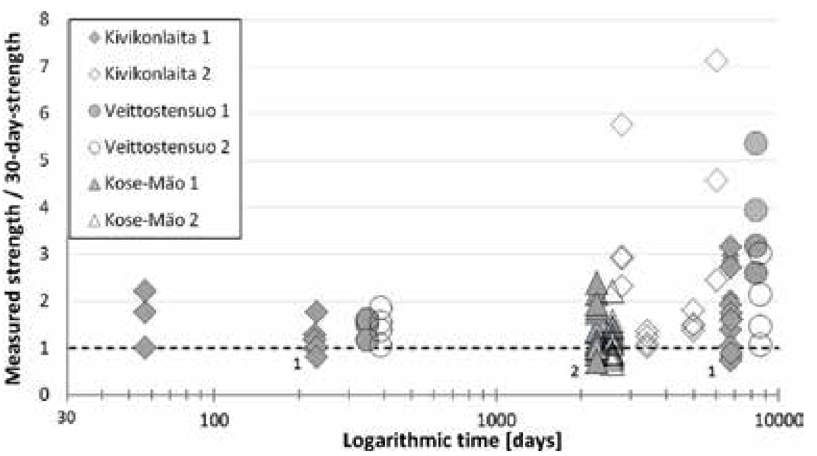

Figure 9. In situ strength development results of mass stabilized peat. Measured strength/30-day strength ratio is presented on vertical axis and time on horizontal axis. Every marker represents that ratio of the same 0.5 m depth range of the mass stabilization at different sounding times. Number A after the site name represents pozzolanic or gypsum (filled marker) and B hydraulic-based binders (empty marker) [24]. (A) Some of the 30 day abnormally high results indicated to an error in measurement and (B) the actual comparison value was 2 months after the mass stabilization and before that the strength increase had been exceptionally strong which indicated that most of the reaction products had already formed.

Site and number of areas	Binder type and amount [kg/m³]	Age [year]	Sounding type and number	Sample size N*	Strength increase ratio [–]**	COV***
Kivikonlaita 1,Finland (3)	Ce + F[70–113 + 70–113]	18.5	CPT 60VP 9	101127	1.71.7	0.60–1.170.14–0.30
Kivikonlaita 2,Finland (3)	Ce + sand[100 + 150]	9.5–16.5	CP 10CPT 12SDPT 20	401729762	1.23.41.5	0.24–0.300.79–1.070.43–0.79
Veittostensuo 1,Finland (1)	RCe + F[125 + 125]	23	CP 6VP 6	10924	3.82.6	0.17–0.230.44–0.84
Veittostensuo 2,Finland (1)	RCe + BFS[150 + 150]	23	CP 6VP 6	28824	1.92.3	0.39–0.620.40–0.62
Kose-Mäo 1,Estonia (4)	Ce + OSA[70–100 + 100–200]	6.5	CP 24	418	1.4	0.19–0.52
Kose-Mäo 2,Estonia (4)	Ce[150–250]	6.5	CP 24VP 3	58111	1.11.7	0.02–0.450.18–0.55

*Number of collected readings of soundings.

**Strength increase compared to 30-day strength.

***Variation of COV values calculated to 0.5 m depth ranges of mass stabilized layer.

Ce = cement (Portland); F = Finnstabi (lime, gypsum); RCe = rapid cement (Portland); BFS = blast furnace slag; OSA = oil shale ash; sand = extra aggregate; CPT = cone penetration test, tip 10 cm^2; PK = column penetrometer, tip 100 cm^2; SDPT = static-dynamic penetration test, tip 50 cm^2.

Table 4. Sites of peat stabilization. Binder type and amount, hardening time of the peat, sounding types and the number of the sounding points, sample size, strength increase ratio and variation of COV [24].

tions for construction at soft soil areas in 25–30 countries [3, 27, 44, 46, 47]. Good experience obtained in those sites has led to expanded application possibilities for this method. Since 1996, mass stabilization has also been applied for processing soft, and in many cases, polluted dredged sediment allowing for their further utilization as material in port development construction works. The largest reported case of this kind is the Vuosaari Port in Helsinki, Finland, at which the amount of mass stabilized TBT-contaminated dredged soft sediment was 0.5 million m^3 [48].

In most cases, mass stabilization method has been used for stabilization of soft and watery silt, clay, and mud soils. Mass stabilization of peat is also popular. An example list of cases is presented in **Table 5**, in which mass stabilization of peat has been executed. Two of those cases, Kivikko and Veittostensuo, are presented in greater detail below.

9.1. Case Kivikko

Approximately 10 hectares of the lots and streets in Kivikko, Vantaa, Finland are situated on soft swamp, which required stabilization to ready the subgrade for construction activities. The mass stabilization method was applied in Kivikko for the first time in 1998, and the latest stabilization work was completed by December 2010 [46].

Location and time of mass stabilization execution	Volume [m^3]	Application	Reference
Veittostensuo, Iitti, Finland, 1993	≈1000	Road, test area	[24, 49–51]
Väg 601, Råneå, Sweden, 1995	10,000	Road	[50, 52]
Skyttorp-Örebro, Sweden, 1996	≈15,000	Railroad	[50]
Väg 590, Askersund, Sweden, 1996	7300	Road	[50]
Tolsa, Kirkkonummi, Finland, 1996	≈1000	Road, test area	[53]
Kivikko, Helsinki, Finland, 1997–2010	270,000	Industrial area	[46, 54–57]
Väg 272, Holmsveden, Sweden, 1997	≈20,000	Road	[50]
Väg 45, Arvidsjaur, Sweden, 1998	11,000	Road	[50]
Enånger, Sweden, 1998	≈1000	Test area	[50]
Lielahti, Tampere, Finland, 2002	≈5000	Street	[57, 58]
Väg 44, Uddevalla, Sweden, 2002	32,000	Road	[59]
IKEA, Vantaa, Finland, 2002–2003	65,000	Yards and street	[60, 61]
Railroad, Mäntsälä, Finland, ≈2004	≈50,000	Piling platform	[58]
Peräseinäjoki, Finland, 2005	≈6000	Railroad	[35, 62]
Edenderry, Ireland, 2005	< 1000	Road, test area	[63]
Key Largo, Florida, USA, ≈2009	n × 100,000	Road widening	[36]
Toukoranta, Helsinki, Finland, 2005–2006	69,000	Park	[46]
Haaga, Helsinki, Finland, 2006	78,000	Sports park and residential area	[46, 57]
Kose-Mäo, Estonia, 2009	≈10,000	Road, test area	[27, 64]
Pitkäjärventie, Espoo, Fin., 2012	85,000	Street, pipeline	*
Nikuviken, Porvoo, Finland, 2012	17,000	Pipeline	*
Simuna, Estonia, 2012	11,000	Road	[27, 65]
Omenatarha, Porvoo, Finland, 2011	≈10,000	Street, pipeline	*
Mellunkylä, Helsinki, Finland, 2011	50,000	Street and residential area	[46]
Roslagsbanan, Täljö, Sweden, 2013–2014	n × 10,000	Railroad	[66]
Turvesuo, Espoo, Finland, 2016	30,000	Yards	*
Honkasuo, Helsinki, Finland, 2016	25,000	Street	*

*Information is from the design documents of the cases.

Table 5. Some examples of mass stabilization cases where intact soil is peat.

Over years, the stabilized area has gradually been expanded. At the beginning of this project, two separate mass and column stabilization development projects were carried out—EuroSoilStab (ESS) and Deep Stabilization Development (DSP). Both took place in the street line at the southern part of the area. In the ESS project, the mass stabilized layer was placed over a clay layer which was column stabilized to the depth of 7 m. The DSP project was the first attempt to perform column stabilization through the mass stabilized layer. After the development projects, mass stabilization was completed at the yard areas [67]. The stabilized areas are presented in **Figure 10**.

The treated soil material included soft peat (water content 400–1000%) and clay. The top layer was 2–3 m thick peat layer and beneath that was a soft layer of clay. The clay layer reached 3–18 m deep until a moraine layer. The combination of column stabilization and mass stabilization was used under the street and pipelines and mass stabilization (**Figure 11**) or column stabilization solely at the yards of industrial buildings. In the cases of thick clay layers, column stabilization was also performed under the yard areas [24, 67].

The binding agent mixtures in the ESS project were three different combinations of gypsum- and lime-based Finnstabi® 70–113 kg/m^3 and cement 70–113 kg/m^3. In the DSP project, the used binder agents were cement (100 kg/m^3) and a mixture of cement 100 kg/m^3 and fine sand 150 kg/m^3. The binding agent in the subsequent mass stabilizations was the similar mixture of cement and sand than in the DSP project. By adding sand, it was possible to decrease the amount of binder needed. Depending on circumstances, in 1 day, 800–1000 m^3 was mass stabilized by one mass stabilization unit [67].

