Food and Agriculture
Organization of the
United Nations

SUSTAINABLE
DEVELOPMENT
GOALS

Peatland mapping and monitoring

Recommendations and technical overview

Graphic, illustrations and layout: Lorenzo Catena

Peatland mapping and monitoring

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13 CLIMATE ACTION

15 LIFE ON LAND

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Contents

Boxes

Figures

Maps

Tables

Foreword

The world's leading peatland experts have come to a collective conclusion – comprehensive peatland mapping and monitoring are urgently needed. Peatlands have a great potential to influence global greenhouse gas emissions, and in this decade we need to take urgent and innovative actions to limit global warming to a maximum of 2 °C. In most cases worldwide, peatlands have been drained and degraded due to the lack of knowledge about their location, extent, benefits and potential for climate change mitigation and risk reduction. Current estimates suggest 11–15 percent of peatlands on Earth have been drained, and another 5–10 percent are degraded due to other changes such as removal or alteration of vegetation. These degrading peatlands consequently emit huge amounts of greenhouse gases that persist for years if not decades.

The scientific basis for mapping and monitoring peatlands has developed rapidly in recent years. Countries must take advantage of and consider adopting practical and innovative approaches and tools for peatland mapping and monitoring into national monitoring and reporting frameworks. Mapping and monitoring can be used to inform climate and biodiversity policies and commitments, as well as to continuously adapt peatland restoration efforts.

Peatland mapping and monitoring are both highly complex endeavours, but are key to understanding the real extent and location of these huge carbon stores and guide the course of action for ecosystem conservation and restoration during this decade and beyond. It is part of FAO's mandate to support developing countries with advancing the sustainable management of peatland landscapes, and develop national capacity for peatland mapping and monitoring, as well as to foster knowledge sharing and data generation. FAO's peatland network consists of dozens of experts and organizations with the shared mandate to jointly find solutions to conserve the carbon in the soil while fostering sustainable livelihoods and development. We recognize the important advances already made in the subject in temperate and boreal regions and stress the need for continuing monitoring of peatland status in tropical as well as in temperate and boreal regions.

"Peatlands mapping and monitoring: Recommendations and technical overview" is the result of 35 contributors from 14 countries and different organizations working together to provide examples, tools, methodologies and solutions to peatland mapping and monitoring challenges, especially in developing countries. These recommendations are an important step forward in guiding the world on the best ways to integrate peatlands into land monitoring systems to further facilitate the conservation and restoration of these unique ecosystems. I encourage you to take full advantage of the information included in this publication.


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Mette Wilkie

Mette Wilkie

Director
Forestry Policy and Resources Division,
Food and Agriculture Organization of the United Nations

Executive summary

Mapping peatlands is the basis for successful monitoring systems. Worldwide, innovative mapping approaches have facilitated the inclusion of peatland areas into sustainable land use management plans and conservation strategies. Monitoring changes in peatland ecosystems, be they natural, degraded, or in the process of restoration, is instrumental in maintaining peatland's water, species richness and carbon. Robust mapping processes offer a solid baseline for monitoring and help establish management objectives for specific peatland areas.

This report presents the peatland mapping methodologies commonly used – based on ground and remotely sensed input data. It also offers an overview of advantages and limitations of different monitoring approaches as a practical guide to facilitate decision-making and cater for country-specific requirements, in order to ensure that emissions and emission reductions are measurable, reportable and verifiable. It also provides information on other benefits from peatland conservation, restoration, rehabilitation and sustainable management. Country case studies present examples of current needs and recent achievements, in both mapping and monitoring. Suggestions for an architecture of peatland monitoring and how it could be organized within a country's institutions are also provided.

Global conventions and national policy frameworks recognize the importance of peatlands for protecting habitats and biodiversity, as large and vulnerable carbon stocks, and (when degraded) as globally important sources of greenhouse gas emissions. Countries should consider mapping, monitoring and reporting peatlands for national and international processes including general land use planning, nationally determined contributions to the Paris Climate Agreement, national adaptation plans, nationally appropriate mitigation actions, as well as fire risk reduction and other disaster risk reduction strategies. The national policy frameworks contribute to the achievement of international commitments, as well as helping to ensure better conditions for communities.

Countries, practitioners, researchers and technical agencies can use this report to identify mapping and monitoring needs, and define suitable approaches and tools to ultimately reflect peatlands into national land use monitoring systems, such as national forest monitoring systems. Soil carbon and emissions from soils have long been underestimated, and existing systems may also need to be adapted to fully integrate peatland considerations.

Keywords: greenhouse gas; peatlands; organic soils; monitoring; reporting; climate change; wetland; IPCC; remote sensing; Earth observation; data; water; plant; peat; UNFCCC; emission reduction

Peatland mapping and monitoring at a glance

Peatland mapping and monitoring require collection and measurement of different data types depending on the status of the peatland area. In pristine peatlands (Figure 1) information on natural characteristics is needed to monitor future changes, including potential climate change impacts that may lead to increased emissions and disaster risks.

If drainage is undertaken (Figure 2), peatlands generally become sources of greenhouse gas emissions, and additional parameters must be monitored to support corrective action and avoid continued degradation, and to contribute information to report for various conventions. Peatland restoration monitoring (Figure 3) can inform the design, strategy, selection of site and management approaches, and improve restoration efforts through technical adjustments.

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Figure 1 Data needed for peatland monitoring – Case 1: Pristine peatlands – no ongoing drainage