The designed target shear strength for most of the mass stabilized yard areas was 40 kPa and the quality of the mass stabilization was assured by in situ soundings. The target shear strength value was exceeded [67]. The quality control soundings were repeated in four areas (*Fin: alue*) ("ESS," "1 ha –alue," "Urakka-alue 4," and "Alue C") in 2017, after 9.5–18.5 years from the

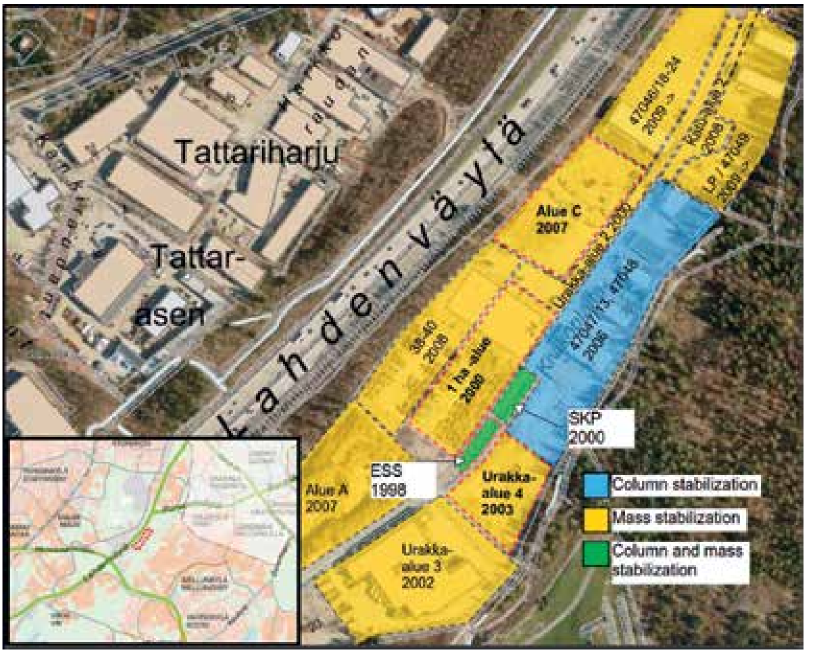

Figure 10. An overview of the locations of the stabilized areas in the industrial area of Kivikko in Helsinki. The length of the area in northeast-southwest direction is 600 and 200 m in opposite direction [24].

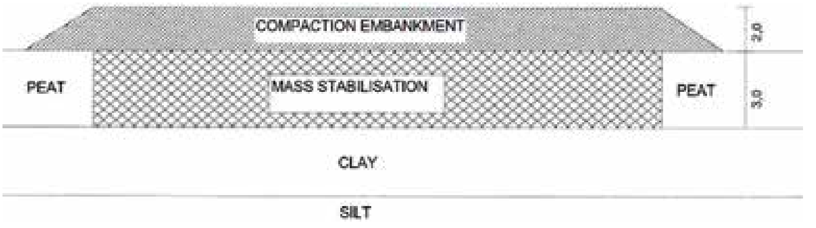

Figure 11. The principle cross section of the peat mass stabilization in the case Kivikko ([67], modified).

stabilization executions. It was concluded that the strength of the mass stabilized material had increased substantially during the observed period of time (**Figure 9** and **Table 4**) [24].

The main objective for the stabilization of the peat layer in Kivikko was to improve the bearing capacity and stability and reduce settlements in a cost-effective way. Another objective was to develop and gather knowledge from the stabilization methods. Both of the objectives were fulfilled.

9.2. Case Veittostensuo

A column and mass stabilized trial embankment was constructed on a swamp in Veittostensuo, Finland in 1993. The upper peat layer was mass stabilized or column stabilized so that columns were side by side. The lower clay layer was column stabilized (**Figures 12** and **13**). The mass stabilization was the first peat mass stabilization ever performed nationally and probably worldwide. The built embankment served as a part of development project on developing feasible and cost-efficient foundation methods for roads built on swamp areas [51].

The construction works were carried out in demanding conditions. The maximum thickness of the peat layer was 5 m, summed up with the clay layer beneath the thickness of the soft soil layer was up to 25 m. The water content of the intact peat was 1300–1700% and the shear strength was 7–25 kPa [51].

A surface area of 13 × 18 m^2 was mass stabilized to a depth of 3 m using two different binder agents. The used binder agents per treated peat volume were combinations of rapid cement 125 kg/m^3 + gypsum-based Finnstabi® 125 kg/m^3 and rapid cement 150 kg/m^3 + blast furnace slag 150 kg/m^3 [33].

The designed target shear strength after a year was 50 kPa and the quality of the mass stabilization was assured by in situ soundings, settlement plates, and sampling. The achieved shear strength after a year was 60–100 kPa and exceeding the target value [33]. The quality control soundings were repeated in 2016, after 23 years from the mass stabilization. It was concluded that the strength of the mass stabilized material had increased substantially with both binder agents during the observed period of time. The settlements were also measured during the 23 years period—no significant settlements were observed for the last 20 years. The taken samples indicated that the pH had decreased approximately a unit between 1 and 23 years from the mass stabilization, still exceeding value 11. The water content had also increased significantly in the same period of time [24].

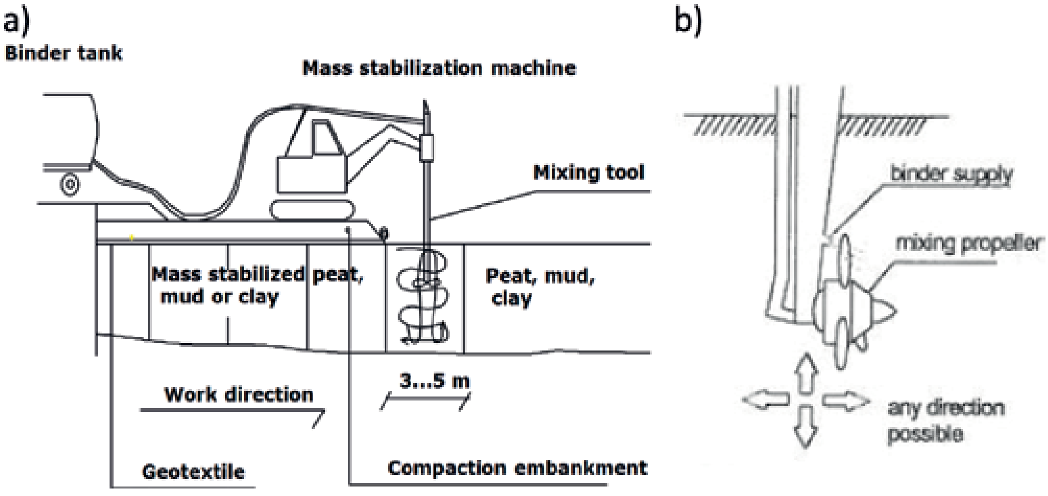

Figure 12. Mass stabilization equipment used in Veittostensuo (a) and the mixing tool (b) ([42] modified [32]).

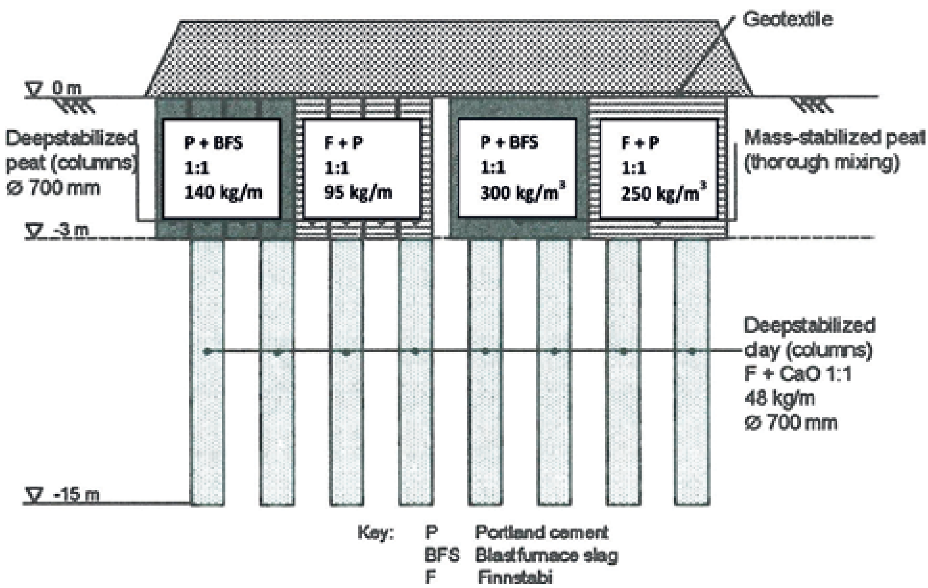

Figure 13. The principle cross section of the combined mass and column stabilization in case Veittostensuo [49].

The case Veittostensuo was a success and embraced the feasibility of the mass stabilization as a ground improvement method; the expectations were exceeded in both short- and long-term studies [24, 33].

10. Summary

Mass stabilization has been used as a ground improvement method in versatile applications for construction at soft soil areas during last 25 years in 25–30 countries. In many of those cases, mass stabilized soil is peat. The development of equipment has been active and can currently be considered to be technically on a high level. The equipment is relatively light, mobile, and therefore easy to use in various locations.

Various long-term studies have demonstrated that the strength of stabilized peats has increased in average 1.6 times compared to the strength observed after 1 month. Similarly, the settlements have mainly ceased, indicating that creep of the stabilized masses is negligible, approximately 5–8% of the creep of untreated peat. Therefore, it can be concluded that the long-term behavior of mass stabilized peat is stable. However, it is emphasized that preliminary stabilization tests should be completed in the laboratory to ensure that the optimum binder and addition rate are chosen for the execution of mass stabilization.

Mass stabilization method is used to replace mass exchange or piling or other alternative methods. Compared to other methods, it is particularly economical in cases where the driving distances for the excavated peat are long, there is not enough material to replace the excavated peat, or there is insufficient space for landfilling. The binder constitutes the largest part of the unit price in mass stabilization. The CO_2 emissions of the binder (e.g. cement) are often high, but because of the added binder, stabilized peat has a large uptake potential of CO_2. The amount of cement in binder can be reduced or optimized, if recycled materials (e.g. fly ash) are used as part of the binder mixture. In the first hand, stabilization is an environmentally friendly method as it saves natural resources, it does not require landfill areas, and it substantially reduces transportation needs and related emissions. However, more research is needed to more accurately complete a life-cycle assessment taking into consideration the reduction of CO_2-equivalent emissions of the untreated swamp masses.