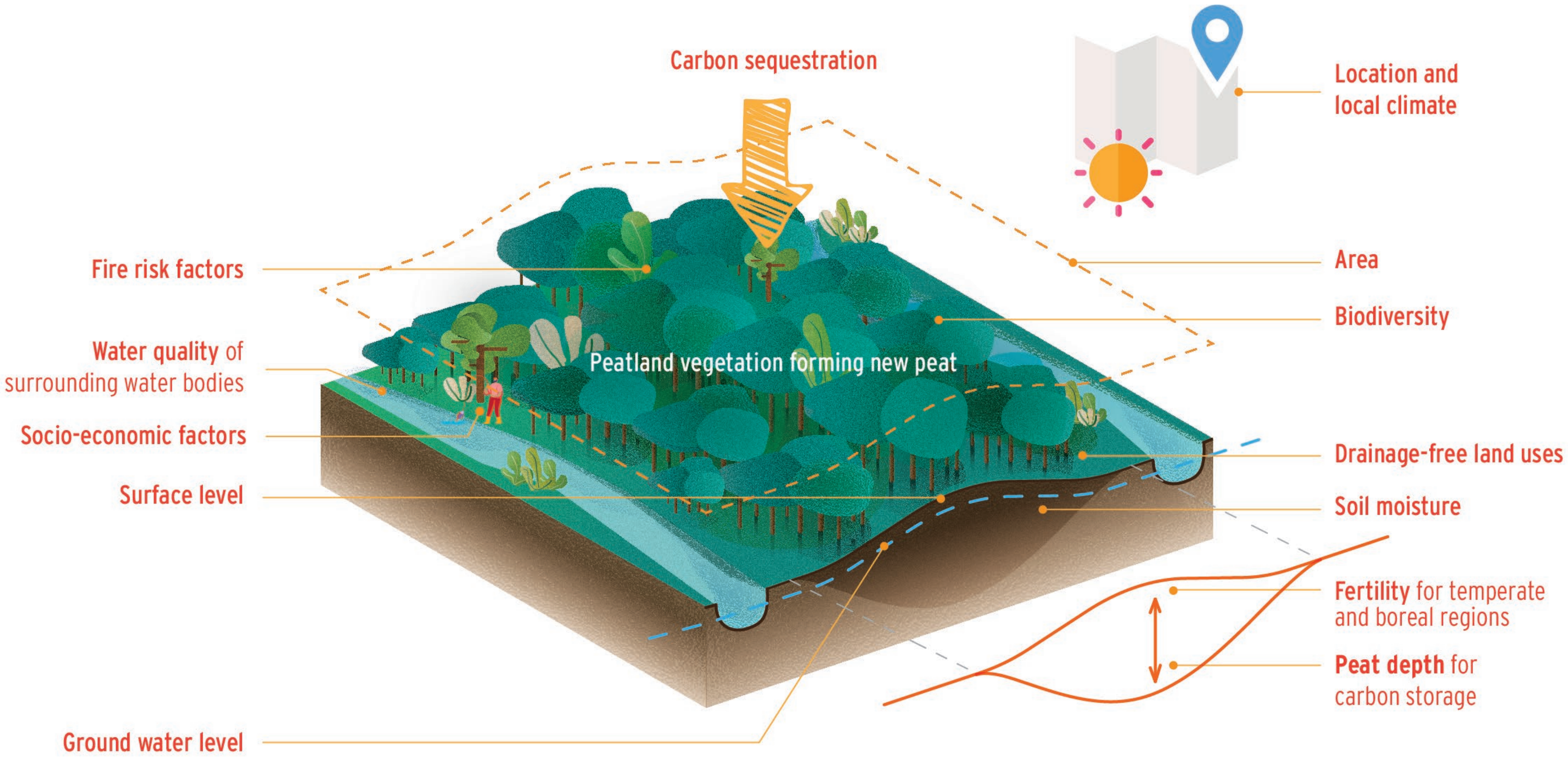


Figure 2

Data needed for peatland monitoring — Case 2: Drained peatland with canals

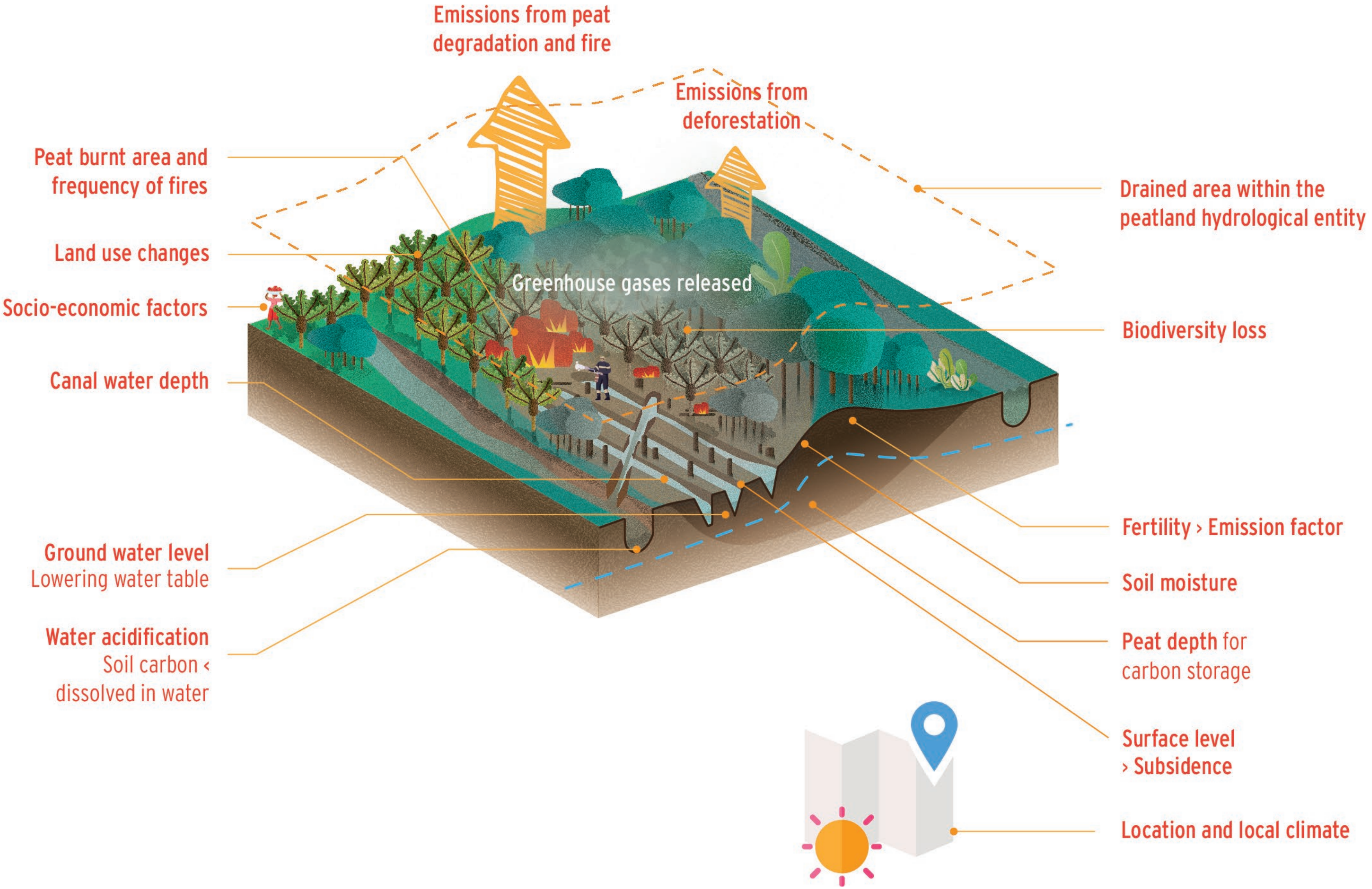
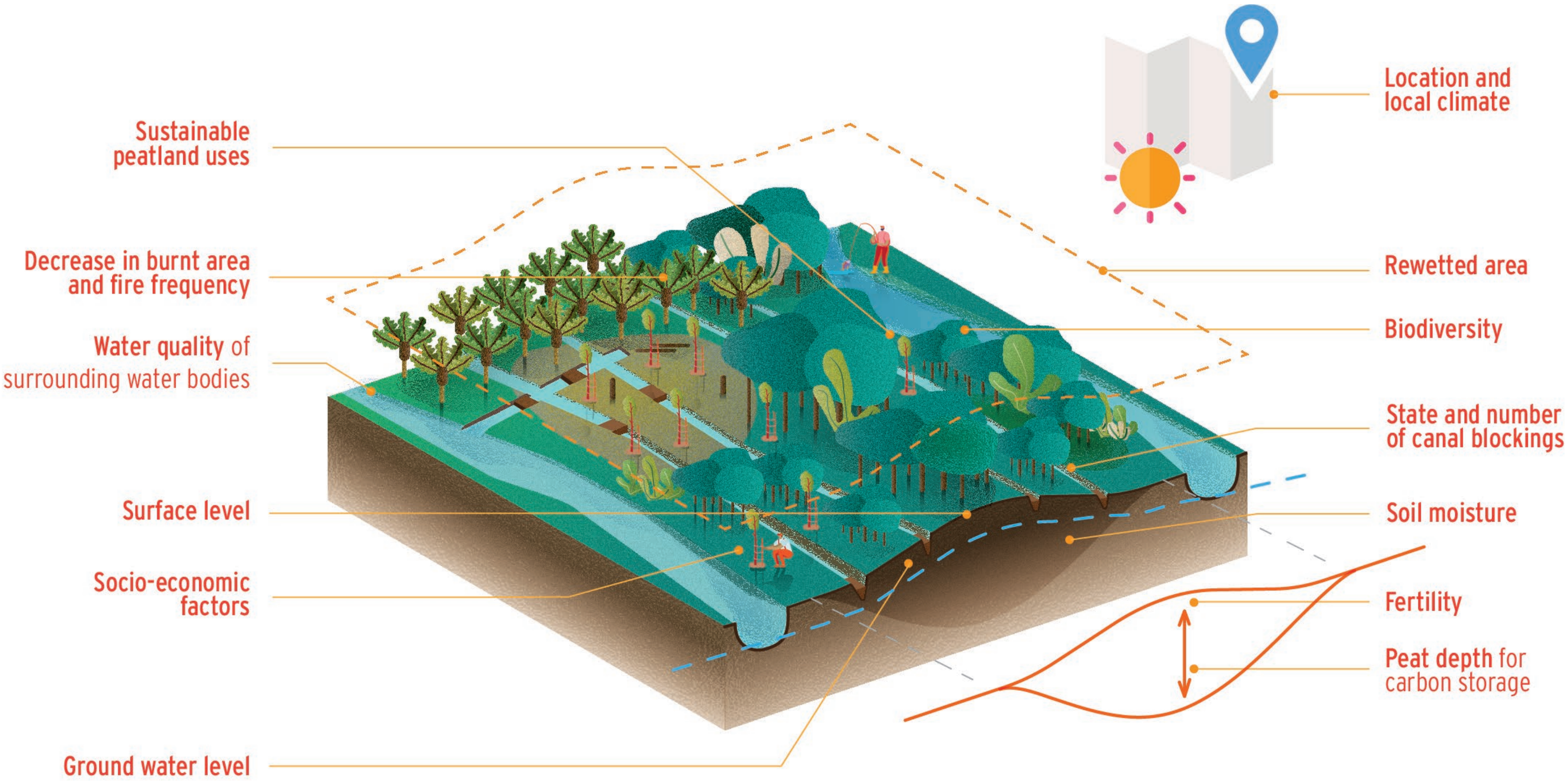


Figure 3 Data needed for peatland monitoring – Case 3: Restoration monitoring



Contributors

Jukka Alm	Natural Resources Institute Finland (Luke)
Muhammad Askary Masjkur	Ministry for Environment and Forestry, Indonesia
Bambang Arifatmi	Food and Agriculture Organization of the United Nations, Indonesia
Amélie Arquero	Food and Agriculture Organization of the United Nations, Democratic Republic of the Congo
Rebekka Artz	James Hutton Institute
Uwe Ballhorn	Freelance
Jean-Jacques Bambuta Boole	Ministry of Environment and Sustainable Development, Democratic Republic of the Congo
Felix Beer	Greifswald Mire Centre
Andrew Coupar	Scottish Natural Heritage
John Couwenberg	University of Greifswald, Greifswald Mire Centre
Ian Crosher	IUCN, Natural England
Rémi d'Annunzio	Food and Agriculture Organization of the United Nations
Chris Evans	UK Centre for Ecology and Hydrology
Julian Fox	Food and Agriculture Organization of the United Nations
Adam Gerrand	Food and Agriculture Organization of the United Nations, Indonesia
Emma Goodyear	IUCN UK Peatland Programme
Andrew Groom	CGI
Dirk Hoekman	SarVision
Aljosja Hooijer	Deltares
Hans Joosten	University of Greifswald, Greifswald Mire Centre
Erik Lindquist	Food and Agriculture Organization of the United Nations
Esther Mertens	Food and Agriculture Organization of the United Nations
Kai Milliken	Food and Agriculture Organization of the United Nations
Peter Moore	Food and Agriculture Organization of the United Nations
Daniel Murdiyarso	Centre for International Forestry Research (CIFOR)
Cleto Ndikumagenge	Food and Agriculture Organization of the United Nations, Democratic Republic of the Congo
Till Neef	Food and Agriculture Organization of the United Nations
Maria Nuutinen	Food and Agriculture Organization of the United Nations
Susan Page	University of Leicester
Marieke Sandker	Food and Agriculture Organization of the United Nations
Laure-Sophie Schiettecatte	Food and Agriculture Organization of the United Nations
Hesti Tata	FOERDIA, Ministry for Environment and Forestry, Indonesia
Pedro Raul Tinoco Rodriguez	Ministry of Environment, Peru
Ronald Vernimmen	Deltares
Laura Villegas	Food and Agriculture Organization of the United Nations
Albert Sulaiman	Indonesian Agency for the Assessment and Application of Technology (BPPT)