Thus, sufficient experience exists to conclude that mass stabilization is a beneficial and acceptable ground improvement method for peats. It has proven to be a flexible, cost-effective, environmentally friendly, and stable treatment for peat layers.

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Chapter 8

Hydrological Function of a Midlatitude Headwater Peatland

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77240

Abstract

Peatland represents quite significant phenomenon in the headstream areas of Czech rivers. Considering the fact that these areas are crucial for streamflow generation process, it is very important to study the mechanism of runoff formation in a peatland and its hydrological function. Natural runoff process is affected by man already by its birth, thus in headwaters where numerous procedures related to runoff retardation and water retention increase in headstream areas could be realized. To understand and clarify the runoff generation process and the effect of various physicogeographic factors on its dynamics, the detailed analyses were carried out in the Vltava River headwaters (sw. Czechia) in recent years. It was necessary to consider the evaluation of peatland retention capacity, its hydraulic communication with draining watercourses and of runoff regime variability during various hydroclimatic conditions. The big attention was focused on findings of a runoff dynamics dependence on the groundwater table in the peatland and of the runoff chemistry and balance using isotopic hydrology methods. Natural tracers were applied at sprinkling plots to identify preferential flow and runoff formation at two opposite hillslopes in this peaty mountain headwater.

Keywords: headwater, peatland, peat bog hydrological function, hydrological extremes, runoff formation, retention potential, Vltava River, Šumava Mts., automatic stations, experimental catchment, oxygen isotopes, tracer experiment, dye

1. Introduction

Mountain peat bogs and peatland represent a significant phenomenon in headwaters of Czech rivers. They occupy a considerable part of the area where the outflow is formed. The study of the hydrological conditions of the most exposed parts of the Czechia therefore requires a very detailed field survey and study of the composition of peatland, its background, development, and hydrological function. These are the areas where the streamflow is generated and then transformed. These headwaters are crucial for the lower parts of river basins from the runoff point of view and in the sense of increasing extremity of climatic and hydrological features. Recently, these effects have been increasingly observed and their effects are mainly attributed to processes related to climate change, also in the mid-altitude part of the European continent.

In the context of catastrophic floods and extreme droughts that have occurred in recent years on the Czech territory, there is an urgent need of solving of issues dealing with protection against hydrological extremes, not using just classical engineering methods. There is a new protection strategy focusing on gradual increase of river catchment retention capacity including its headwater regions where numerous procedures related to runoff retardation could be realized. However, the realization of such measures must be preceded by a thorough research of these areas, not only in terms of hydrological, but also soil or vegetation point of view. It calls for an interdisciplinary concept of research and a comprehensive understanding of the existence of this phenomenon from many perspectives.

Suitable conditions for the research realization at present are related to the mid-latitude Vltava R. headwaters (sw. Czechia) representing the core zone of frequent extreme runoff events with high heterogeneity in terms of physicogeographic and socio-economic aspects. Due to the significant existence of peatland phenomenon in this area, detailed assessment of peat bogs hydrological function, its retention capacity and hydraulic communication have been done in order to evaluate its retention potential. Both classical hydrology approaches and modern methods were used to answer actual questions.

2. State of the art

A number of foreign and domestic projects have solved the matter of peat bog hydrological function but no one has been fully comprehensive. Opinions on their function, already appeared in the second half of the twentieth century, vary a lot. Ferda [1] made the detailed analysis of various approaches to tackle these questions in the Šumava Mts. On the base of "theory of sponge," that occurred in the late 1960s, peatland was distinctive for its significant water retention and discharge regulating ability, and for its discharge heightening ability in dry periods. Other studies from the late 1970s then confirmed the peat bogs retention capacity and show that the only possible way to increase the retention capacity is to lower groundwater level (GWL) by means of drainage. Since that time, the issue of hydraulic communication between peat bog complexes and draining streams (incl. procedures of drainage) has become a field of broad debates among experts (e.g., [2–7]). An interesting and detailed study of the literature covering opinions on both sides can be found in the paper of Holden et al. [8]. Conflicting results presented in the abovementioned papers depend on the different physicogeographical conditions. However, in general, acquired findings proved significant runoff variability of watercourses draining peatland areas. It can be said that the peatland influence on hydrological regime balance had been quite overestimated in the past.

http://dx.doi.org/10.5772/intechopen.77240

The same result was acquired in the study area of the Vltava R. headwaters in Šumava Mts. [9–13]. Papers show a significantly negative influence of unaffected peatland on a runoff process from its variability point of view. This mountain range has the largest peat bog areas in the Czechia as well as in Central Europe. The existence of large amounts of peat bogs in this area is caused by a humid climate and by optimal relief configuration [14]. The influence of peat land on water quality in watercourses is assessed as unambiguously negative, while intensity of the effect is related to its area and volume in a catchment. Waterlogged areas in Central Europe are formed mostly in flat areas or shallow valleys (e.g., in Biebrza, Poland [15], or in western Slovakia [16]) but climatic and hydrological conditions are different from those of mountainous peat bogs. Quite similar conditions for upland peat bog development can be found in Scandinavia and Scotland. Therefore, it is better to compare hydrological processes within the Šumava Mts. peat bogs to those in Scottish or Scandinavian waterlogged areas.

The influence of peat bogs on hydrological processes has also been discussed with respect to the effect on water quality, especially the ionic structure of water in periods of high or low discharges [17–21]. In dry periods, runoff from peat bogs decreases or becomes almost intermittent. This results in improvement in the quality of the water in the streams draining the peat bog. This was confirmed by studies carried out by Ferda et al. [22] and others [23–25]. However, during spring snowmelt and summer rainfall totals, decline in water quality is observed as peat bog complexes are fully saturated. In case of water release during dry periods, this would be expected to result in decreased quality.

Defining the environment in which hydrological processes take place is quite complicated. Determination of basic hydrological processes using information about the qualitative composition of water is inconvenient and the concept of surface runoff is not sufficient. Hydrogeochemical approaches are suitable to explain the streamflow generation process and to understand the mechanism of water retention in a catchment. Since the theory of so-called "effective precipitation "[26] was accepted, the hydrological response of runoff to causal rainfall has been extensively studied. Despite this, the real mechanism of water behavior underground has not been so clearly described [27]. The absence of such detailed data results in simplified assumptions and insufficient description of complicated processes such as causal aspects of runoff generation. Rainfall-runoff transformation requires additional data that can be obtained using a natural indicator. This information can be provided by a combination of isotope and geochemical approaches [28, 29]. This new dimension to hydrological studies has proven extremely simple and superior to previous theories [27, 30]. Using information about isotopic structure within the soil, subsurface water and causal precipitation amount, proportion of these phases in extreme runoff episode based on isotope concentration in the outflow can be determined. However, mechanism causing this exchange is not completely known [29, 31]. Water can often move apart through isotopically and geochemically specified spaces, channels, or be retained [32]. These spaces are not space-homogenous, and their contribution over time to the proportion of runoff is not necessarily constant [33].

The main anthropogenic changes in the Šumava Mts. peat bog complexes have been caused by efforts of draining and drying. Peat bogs have been traditionally drained for the purpose of peat exploitation, agricultural land cultivation, or increase in wood exploitation in waterlogged forest areas. Nevertheless, the extent of surface drains was already considerable at the turn of the nineteenth and the twentieth century. However, the major period of drainage digging was in the 1970s and 1980s of the twentieth century. Nowadays, the drainage systems are still visible. Stocktaking researches have displayed that drainage has affected almost 70% of peat bogs in the Šumava Mts. [34]. The open system of drains causes especially: fast surface flow, steeper culmination, and higher fluctuations of GWL [35]. Performed restorations can improve these aspects and consequently increase the GWL by several centimeters in a year [36]. A research from Schachtenfilz in the Bavarian Forest has confirmed that restoration measures increased GWL and decreased its fluctuation [34]. Since 1998, a complex restoration program has been implemented in the area of the Šumava National Park. The program is primarily aimed at a general improvement of disturbed water regime in the peat bog area [37]. A concept of so-called "target water level" has been exercised during the restoration in the Šumava Mts. The method is based on determination of necessary water level, which is particular for each peat bog and which is desirable to be achieved by restoration measures. The necessary water level can be described as a maximal tolerated decline of water in a ditch under the dam head, which is bearable for a given type of a peat bog [38].

Peat bogs are physically and ecologically adapted on the depth of GWL. The depth has a great significance for ecological niches of vegetative species and hence even for peat development [39]. The response of GWL on an exercised restoration is usually very fast; nevertheless, the changes in water chemism and consequent reactions of peat bog species are very slow. Peat bog vegetative species are vulnerable and sudden changes of pH factor or changes in the amount of nutrients after exercising restoration can also have negative effects. Peat bog restoration consequently includes stabilization and increase of GWL and a repeated habitation of the standpoint by peat bog species. It is thus important to limit the amount of water drain [40].

3. Study area

The subject area is located within the upper Vltava (Moldau) R. basin, the left tributary of Elbe River, in Central Europe (see **Figure 1**). Headstream part of this basin, where experimental research was undertaken, represents an area with the significant existence of a phenomenon of a peatland that is of mountainous type, mainly fed by atmospheric precipitation. Although the studied area is mountainous, its exposure in the planed and highly exposed part of Šumava Mts. gives it a flat watershed character favorable for the existence of high moor. The catchment is formed by a typical old-aligned surface with an altitude varying between 1.100 and 1.300 m a.s.l. From the geological point of view, according to the tectonic zoning, the basin belongs to the area of Moldau-Danube elevation. Within the various parts of this area, a number of specific experimental catchments were chosen. Their area and slope are similar with the exception of the Rokytka Brook basin, which is slightly flatter. They also have similar soil and vegetative conditions, and most of the area was influenced by a bark beetle infestation. The biggest difference is the extent of peat soils which represents the main reason that why these comparable experimental basins were chosen. All catchments have been monitored several years by installed water level gauges in their closing profiles.

In the Rokytka B. basin, our "field laboratory," the peatland complex comprises several large and many small mountain peat bogs, which are surrounded by forest peat bogs, waterlogged

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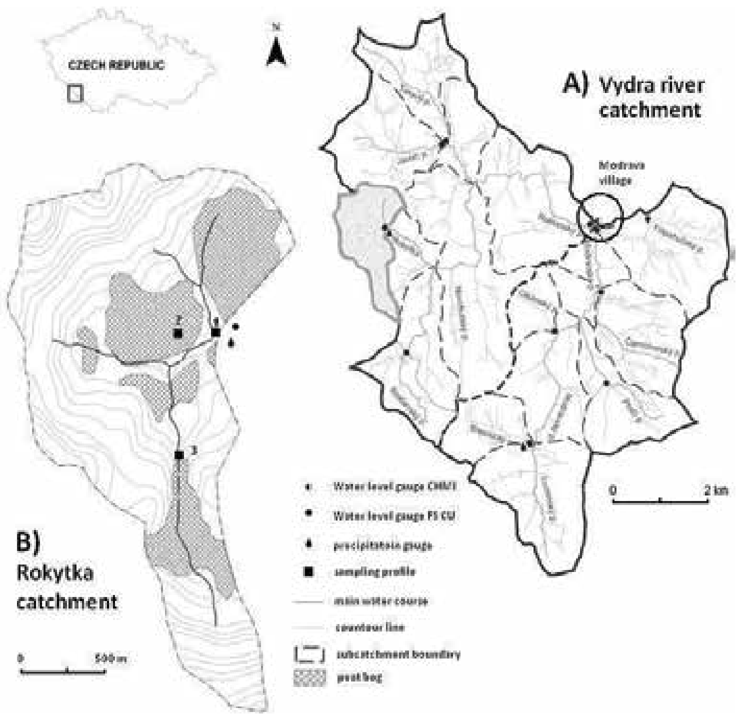

Figure 1. Localization of the study area incl. the CHMI (Czech Hydrometeorological Institute) and FS CU (Faculty of Science, Charles University in Prague) water stage recorders and automatic precipitation gauges within the Vltava R. headwaters. (a) Rokytka B. Experimental catchment within the Vydra River headstream area; (b) sampling profiles and the main peat bog complexes. Sampling profiles: (1) outflow, (2) peat bog lake, and (3) tributary.

pine stands and minerotrophic sedge peat bogs. According to the ZABAGED digital terrain model (the basic platform for geographical data of the Czech Republic) and to the TGM Water Research Institute DIBAVOD (digital basis for water management data), the experimental catchment of Rokytka B., down to the closing profile with installed water level gauge, has an area of 3.86 km^2. The total area of the main studied peat bog within the Rokytka B. catchment is almost 250 ha and its depth reaches up to 7 m. Maximum depth of the peat bog was measured in its central part. It represents historically the deepest analyzed profile in the whole Šumava Mts. with the oldest dating. The research of the Rokytka peat bog was also focused on a selected experimental drainage ditch as the anthropogenic impact, which is located in the northern part of the catchment, at 1.100 m a.s.l. It drains an area of 0.14 km^2. The drainage ditch was partially dammed by small restoration dams; partially it was left functional, with a depth of 1 m.

The bedrock is composed of weathered rocks, mainly granite. Soil conditions in the study area include the features of on-site Organosols, as described by Šefrna [41]. Local soils are typical for the area of Šumava Mts. with characteristic vertical sequence of several types of soil, with Histosols on the ridges and in basins. The largest area of the basin is covered by Entic Podzol, the second most common type of local soil is Histosol (about 26%). Lower part of the basin is filled with a relatively broad peat bog complex with quite significant cubic capacity up to 7.2 m depth. Number of peat bog lakes can be found here as well

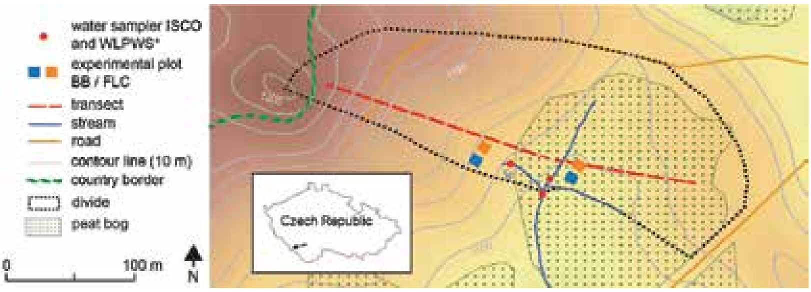

Figure 2. Overview of the Rokytka B. headwater test site (0.6 km^2); SpDspring; * water-level proportional water sampler [44].

(see **Figure 1 (b)**). In certain lower parts of the basin, Gleysols are spread out. To consider runoff conditions, water-saturated Organosols can be considered as extreme runoff accelerators. Their retention effect is not approved in the status of full water saturation, even if Organosols have a broad capacity for retention of water. Local vegetation is linked to peat bogs themselves, and forest. Peat bogs are surrounded by waterlogged spruce forest and minerotrophic sedge peat soils [42]. The rest of the forest vegetation is mainly composed of spruce with the addition of fir and beech, and is present predominantly on the south-facing slope. The forest has been influenced by the spruce bark beetle calamity.

To identify the runoff formation in detail using dye tracer experiments, the study site in the northern part of the Rokytka B. catchment was marked out (**Figure 2**). This second-order stream drains the area of 0.6 km^2 in the altitude between 1.100 and 1.260 m a.s.l. The test site can be divided into two parts represented by two opposite hillslopes with different soil types and vegetation cover. The mineral soil hillslope composed of a Podzol (PZ hillslope) is covered by beech stands at the upper hillslope zone and by dead spruce stands with healthy seedlings at the lower part. The soil profiles do not show a clear gradient toward the stream and are similar throughout the slope. Entic Podzol has been identified, with quite shallow organic top layer (<5 cm) and similar soil texture to a depth of about 1 m. Small parts of the PZ hillslope are covered by Haplic Podzol, but excavation is needed for proper identification. Neither there was a sharp transition between the mineral soil and the bedrock (well-weathered Gneiss or Granite) perceptible with electrical resistance tomography (ERT) measurements nor could a persistent GWL be detected. The organic soil hillslope is covered by a well-developed mountain peat bog (PB hillslope). The entire area consists of a mixture of various stages of decomposed peat. However, Acrotelm and lower Catotelm can be distinguished at depths ranging from 8 to 25 cm [43].

4. Materials and methods

To assess the hydrological balance and runoff formation in a peaty mountain headwater several methodical approaches and various data were used. Automatic stations for the variability monitoring of hydro-meteorological features and physiochemical parameters of surface water were installed in closing profiles of studied experimental catchments. Modern experimental hydrology also uses hydrochemical and geochemical approaches to explain the mechanisms which are related to water retention and runoff formation in headstream areas. Geochemical approach using stable oxygen isotope principle was applied to understand and clarify the streamflow generation processes in the highly peaty catchment. Contribution of water from peat bog areas to the total surface runoff has been assessed for unit hydrogram separation by means of anion deficiency. Tracers such as Brilliant Blue and Fluorescein-Sodium were used and applied at sprinkling plots to identify preferential flow and runoff formation at two opposite hillslopes in this peaty mountain headwater.

4.1. Monitoring of hydroclimatic conditions

The crucial means of obtaining high-quality data for consecutive analyses is represented by the functional system of automatic ultrasound or hydrostatic pressure water-stage recorders, climatic stations and shuttle precipitation gauges (**Figure 1**). Monitoring stations are provided by GSM module that can transmit data through GPRS network. Other modern equipment and methods were used in chosen experimental locations to determine rainfall-runoff relations. A number of experimental profiles also contained sensors for the observation of physiochemical parameters. This network, complemented by the Czech Hydrometeorological Institute (CHMI) state profiles, represents a crucial basis for precise analyses of a local runoff regime. In the profiles given, needful instantaneous discharge measurements using a hydrometric propeller or flow tracker were performed in order to construct accurate consumption curves with high confidence coefficients. Primarily, the influence of peat bog complexes on hydrological conditions was assessed by detailed comparison of runoff regimes in a number of chosen subcatchments with respect to diverse peatland extent and to other relevant physicogeographical parameters. Mechanism of a runoff formation (incl. recent peat bog revitalization processes) was studied primarily using basic hydrological statistics with particular attention to periods of high or low discharge rates. This approach was afterward complemented by much more predicative ion, carbon and oxygen isotope balance analyses (see Chapter 4.5).