Abbreviations and acronyms

AFOLU	agriculture, forestry and other land use
AGB	aboveground biomass
ASEAN	Association of Southeast Asian Nations
BRG	Badan Restorasi Gambut (Peatland Restoration Agency of Indonesia)
C	Carbon
CBD	Convention on Biological Diversity
CIFOR	Centre for International Forestry Research
DOC	dissolved organic carbon
DRR	disaster risk reduction
EbA	ecosystem-based adaptation
ENSO	El Niño-Southern Oscillation
FLR	forest and landscape restoration
GFMC	Global Fire Monitoring Centre
GHG	greenhouse gas
GPI	Global Peatlands Initiative
GWFN	Global Wildlife Fire Network
GWL	ground water level
InSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LAPAN	Lembaga Penerbangan Dan Antariksa Nasional (National Institute of Aeronautics and Space of Indonesia)
LDN	Land degradation neutrality is a target defined under the UNCCD
LIDAR	Laser Imaging Detection and Ranging
MEAs	multilateral environmental agreements
MINAM	Ministerio del Ambiente (Peruvian Ministry of Environment)
MoEF	Indonesian Ministry of Environment and Forestry
MRV	measurement, reporting and verification
NAMA	Nationally Appropriate Mitigation Action
NAP	National Adaptation Plan
NDC	Nationally Determined Contribution to the Paris Climate Agreement under the UNFCCC
PRIMS	Indonesian Peatland Restoration Information and Monitoring System
RFMRC	Regional Fire Management Resource Centre (Indonesia)
RSPO	Roundtable on Sustainable Palm Oil
SDGs	Sustainable Development Goals
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SFDRR	Sendai Framework for Disaster Risk Reduction 2015-2030
UNFCCC	United Nations Framework Convention on Climate Change
UNCCD	United Nations Convention to Combat Desertification
VHR	very high resolution

Chemical formulae and units

CH_4	Methane
CO_2	Carbon dioxide
CO2eq	Carbon dioxide equivalent
Gt	gigatonne
N_2O	Nitrous oxide
Pg	petagram

Chapter 1

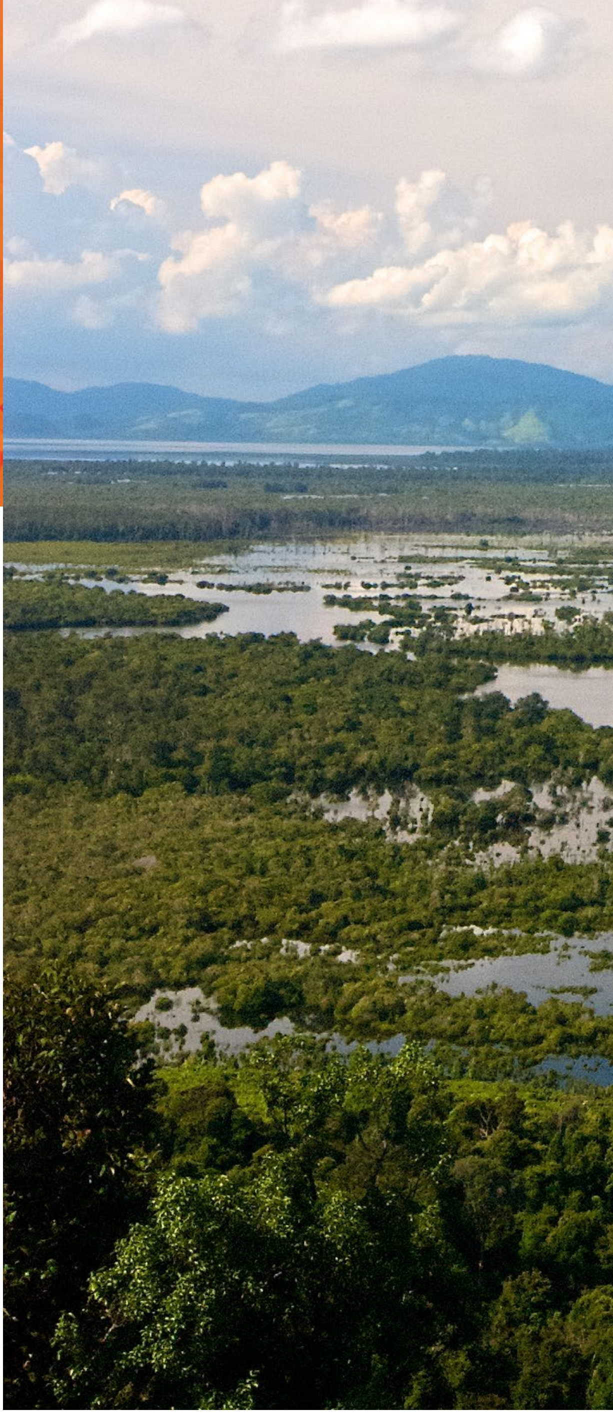
Introduction: why map and monitor peatlands?

by Susan Page

Chapter 1

Introduction: why map and monitor peatlands?

by **Susan Page**



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Peatlands, also called "organic soils", "bogs", "fens", "swamps" and "mires", are the world's most carbon-dense terrestrial ecosystems. Peatlands are formed from partially decomposed plant remains that have accumulated over thousands of years under conditions of waterlogging. Peat soils hold an estimated 650 billion tonnes (Gt = Pg) of carbon on only 3 percent of the Earth's land surface – a carbon store that is equal in magnitude to the amount of carbon in the Earth's vegetation, and more than half of the carbon in the atmosphere (Yu *et al.*, 2010; Page *et al.*, 2011; Dargie *et al.*, 2017). Peatlands thus play a critical role in the global carbon cycle and in climate regulation. However, peatlands also deliver a range of other benefits for humanity, including water regulation, flood control, food, and cultural and livelihood opportunities. They support a diversity of habitats and unique and rare plant and animal species. The layers of accumulated peat contain an archive of information on changes in climate, vegetation and human activity since the last Ice Age.