4.2. Runoff variability assessment

To assess the runoff variability in chosen profiles, classic hydrological statistics were used at the first step. To assess the degree of extremity in the ascending phase of a flood wave, the method of extremity indices was used [11]. In its first phase, it consists of the determination of the mean discharge of individual streams in the period before the flood wave (D-8 to D-2). The assumption is that this discharge would be reached in the following days if there were no causal situation. For the same period (D-8 to D-2), coefficient of variation (Cv1) from the mean hourly discharges was calculated. The calculated values give us a picture of the degree of fluctuation of individual streams in the period before the flood wave. In the second phase, the variation coefficient for the D-1 to DD period was calculated for each stream, referring to detected theoretical mean discharge of the stream in the period before the causal situation (D-8 to D-2) obtained by the above procedure. D-1 to DD period is the range in which the flood wave increased, culminated and decreased in this case. Calculated values of the coefficient of variation (Cv2) thus represent the rate of flood flow variability from their normal course, which would be theoretically reached without the flood situation. Mutual evaluation therefore provides a good picture of the extent of the flood wave extremity of individual streams in relation to their mean discharge. The use of this method is only applicable to certain flood situations, assuming similar causal conditions for all monitored streams. The following procedure was used to control and eliminate the possible distortion of values of the variability coefficient, depending on the duration of the peak flow and the wavelength on the individual streams. This consists in expressing the value of the mutual share of the maximum reached value of the 10-min discharge in the period D-1 to DD (hereinafter referred to as KP) and the mean discharge in the period before flood wave (hereinafter referred to as PP), in this case D-8 to D-2. The value obtained is referred to as the I_{EKP} peak flow extremity index (I_{EKP} = KP/PP).

4.3. Hydropedological survey

Detailed description of soil profiles and soil sampling for laboratory analyses was carried out. In general, soil retention capacity is measured using a number of methods. One of the most widely used is measurement by the neutron method, the method of retention curves [45], measurement of water isotopes change after passing through the soil [46], and other techniques. Gravimetric method, used in our research, still has many advantages. The most important thing is the simplicity of this method, little time-consuming, and it can be used to evaluate multiple factors at once (soil type, vegetation, etc.). Moreover, in many cases, this method provides results that are more accurate. The retention capacity of the individual parts of the bog was compared with the GWL. Between GWL and surface runoff from the bog, its relation with respect to other factors such as precipitation amount was assessed.

4.4. Groundwater level observation

Groundwater level measurements were implemented during the period from August to October 2014 [47]. This period was crucial for the evolution of GWL within the year. The GWL was measured manually in tubes which were inserted into the peat to a depth of 1–1.5 m. The water level was measured in lines which were copying parts of the drainage ditch. Thus, a regular net with 27 GWL measurement points, placed in regular distances, was created. The GWL was measured from the surface. For this purpose, particular segments were created from the measuring areas, and the GWLs were then compared with each other within the scope of the individual sections and lines (see **Figure 3**). The line 1 was divided into part A and part B for better accuracy. Part A is located directly to restoration dams, and part B is placed in area which is not affected of restoration measures. At each point, 28 values of GWL were measured. Further, particular level changes were statistically evaluated in the scope of individual sections and lines to better demonstrate the dependence of GWL fluctuation on the distance from a drainage ditch, or from restoration dams. Data of GWL from an automatic station in Rokytka peat bog were also used. At first, the whole dataset was analyzed by basic statistical characteristics and data testing. For distribution of measured values of GWL in various intervals, box plots were used. Statistical characteristics variance, correlation coefficient and directive deviance were calculated in software Stat-Soft Statistica. GWL fluctuation was put into context with particular significant factors of rainfall-runoff process, such as potential evapotranspiration. In this research, Penman-Monteith equation was used for the determination of daily potential evapotranspiration [48]. The antecedent precipitation index API [49] was also applied and calculated for five previous days. The index is used for determination of catchment saturation and it expresses the influence of precipitation which occurred in previous days to the given date. It thus demonstrates the ability of a catchment to absorb more precipitation.

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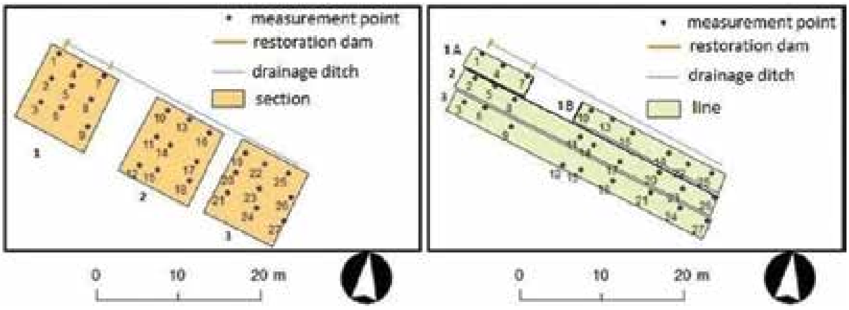

Figure 3. The scheme of particular measurements of GWL and of the segments where the GWL was measured.

4.5. Geochemical analyses

Precipitation and surface water sampling for chemical and isotope analyses was carried out in monthly and two-weekly time steps, respectively, with respect to the whole discharge range, in order to obtain data from extreme episodes such as thaw, snowmelt, rainfall and drought. Precipitation amount and its isotopic composition (δ^{18} O-H_2O) were measured in the adjacent catchments of Roh and Doupě, which have very similar characteristics and are close to the study area. Surface water sampling was carried out in three different sampling profiles: outflow profile (water level gauge), bog profile (organogenous lake) and inflow profile (tributary). The study catchment was closed by the automatic ultrasound hydrological gauge for continual discharge monitoring. The principle of $^{18}O/^{16}O$ fractionation was used for runoff formation modeling. It can be applied due to the uniqueness of the $^{18}O/^{16}O$ isotope ratio of each source—precipitation, subsurface water, surface water—at a particular time. The symbol "delta," used to express the $^{18}O/^{16}O$ isotope ratio, represents the relative proportion of measured $^{18}O/^{16}O$ to a standardized $^{18}O/^{16}O$ proportion (Standard Mean Ocean Water) [28, 30]. Simple model (incl. the inputs from the bog and tributary) was applied to calculate the contribution of the bog to the Rokytka B. outlet. Due to similar signals of δ^{18} O-H_2O in the bog and precipitation total, it was not possible to assess the input of direct precipitation separately. Water balance of the Rokytka B. experimental catchment stems from a mass balance [50]. The contribution of the bog to the Rokytka B. runoff was therefore calculated on the basis of the following equations:

$$Q_O \, \delta^{18} O_O = \sum Q_i \, \delta_i = Q_B \, \delta^{18} O_B + Q_T \, \delta^{18} O_T \tag{1}$$

$$p = Q_B / Q_O \tag{2}$$

$$p = \left(\delta^{18} O_O - \delta^{18} O_T\right) / \left(\delta^{18} O_B - \delta^{18} O_T\right) \times 100 \tag{3}$$

where $\delta^{18} O_O$ is the outflow isotopic composition, $\delta^{18} O_T$ is the tributary isotopic composition, $\delta^{18} O_B$ is the bog isotopic composition, p is the relative contribution of bog water (%) and Q is the discharge in observed profiles.

4.6. Dye tracer experiments

The dye tracer experiments were carried out at the mineral soil hillslope and organic soil slope of the Rokytka B. headwater during baseflow conditions. At each hillslope, two 1.5 m x 1.5 m plots were sprinkled with both dyes (Brilliant Blue (BB), CAS#3844–45-9, concentration 5 g L^{-1}; Sodium-Fluorescein (FLC), CAS#518–47-8, concentration 2 g L^{-1}). All sprinkling plots were located at the transition between the concave, lower part of the hillslope and riparian zone in the vicinity of the stream [43]. The overall sprinkling time at each plot was ~ 2 h in order to simulate a rainfall intensity of 20 mm h^{-1}. These amounts and intensities represent a heavy rainfall storm in the Šumava Mts. Excavation of the FLC sprinkling plots followed out. After about 4 h sprinkling, exposing of soil profiles and the photography of FLC-stained soil structures were performed under short-time UV illumination (410 nm). As FLC is strongly light sensitive, it was carried out at night [51]. Pictures of the soil profiles were taken during the excavation with a digital Micro Four Third camera with a crop factor of 2.0 under daylight conditions beneath a shading tarp to avoid direct sunlight and shadow effects in case of the BB plots. Pictures at the FLC plot were taken at night with the same camera. Each FLC soil profile was illuminated separately with two light sources (500 W Halogen lamp, 27 W UV LED lamp) to visualize fluorescent FLC-stained soil structures similar to Gerke et al. [52].

The dye-stained flow patterns for both dyes BB and FLC at all soil profiles were analyzed according to a method described by Weiler and Flühler [53]. This method was originally developed for analyzing BB. Therefore, the color space of photographs is converted from the Red-Green-Blue (RGB) color space taken by the camera sensor into the Hue-Saturation-Value (HSV) color space. It was afterward classified and spatially analyzed with an algorithm written in IDL code [54]. This procedure was applied for both dyes (BB and FLC), thus for two different groups of photographs. To detect and analyze FLC in the soil profile photographs similarly to the BB photographs, the dye detection routine in the original IDL code was adapted for optimal FLC identification [43].

5. Results

5.1. Hydroclimatic conditions

In order to assess characteristics of runoff regime and hydroclimatic conditions, hydrological year 2008 was chosen. This year was very average in the sense of hydrometeorological features in recent years. Year 2008 was chosen also because of the fact that cooperation with the Czech Geological Survey (CGS) on geochemical analyses started this year ([55], see Chapter 5.5). The total amount of precipitation in the Rokytka B. catchment in this year was 1485 mm. The seasonal course of $\delta^{18}O$-H_2O in precipitation was very consistent. Rokytka B. represents typical hydrological behavior of streams in the central Šumava Mts., with peak flows occurring in April and May during snowmelt (**Figure 4**). The annual discharge was 0.18 m^3 s^{-1}, so the studied year, 2008, showed an average value. Potential evapotranspiration was calculated using the Penman-Monteith Equation [48] from the set of 2007–2014 data. Evapotranspiration data varied little within the year, with a maximum movement of around 100 mm $month^{-1}$, see **Figure 4**. Observed data were homogenized and deemed representative for consecutive analyses. To evaluate general features of rainfall-runoff regime, mean daily and monthly discharges were calculated.