Peatlands are, however, highly vulnerable. Undisturbed peatlands are characterized by water levels that are close to the surface throughout the year. Near-constant waterlogging and the consequent lack of oxygen slows down decomposition by micro-organisms and, as a result, the organic material (peat) accumulates slowly over time. In northern peatlands, the accumulation of 1 m of peat may take over a thousand years, but as some peatlands have been accumulating over several millennia, they have reached depths of 5 m or more (Yu *et al.*, 2010). In the tropics, higher plant productivity has resulted in even deeper deposits – exceeding 15 m in some locations (Page *et al.*, 2011).

When the water table in a peatland is drawn down, for example to permit agriculture or forestry, oxygen enters the upper peat column. This facilitates microbial degradation (oxidation) of the peat and a rapid loss of stored carbon to the atmosphere, mainly in the form of the greenhouse gas (GHG) carbon dioxide (CO_2). Undamaged peatlands are usually net accumulators of carbon – i.e. more carbon is taken up via photosynthesis and carbon capture by the vegetation and peat than is lost from decomposition and subsequent release into the atmosphere. The capacity of intact peatlands to sequester carbon from the atmosphere and to store it over a long term is key to their role in climate change mitigation.

In drained peatlands, however, this role is reversed, with decomposition rates many orders of magnitude greater than in the absence of oxygen. Ongoing anthropogenic disturbance can therefore convert peatlands from slow carbon sinks and long-term stores to fast carbon sources, as carbon stored over millennia is released back into the atmosphere within a matter of decades. Understanding the location and scale of these disturbances is vital in supporting efforts to rehabilitate and restore peatland functions, including their role in climate change mitigation.

The most widespread drainage-based uses of peatlands today are for agriculture and forestry and, to a lesser degree, for peat extraction. Although enormous extents of peatlands in North America and the Russian Federation are still intact, around 20–25 percent of the world's peatlands have been moderately or significantly degraded through disturbances to their hydrology and vegetation, especially in Europe, Central and Southeast Asia, East Africa, southernmost America and the Amazon. Globally, the most widespread uses of peatland today are for forestry and agriculture, amounting to an estimated total area in excess of 1 million km^2 (Joosten and Clarke, 2002) and possibly exceeding this area if peatland used as pasture for extensive livestock grazing is also included (FAO, 2014). (See also: Leifeld, J., *et al.* 2019.) Some of the most rapid and extensive land use changes have taken place recently in Southeast Asia as a result of land conversion to large-scale plantations or smaller-scale agriculture. Around the world, peatland drainage and associated peat fires are estimated to be responsible for approximately 5 percent of anthropogenic CO_2 emissions (IPCC, 2014b). Next to the globally significant emissions, important local and regional impacts of peatland drainage include increased risk of peat fires and haze, which cause severe impacts on human health – for example, the peatland fires in Southeast Asia and the boreal zone during 2019 – and of flooding (due to land subsidence caused by peat compaction and oxidation).

At global and national levels, peatlands receive growing recognition and are integral to a number of national and international conventions and policies aimed at protecting habitats, biodiversity and carbon stocks, and reducing GHG emissions.

The most relevant conventions are:

- **The United Nations Framework Convention on Climate Change** (UNFCCC) includes peatlands (organic soils) in its Kyoto Protocol, the Paris Climate Agreement, and national GHG reporting and accounting. The Intergovernmental Panel on Climate Change (IPCC) gives technical recommendations to the UNFCCC, and has produced guidance on reporting on GHG emissions from drained, rewetted and burning organic soils. Reporting has to follow the principle of transparency with respect to measurement, reporting and verification (MRV).
- **The Convention on Biological Diversity** (CBD) requires in its Aichi Targets the conservation and restoration of peatlands, highlighting their role in mitigating and adapting to climate change, as well as supporting rare and threatened wildlife.
- **The Ramsar Convention on Wetlands** has passed several resolutions and recommendations on peatland conservation, wise use and climate change.
- **The United Nations Convention to Combat Desertification** (UNCCD) acknowledges peatlands as an important component of land use planning and integral to the climate change agenda, because of their carbon storage and the opportunity their restoration offers for reducing GHG emissions (UNCCD, 2015) and achieving part of the land degradation neutrality (LDN) target.

A growing number of international agencies and initiatives also underline and support improving management, including the conservation and restoration of peatlands:

- **The United Nations Environment Programme**, leading the global environment agenda, and the Food and Agriculture Organization of the United Nations (FAO) have recently been asked to lead the implementation of the 2021–2030 UN Decade on Ecosystem Restoration as a measure to fight the climate crisis and enhance food security, water supply and biodiversity. The Decade covers all ecosystems, but focuses on terrestrial, freshwater (including peatlands) and mangrove systems (UN, 2019a).
- **FAO** is a technical agency of the United Nations supporting countries to improve the sustainability of cropland, livestock, forestry, fisheries and aquaculture management, including support to reduce GHG emissions and avoid losses of other ecosystem services caused by unsustainable peatlands management. FAO provides tools and guidance for peatland monitoring and development of sustainable livelihood sources from peatland landscapes.
- **The International Union for Conservation of Nature** (IUCN) passed a resolution, "Securing the future for global peatlands", at the 2016 World Conservation Congress, calling for action to protect, restore and sustainably manage peatlands (IUCN, 2016).
- **The Bonn Challenge** is a global effort to bring 150 million ha of degraded and deforested land into restoration. By 2020 and 350 million ha by 2030. The initiative, launched by an international coalition in 2011, also encourages the restoration of peatlands.
- Within Europe, **the EU Habitats Directive** includes peatland ecosystems as priorities for conservation and restoration, while the European Climate Change Programme requires most peatlands and organic soils in Member States to be accounted for by 2020.

UNFCCC has particularly important implications for peatlands because countries have to account for GHG emissions associated with peatland use, such as from forestry, agriculture and extraction, in their national inventory submissions under the Kyoto Protocol.

Building on these international agreements and policy initiatives, various countries have taken steps to conserve and protect their peatlands, and restore degraded sites. Successful results depend on robust and user-friendly assessment and monitoring methodologies to identify and better understand the changes and impact of activities in both pristine and particularly valuable peatlands, as well as in degraded sites. Effective peatland mapping and monitoring would enable users to:

- locate peat deposits to more accurately assess peatland area and carbon stock, including remote and inaccessible sites;
- obtain information on the peatland condition (i.e. intact or degraded, and the extent, type and likely causes of degradation), in order to identify areas at risk of degradation or in need of restoration;

- formulate appropriate action plans, including law enforcement, rehabilitation or restoration; and
- monitor the success of management interventions and allow corrective action if targets are not being met.

Mapping of peatland occurrence is a prerequisite for monitoring peatland change. Maps of peat location, extent and condition are required to monitor potential conflicting land use activities (such as agriculture or forestry, infrastructure development or extraction). The location of drainage canals or ditches, logging tracks and roads is required in order to identify current and incipient threats. Moreover, historical examples of fire occurrence are also useful indicators for anticipating additional threats and emissions.

Peatland monitoring methods will differ, depending for example on the extent of the peatland, the nature of any human disturbances, planned restoration interventions, required resolution, objectives, accessibility, available resources, and target environmental parameters. The ideal approach would ensure that emissions and emission reductions are measurable, reportable and verifiable, while also providing information on the delivery of other peatland ecosystem services in order to fulfil the reporting requirements to other conventions and the overlying United Nations Sustainable Development Goals (SDGs, see Chapter 5). Ideally, peatland monitoring will form part of national land monitoring and reporting system(s) and build on them.

Sound methodologies are needed in the collection and collation of key indices that allow the assessment, through widely recognized proxies, of peatland hydrological function and carbon loss. This will require robust, accessible supporting assessments and monitoring methodologies, for the identification of both pristine and particularly valuable peatlands and of degraded sites, which should be targeted for management interventions. The value of peatlands can be defined as water provision and storage, flood control, carbon storage, biodiversity and other ecosystem services.

Especially at the early stages of mapping, remote-sensing approaches need to be combined with on-site measurements of, for example, GHG emissions, peat subsidence, ground water level (GWL), soil moisture, vegetation cover and diversity, in order to calibrate and validate the remote-sensing results. On-site measurements - or "ground-truthing" - of remote-sensing approaches offer opportunities as well as technical challenges. The main challenge is to obtain on-site high-quality measurements across satisfactory temporal and spatial scales (encompassing different site conditions, diurnal, seasonal and annual variability), which may require substantial financial and technical resources.

The case studies show that some countries have already applied various peatland mapping and monitoring approaches, although these are rarely sufficiently comprehensive. Others have developed some elements but need technical support and capacity-building to set up and integrate peatlands into national systems. Effective peatland mapping and monitoring will probably combine contemporary remote-sensing techniques with the necessary ground-truthing and field measurements. For example, established remote-sensing techniques can be used to assess land cover, land use and vegetation condition at landscape scale, whereas newer developments may allow the monitoring of GWL and soil moisture (a proxy measure for water level and GHG emissions) as well as peatland subsidence (a proxy for water level and carbon loss).

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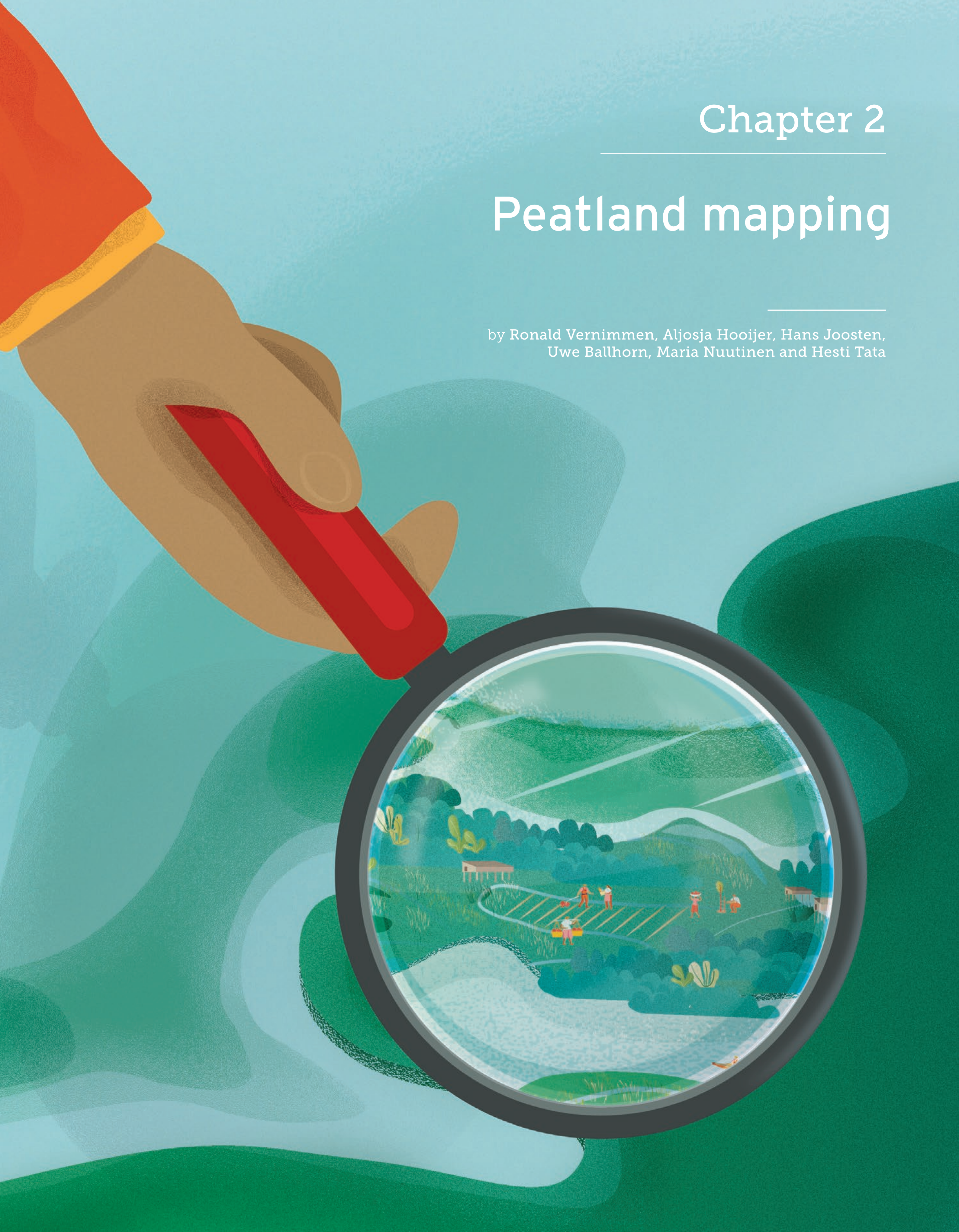
Chapter 2