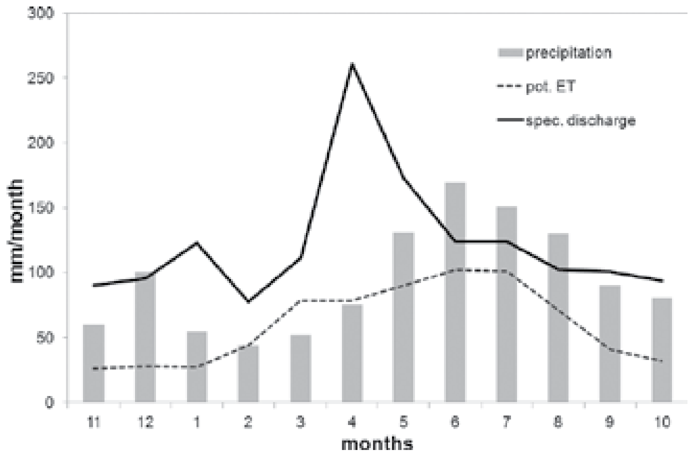

Figure 4. Mean monthly precipitation, specific discharge and potential evapotranspiration (pot. ET) in the study catchment of Rokytka B.

Studied year 2008 was from this point of view determined as an average year (**Figure 4**). The time series show a typical course every year with occasional exception related to thaws. Total runoff (1437 mm) was comparable to the measured amount of precipitation (1485 mm). The precipitation amount did not include water from snow during winter, so it seems quite low compared to the discharge. Higher rate of total precipitation was probably caused also by horizontal precipitation such as fog or frost. In general, the contribution of horizontal deposition in the area of Šumava Mts. is estimated at a minimum of 10%. Most elevated locations, incl. the Rokytka B. catchment, should have a higher horizontal deposition of around 15% [56–58].

5.2. Runoff regime variability

Based on hydrological time series analysis carried out within the upper Vltava R. basin, Kocum [12] determined the significant dependency of runoff variability on a peatland extent in a catchment. Continual records of instantaneous discharge offer an extraordinary database that is unique. Homogenized data can serve as an input for comprehensive analyses of ascending and descending phases of flood waves, and of minimum runoff episodes during dry periods. Detailed statistical analysis of daily, monthly, and yearly time series identified significantly higher runoff variability in the Vydra R. basin. This part of upper Vltava R. basin represents quite peaty area, compared to the nonpeaty Křemelná R. basin. Runoff variability in experimental subcatchments was assessed using the peak flow frequency analysis with respect to the different rates of discharge (**Figure 5**). Analysis of runoff reaction to causal rainfall amount during several rainfall events was also used. These analyses of extreme runoff phases (peak flow frequency method, e.g., [59] or [60]) showed much higher frequency of peak flows and their shorter reaction to causal precipitation total (i.e. lower water retention potency) in the case of highly peaty areas (Rokytka B.). Therefore, it can be said that there is more distinct runoff variability of streams draining peatlands and peat forming soils [61, 12].

Extremity of a hydrologically significant runoff event and specific p-g conditions in individual catchments were subjected to correlation analysis which was based on the method of extremity

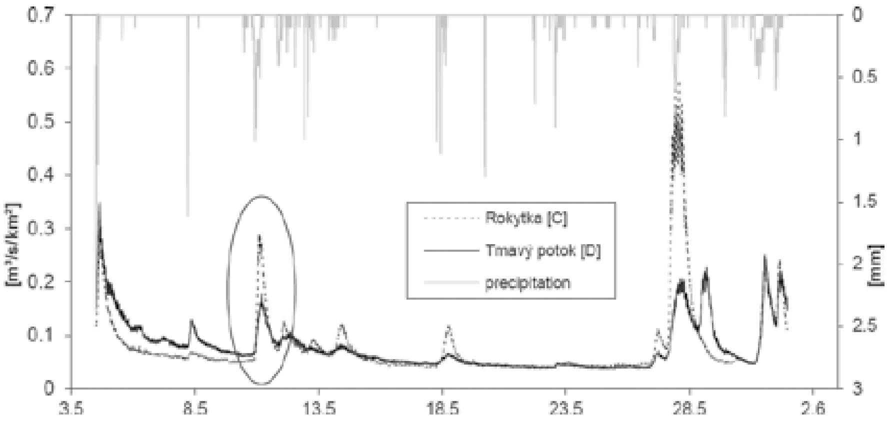

Figure 5. Specific discharge of Rokytka B. (C; 23.1% peat bog extent) and Tmavý B. (D; 2.3%) in May 2013.

indices and on the p-g parameters of the studied catchment. Similar index was used for estimating 100-year flood flows in unobserved catchments [62, 63]. The analysis shows that the extremity of the flood flow is affected mainly by a peat bog extent and by a catchment shape.

5.3. Retention capacity of peatland

Literature suggests that the landscape in the Czech conditions is able to accommodate up to 400 mm of water, an average of 40–90 mm [64, 65]. When considering the average groundwater table (GWL) bogs in the experimental catchment represent areas with the smallest retention capabilities. Retention values are similar to those found in shallow soils (about 140 mm excluding the actual humidity). Considering the lowest GWL bogs represent a significant retention areas within the catchment (230 and 267 mm). Since GWL is higher than its average value for three quarters of a vegetation period, peatland represents within the catchment the area with the smallest retention capacity. However, it is questionable whether the actual moisture measurement was sufficient. In terms of hydrological features, peatland therefore has crucial influence on the retention potential in the landscape [66].

5.4. Evaluation of the influence of peat bog restoration measures on the groundwater level

The variability of GWL represents an important factor of the evaluation the peat bog retention potential. Two different episodes were selected for the evaluation. The first one, the **episode of an intensive precipitation** (55.4 mm), was analyzed between the September 11, 2014 and September 15, 2014 at the Rokytka catchment. It is obvious that GWL along the drainage ditch shows a high amplitude (see **Figure 6**). With longer distance from the drainage ditch, the GWL increases and its change during an episode decreases. The level is the highest in the section close to restoration dams. Their influence is perceived as positive, as they raise GWL. They also have a stabilizing effect. However, the results also imply that in a certain distance from restoration dams, their effects can no longer be seen and GWL fluctuates naturally as in the

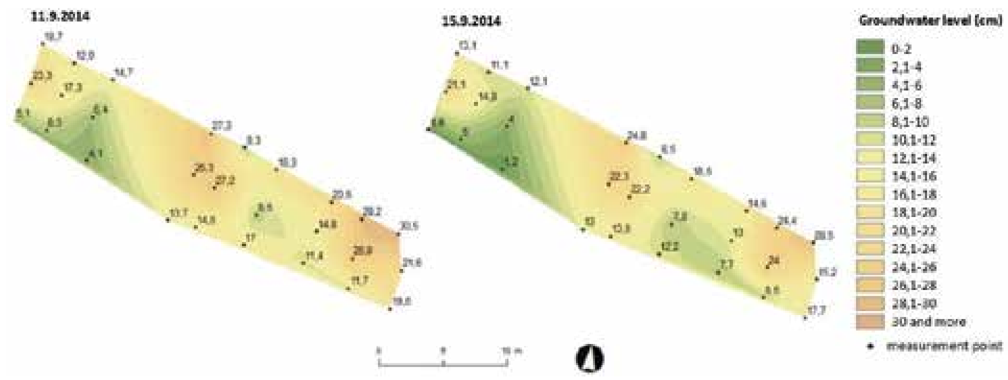

Figure 6. Changes of GWL during a selected episode of intensive precipitation between the September 11, 2014 and September 15, 2014. The given numbers in the graph represent measured GWL in centimeters on a given day.

peat bogs, which are not influenced by a drainage. It is also evident that the decreases or increases of GWL are very variable, and there are noticeable differences between individual points (up to 6.4 cm), in spite of the fact that it is a small homogenous area. On the contrary, in areas near restoration dams, the GWL was increasing very gradually and a similar increase was reached at all the measurement points. Another observed episode was during a **dry period**, when there was only 1.4 mm of precipitation from the September 2, 2014 to September 7, 2014 (see **Figure 7**). The smallest changes of GWL in a period with low precipitation were reached in the middle line of the observed area (3 m from the drainage ditch). It is interesting that in this episode, rather big amplitudes can be found, even in the area of restoration. It can be caused by the fact that before the period of drought, the GWL was very high, precisely right under the surface; hence, following decreases could have progressed faster there. The biggest difference between water levels is significant again and it is even up to 9.2 cm during the monitored 5-day range. It has been confirmed repeatedly that in the areas located further from restoration, the GWL is distinctly lower, and, moreover, there is a remarkable and fast fluctuation of GWL, which is not beneficial for the evolution of mountain peat bogs [47].

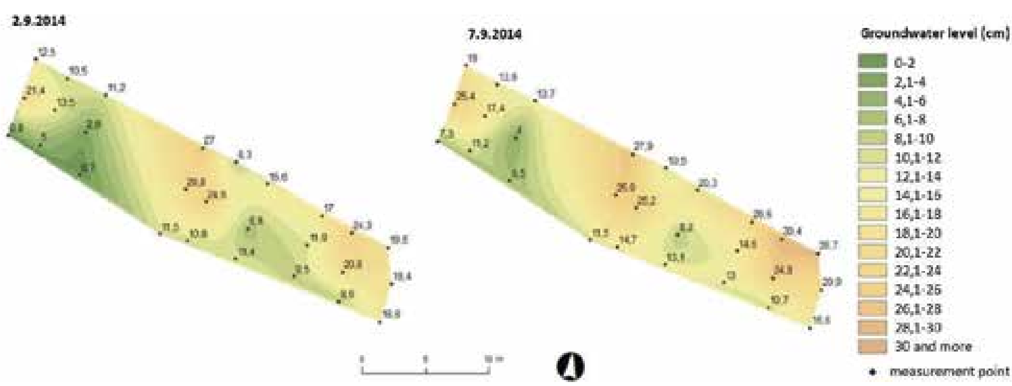

Figure 7. Changes of GWL during a selected episode of drought between the September 2, 2014 and September 7, 2014. Given numbers in the graph represent measured GWLs in centimeters on a given day.