Peatland mapping

by Ronald Vernimmen, Aljosja Hooijer, Hans Joosten,
Uwe Ballhorn, Maria Nuutinen and Hesti Tata



Chapter 2

Peatland mapping

by Ronald Vernimmen, Aljosja Hooijer,
Hans Joosten, Uwe Ballhorn, Maria Nuutinen
and Hesti Tata

Mapping of peatlands has been addressed with many different methodologies, and detailed guidelines are available for a variety of locations (e.g. Barthelmes, Ballhorn and Couwenberg, 2015; Bourgeau-Chavez *et al*., 2018; Gumbricht *et al*., 2017) Peatlands are formed in different climatic zones, and thus hold several vegetation types and occur in different ecosystem settings. In tropical climates, for example, they might occur in mangroves and peat swamp forests, while in subtropical and warm temperate climates most have reed or sedge vegetation, and in boreal, cool temperate, subarctic and arctic regions most are dominated by mosses (Gumbricht, 2012; Prager, Barthelmes and Joosten, 2006). Consequently, approaches to mapping need to vary depending on ecologic and landscape features, and the availability of information to define the occurrence of peatlands and peat soils. A combination of various ecologic and landscape variables - as well as expert analyses - is used to identify probable peatlands, and produce detailed peatland maps.

Prior to defining monitoring needs, baseline maps are required to identify the peat location and the historic and current land cover and land use characteristics. It is recommended to incorporate an internationally recognized definition of peatland for mapping (see e.g. Box 1, Box 2, and the Chapter 8. Recommendations). Knowing the location of drainage canals or ditches, logging tracks, roads, and preferably local livelihood sources (e.g. hunting, fishing, gathering non-timber products, irrigation with water extracted from peatlands, peat extraction) helps to identify current and future threats and processes affecting and/or protecting peatlands. Historical fire occurrence is also a useful indicator for further threats given that once-burnt areas burn more easily again. Maps of legal status and concession extents, together with potential spatial and other land use plans, are recommended to be integrated into the maps to identify and avoid potential issues and future threats.

This chapter presents the main components for peatland mapping and delineation, which correspond to the essential monitoring parameters discussed in the following chapters. Also, the data sources listed here - focused on remote-sensing techniques - are intended to build upon the field and secondary data already available in different countries, and the data sources usually considered in peatland mapping exercises. Bearing in mind the key features for peatland delineation and mapping, countries are encouraged to design their mapping methodologies and adapt them to their specific needs, goals, information availability and landscape features. Mapping activities are necessary to integrate peatlands into productive and conservation planning.

BACKGROUND

Key features of peatland delineation

Comprehensive field-based information on the extent of peatlands is often lacking, particularly in the case of inaccessible tropical peatlands. In such cases, the combined use of remote sensing and field measurements may provide comprehensive peatland distribution maps with reasonable accuracy and quantifiable uncertainties. Lawson *et al*. (2014) identified four features, detectable with the help of remote sensing, which distinguish pristine peatlands (especially tropical peatlands) from surrounding non-peat ecosystems:

- low vegetation species richness;
- distinctive vegetation structure;
- distinctive topography; and
- high water tables.

Pristine peatlands often have a lower vegetation diversity compared with surrounding ecosystems. For example, within the peatlands of South and Central America, some parts of Africa, and on the island of New Guinea, palms are often more dominant than in upland forests, and even sometimes occur as mono-dominant stands. However, in some peatland forests vegetation diversity can also be high (Brady, 1997; Rieley and Page, 2005). As low vegetation species richness cannot be directly detected with remote-sensing systems, distinctive vegetation structure acts as proxy.

The vegetation structure of pristine peatlands is very often (but not always) distinct from that of surrounding vegetation. For example, tropical low-pole peat swamp forests are characterized by more open canopies, low canopy height with thin stems, and high stem density, or no trees at all (Anderson, 1983; Ballhorn, Jubanski and Siegert, 2011; Jaenicke *et al.*, 2008; Lawson *et al.*, 2014; Page *et al.*, 1999; Phillips, Rouse and Bustin, 1997).

Most peatlands occupy a specific topographic or geological setting, such as coastal peatlands in Southeast Asia, subsiding basins, dendritic drainage river networks (many contributing streams), etc. Furthermore, many peatlands, such as Indonesia's tropical peatlands, are dome-shaped and can be detected by elevation data (e.g. Ballhorn, Jubanski and Siegert, 2011; Jaenicke *et al.*, 2008; Lähteenoja *et al.*, 2009; Phillips, Rouse and Bustin, 1997).

Water tables in undrained peatlands lie close to or above the surface throughout the year but can be also subject to natural fluctuation of several decimetres depending on the season - wet or dry.

Low vegetation species richness, distinctive vegetation structure, and topography can directly be detected through remote sensing. Whereas any of these features alone would not be sufficient to definitely detect peatlands, a combination of two or more often leads to much clearer results (Draper *et al.*, 2014). As all key features related to vegetation and high water tables are immediately altered through vegetation clearance and drainage, it is crucial to assess historical remote-sensing data. Finally, all approaches based on remote sensing need a satisfactory set of field data - such as soil sampling - to validate the mapping results.