5.5. Runoff chemistry and balance

Peat bog: Water in the Rokytka peat bog had low dissolved solids concentrations. Seasonal profile of δ18 O-H_2O (see **Figure 8**) was similar to that for precipitation, as it represents the main source of water in the bog. The hydrogen ion concentration (pH) in bog water is predominantly regulated by total organic carbon (TOC). This concentration shows quite strong seasonal profile related to evaporation and organic matter production (high TOC in summer and low TOC in winter period). Naturally higher content of organic acids along with a low total mineralization results in low pH and low alkalinity of water. Nitrates can be observed in the bog only in winter, while their source is represented by winter precipitation.

Tributary: Study catchment of Rokytka B. is supplied with a number of tributaries. However, two of them are the most significant. Since they show very similar chemistry, due to the fact that both affluents showed very similar chemistry, data from that with higher discharge were analyzed. Total mineralization of Rokytka B. was higher than in the bog. Its δ18 O-H_2O profile was more balanced as shown in **Figure 8**. The δ18 O-H_2O balance is a result of the prevailing supply of groundwater. Only in periods of higher precipitation, Rokytka B. can contain water from shallow soil horizons with a higher TOC content. Hydrogen ion concentration of Rokytka B. was significantly dependent on discharge and the profile of affluent discharge was very similar to that of brook itself. Increased concentration of TOC was probably related to the production of organic substances during the summer period. There was no significant correlation between TOC and pH.

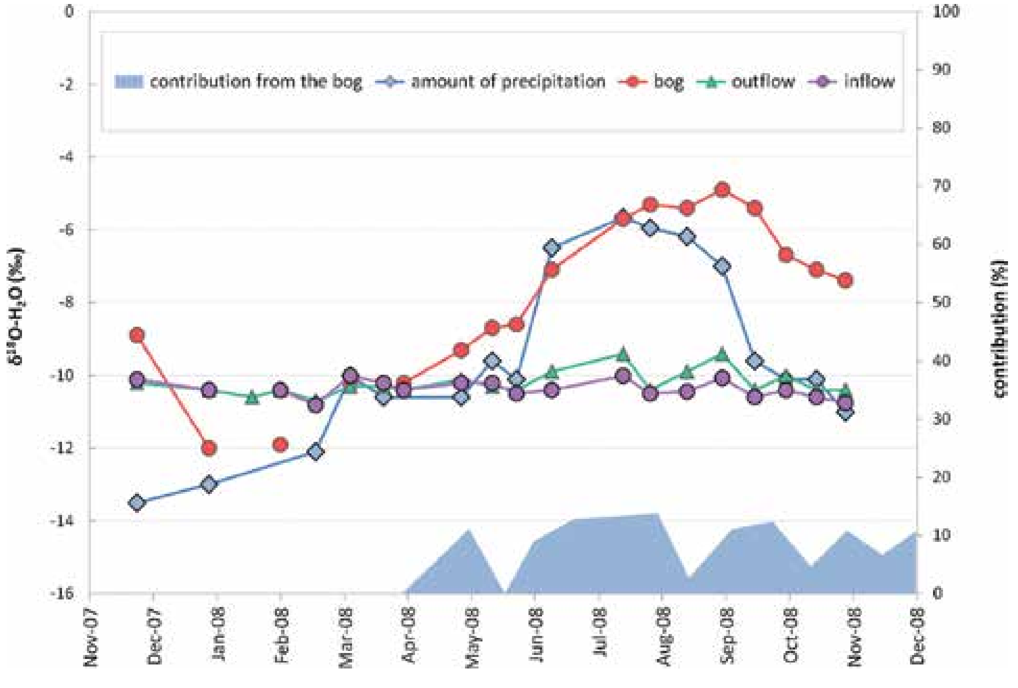

Figure 8. Profile of δ18 O-H_2O in surface water and precipitation in the Rokytka B. catchment for the hydrological year 2008; the y-axis shows the relative balance contribution of bog water to the total runoff from the catchment.

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Outflow: Chemistry of Rokytka B. in the closing profile looks very similar to the chemistry of the main affluent. On the base of the results (see **Figure 8**), it is clear that the contribution of bog water to the outflow of Rokytka B. was negligible, ranged not more than about 10% of total runoff outside the winter period. During winter, the bog contribution was insignificant and the total runoff was formed only by tributaries, that is, underground water. General character of chemistry of Rokytka B. comes mainly from water sources that have been in contact with mineral soils, even during the period of increased runoff (see stable $\delta^{18}O$-H_2O, **Figure 8**). A strong argument for claiming that the main sources of Rokytka B. runoff are represented by its tributaries, which are mainly supplied by groundwater, is that, compared to the bog, there was also a high concentration of cations in the brook. Regularly increasing TOC concentrations are most likely from the riparian zone, where TOC is washed off during the increased runoff period. Production of seasonal organic matter would also have some influence [55].

5.6. Identification of runoff formation using dye tracers

Near-surface flow in the NW direction toward the stream was revealed by the visual survey of the soil surface in the vicinity of the BB sprinkling plot. Brilliant Blue was detected in a small, water-filled depression 10.5 m downslope from the sprinkling plot. The BB stained flowpaths went from the NW side of the sprinkling plot and followed mostly lateral preferential flow structures formed by decomposed trees or roots. They did not strictly follow the terrain gradient. This lateral preferential flowpath was identified as the main direction of subsurface flow.

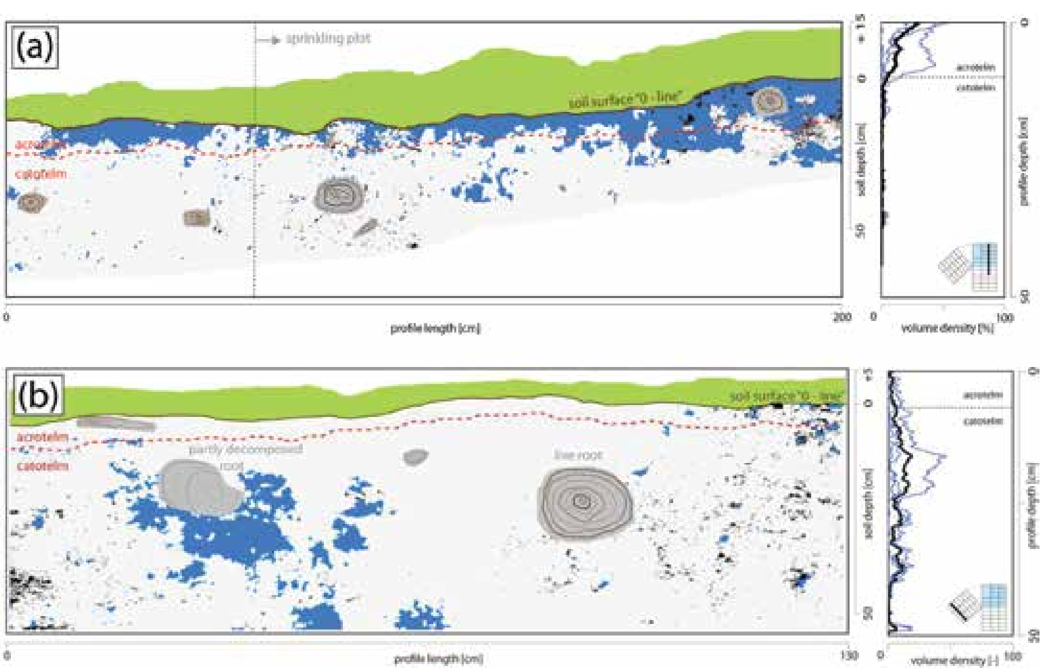

Figure 9. (a) Scheme of lateral soil profile (IL0.5) and (b) frontal soil profile (FD0.25) at the BB sprinkling plot PB3 at the organic soil hillslope (i.e. peat bog). The position of the profile is visualized in bottom right corner. Blue = BB dye, gray = roots, green = vegetation, black = unclassified shadows, red-dotted line = soil horizon dividing line. Charts on the right represent the vertical distribution of the volume density of the BB.

Smaller and less stained flowpaths were detected downslope from the sprinkling plot. BB was disappearing 2 m from the sprinkling plot. BB followed lateral soil pipes that were formed by decomposed roots or fallen trees. Undecomposed timber and healthy trees did not create such effective lateral preferential flowpaths. Accordingly, they had no significant impact on dye-stained patterns (see **Figure 9**). Major flowpaths of BB could be detected even several days after the dye application because BB created clearly detectable dye-stained patterns on the dark peat particles as well. The excavation of BB stained soil patterns at the organic soil hillslope (PB3) proceeded from two directions, NW and SW, following the stained flowpaths in the soil. Near the sprinkling plot, most of the dye was detected at the surface and in near-surface soil horizons, which correlates with Acrotelm (**Figure 9**). About 2.0 m downslope from the BB sprinkling plot at hillslope PB the dye-stained patterns diminished in the Acrotelm and were observed mainly in and around macropores in the Catotelm [43].

6. Discussions

Within the long-term project, *various approaches for the evaluation of hydrological balance* of mid-latitude mountain peatland and peat bogs were used. Classic statistical methods and modern research approaches were implemented in order to understand the real mechanism of the streamflow generation process in areas with significant peat bog phenomenon. The 12-year duration of the project entails the crucial findings that were used in this paper and complement the long-term time series of data from the state profiles. However, different approaches were not used throughout the whole period but in chosen terms. Application of all used methods in the whole period was not possible because of financial and personal resources, as well as the ongoing technology development. However, what was supervised very much in detail was always the choice of correct and relevant data base of needed parameters and suitable time periods. Combination of such corresponding analyses was crucial for complex outcomes that were presented. It has to be stated that every each methodology approach and acquired result casually supports and supplements one another. Such a broad and detailed study has never been carried out in this area and brings completely new findings that are minimally comparable with different types of peat bog complexes.

Thus, general solution of the issue of a *peat bog impact on the runoff process* is not possible. It depends on many factors, mainly on the type of a peat, on its condition and on the extent of anthropogenic influence. Opinions on the peat bogs hydrological function have undergone considerable development and are often contradictory. Generally, the hydrological importance of peat bogs has been overestimated in the past and cannot be regarded as flow regulators because draining streams show extremely high volatility. More controversial discussions within the foreign and domestic literature (e.g., [2, 5, 6]) can be found within the question of drainage of former ameliorative channels or its torrent control respectively. Based on research in the upper Vltava R. basin, it could be stated that it is crucial to take into account the specific characteristics of peat deposits and its surrounding natural conditions while evaluating the revitalization measures effect on runoff dynamics.

Within the literature, a number of *positive and negative examples* of the peat land influence on hydrological regime can be found. These contradictory claims can be paradoxically united. When the bog is drained, runoff variability decreases, but it leads to destruction in time by the bog succession. If GWL would be regulated and reduced in time of need, bog retention potential could be used without the threat of its existence. Periodical fluctuations of GWL in the bog are natural constituents of its development. Minimum time lag between the monitored GWL and surface outflow points to a negligible ability to absorb significant rainfall totals by the bog complex and to a minimum hydraulic communication between the bog complex and its draining stream.

Detection of natural tracers is a useful method to provide the key information in hydrological observation studies of catchment runoff formation. These methods use the different behavior of a small quantity of water molecules. Study of water dynamics by means of natural tracers is typically oriented on usage of oxygen (^{18}O) and hydrogen (^{2}H) isotopes [31]. Stable oxygen and hydrogen isotopes are elements that occur naturally, in variable concentrations, in the hydrological cycle. It provides the unique information about the water that enters a catchment in the form of precipitation, that retains in the catchment and that passes out in the form of runoff. Hypotheses and knowledge of runoff regime dynamics of studied areas gained on the basis of classical hydrological approaches were therefore confirmed by detailed hydrochemical and geochemical analyses. The application of this modern approach in such an optimal model catchment, such as the Rokytka B. catchment, appears as a legitimate shift in research. According to above stated fact, geochemical data show no significant hydraulic connection of the studied bog with the Rokytka B. bed. Moving at a maximum of around 10% out of winter period, as a consequence, the contribution of surface runoff by water from the bog is very insignificant. The predominant portion of underground water (forced out due to the pressure gradient) in total runoff was also confirmed by separation of each runoff component according to geochemical parameters. The problem of hydraulic communication between peat bog complexes and draining streams needs to be solved strictly with respect to local p-g conditions! As it was already said, these findings represent the first knowledge of such a focus in conditions of the Vltava R. headwaters. A similar study describing the use of stable oxygen and hydrogen isotopes was carried out on Uhlířská catchment in the upper part of Černá Nisa River basin in Jizerské Mts. [29, 67]. The prevailing share of subsurface water in the total runoff was confirmed, as in the case of the Rokytka B. study, by the separation of runoff components according to geochemical parameters. During the accelerated runoff, the proportion of water from the causal precipitation episode is gradually increasing, thus contributing to dilution of the draining water. The study of Šanda and Císlerová [67] shows that the drainage of this water is accelerated by the system of partial drainage bases of underground and groundwater in the form of artificial and natural forest gutters, chasms and saturated areas with an ongoing return flow. This course can also be observed in the case of selected catchments in the Šumava Mts. with the existence of nonrevitalized peat bog areas with melioration channels.

If we assess abovementioned outcomes from a hydrological point of view, we have to state following: In physicogeographical conditions of Vltava R. headwaters, peatland acts as a negative element for runoff transformation. Hydrological features of local waterlogged areas are disfavorable. Our primary hydrological assumption of insignificant impact of peatland on runoff dynamics, especially during extreme episodes (floods, droughts), was confirmed by acquired findings from geochemical analyses performed. Considerably weak impact of a peat bog on runoff was also supported by a high concentration of cations in the surface runoff compared to the bog. Much more significant contribution to surface runoff of Rokytka B.

has a groundwater from the basin. In general, very close correlations between pH and actual discharge in experimental profiles were found regularly. A reasonably close relationship was also observed in the closing profile of Rokytka B. catchment. Our research findings strongly support the fact that peatland areas within the studied catchment do not significantly communicate hydraulically with surface streams and their hydrological function is, in the concrete area of Vltava R. headwaters, insignificant [9, 11].

Within the research, the question of impact of ongoing *revitalization measures of the local peat bogs* (made by Šumava National Park management) on the runoff dynamics was opened. Its wholly satisfactory solution, although it should be decisive in the selection of measures to improve the runoff conditions in the area, does not yet exist. Significantly, higher extremity of flood situations was found out in cases of revitalized streams. Local revitalization process consists in damming of former ameliorative channels draining peat bogs. Detailed analyses approved that these revitalization measures stabilized runoff conditions in yearly course and had balancing effect during average runoff situations. In a number of experimental catchments, the presence of revitalization measures can also impact negatively on given flood event. Studies confirmed that revitalization adjustments in selected subcatchments had balancing effect on runoff conditions only to the certain level of its extremity. In most cases, runoff extremity was intensified as soon as the certain water-level stage (respectively discharge) was exceeded. To confirm the correctness of these statements and to correctly understand the functioning of this mechanism, broader data base is needed.

In peaty catchments, the retention ability depends mainly on the shallow depth of the phreatic zone in the peat bog, whereas the deep phreatic zone in the Podzol plays a minor role [13]. Peat bog areas are hypothesized to control storm runoff formation in these headwaters. Peat bogs can significantly contribute to stormflow when the peat is fully saturated, that is, storm events exceeding a threshold of 10–15 mm [68]. As mentioned above, according to a geochemical study based on 2 years of monthly stream water sampling [55], peat bogs contribute only 10% to baseflow at the outlet of the entire Rokytka B. catchment. However, some zones of a peat bog area, such as springs or soil pipe systems connected to the stream, exhibit high fluctuations in discharge [69]. This fact could explain the observed spiky storm hydrographs at the entire Rokytka B. catchment outlet (area of 3.8 km^2) and at the Rokytka headwater test site (0.6 km^2). Presented runoff fluctuations from peaty areas could be caused by surface flow (as observed within a field survey at the Rokytka peat bog), near-surface flow [7, 40] or subsurface stormflow in soil pipes [70, 40, 71]. Outcomes of Holden and Burt [72] at a blanket Peat site showed that near-surface flow (i.e., Biomat flow, BMF) up to the depth of about 10 cm can contribute more than 90% to the plot's outflow. Biomat flow can be defined as a lateral stormflow in the organic litter layer which has quite high porosity and high hydraulic conductivity in the topsoil [71]. Storm hydrographs at the Rokytka B. headwater are highly volatile and are characterized by quick and steep rising and falling limbs. The hydrologic response to rainfall events is fast and the recession to antecedent baseflow occurs rather quickly [43].

7. Conclusions

Based on acquired outcomes from time series statistical analyses, much more distinct runoff variability of streams draining highly peaty catchments in the Vltava R. headwaters (sw. Czechia), especially during extreme hydrological situations, was observed. This fact was

http://dx.doi.org/10.5772/intechopen.77240

confirmed by hydropedological, hydrochemical and geochemical approaches. Geochemical data show no significant hydraulic connection of the studied bog with its draining stream. The predominant portion of underground water in total runoff was also confirmed by separation of each runoff component according to geochemical parameters. However, this subject needs to be solved strictly with respect to local physicogeographic conditions. These conclusions correspond to the typical mid-latitude peat bog area in conditions of Czech mountainous areas. Their restoration measures carried out in recent years have a positive effect on GWL. It was proven that restoration decreases fluctuation and increases GWL, which is essential for a natural evolution of a mountain peat bog. Tracer experiments detected biomat flow, shallow lateral subsurface flow and mostly deep percolation at the Podzol hillslope. At the organic peat bog biomat flow at short distances and mostly lateral pipe flow following decayed tree-root systems with long lateral subsurface flow distances were recognized. It can be stated that bogs in the studied basin represent separate hydrological units with their own typical runoff regime, which does not contribute to the discharge curve balancing (during both floods and droughts), and that their hydrological function in this mountainous area is insignificant.

Acknowledgements

This work was supported by the Grant Agency of the Czech Republic (grant number GA 13-32133S).

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Edited by Bülent Topcuoğlu and Metin Turan

Peatlands are formed in limited areas and have significant effects on our planet. As a result of their use peatlands are continually shrinking on a daily basis. This edited book, Peat, is intended to provide an overview of different perspectives of peat material in relevant disciplines. We hope that this book will contribute to the expectations and needs of all relevant disciplines that share their findings for future research.

Published in London, UK

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ISBN 978-1-83881-395-6