Box 1

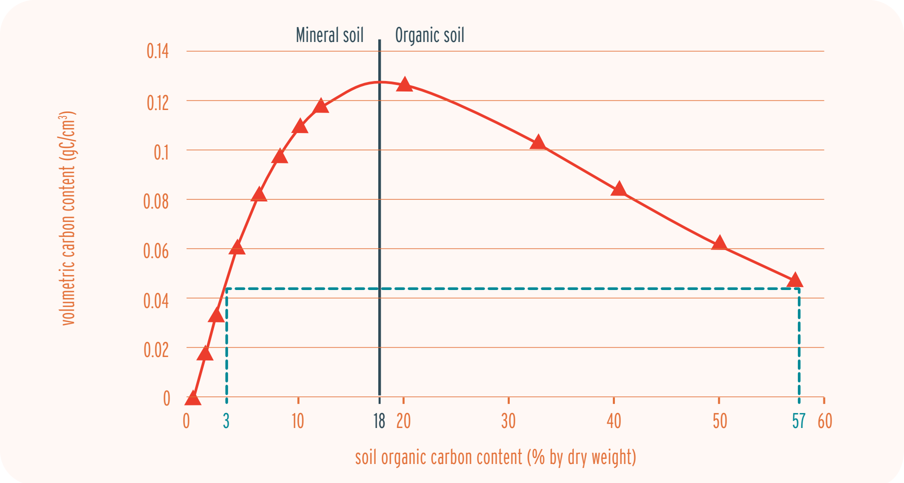
How much soil organic carbon defines peat?

The proportion of organic matter that a soil layer must hold to be called "peat", varies greatly among countries and disciplines. In soil science, peat soils are included in "organic soils", which are distinguished from "mineral soils" based on the dry weight percentage of organic carbon (gram of carbon per gram of soil x 100). The vertical solid line in Figure 4 denotes 18 percent carbon content by weight, which is the threshold above which soil is called "organic". This boundary varies between 12 and 18 percent depending on the proportion of clay in the soil. However, this boundary is not very appropriate from the climate point of view, because the percentage reveals little about the volumetric carbon content (g/cm^3), i.e. the amount of soil carbon that upon drainage is exposed to oxygen and that can thus be emitted as CO_2.

Pure peat has a high percentage of carbon by weight (approx. 57 percent), but a low volumetric carbon content (Warren *et al.* 2012; Roßkopf *et al.* 2015). In comparison, mineral soil weighs much more and with three percent of carbon by weight can have just as much carbon per volume (Figure 4, based on Ruehlmann & Körschens 2009). After drainage, both soils emit the same amount of CO_2. The traditional definition of a peat soil based on 18 percent carbon content by weight or higher is thus problematic as many soils with lower carbon content – but equal or higher emission potential – can be overlooked by such standard country definitions.

Figure 4

Volumetric carbon content vs carbon by dry weight in soils in percentages



Source: based on Ruehlmann & Körschens, 2009

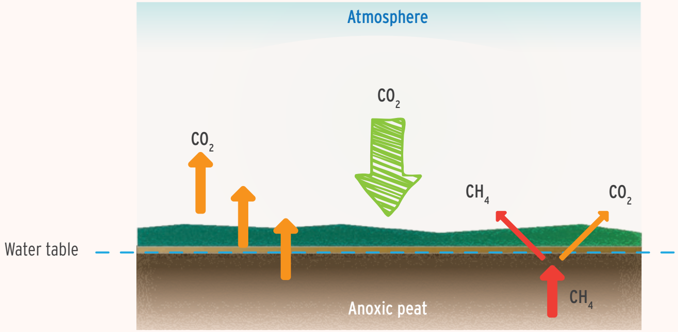
Box 2

Greenhouse gas emissions from peatland drainage and fires

In a pristine peatland, a high water table maintains the anoxic conditions of the peat and the peatland is a net CO_2 sink (Figure 5). When a peatland is drained and water is no longer present in the soil pores, oxygen enters and oxidizes the peat through biological and chemical processes. Drainage also increases the risk of fire. As a result of biological oxidation carbon is lost to the atmosphere, mainly as CO_2 (Figure 6), and as a result of peat fires, a combination of various gases including CO_2, CO and methane (CH_4) is emitted. Climate and temperature, as well as GWL, have a clear influence on the rate of peatland CO_2 emissions. Both drainage and fire also cause enhanced discharge of carbon as dissolved organic carbon (DOC) and particulate organic carbon (POC) into downstream aquatic ecosystems. Due to losses of organic matter, the peatland surface subsides, and this subsidence can be measured and used as an indicator of carbon losses. CH_4 emissions are also generated in ditches and canals, where plant materials and peat detritus flushed from the land accumulate and decompose under anaerobic conditions.

Figure 5

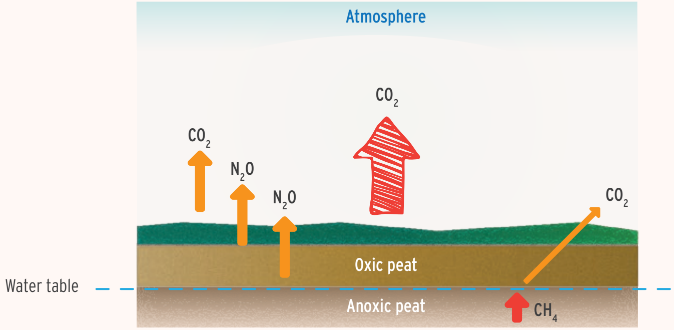
Carbon dynamic in an undrained peatland



Source: Renou-Wilson *et al.*, 2011

Figure 6

Carbon dynamic in a drained peatland



Source: Renou-Wilson *et al.*, 2011

Non-carbon GHG emissions, mainly nitrous oxide (N_2O) from drained peatlands are a consequence of the mineralization of nitrogen compounds during peat decomposition and are further enhanced by applications of mineral and organic nitrogen fertilizers. Nitrous oxide is an important GHG as it has a global warming potential of 310 times higher than that of CO_2 over a 100-year time horizon (FAO, 2014).

Remote sensing mapping and data sources

In addition to the secondary and field data used in previously developed mapping methodologies, remote sensors have been widely used for peatland identification. Main types are high-resolution optical sensors and radar satellite systems, which differ in the way they function and offer information.

High-resolution optical sensors

Optical remote sensing makes use of visible, near-infrared and short-wave infrared sensors to form images of the Earth's surface by detecting the solar radiation reflected from targets on the ground. Freely available optical imagery from high-resolution satellite sensors (with resolution of 10–30 m; e.g. Landsat, Sentinel-2, etc.) has been primarily used to map peatlands (e.g. Lähteenoja and Page, 2011; Langner, Miettinen and Siegert, 2007; Miettinen and Liew, 2010; Phua *et al.*, 2007; Wahyunto, Heryanto and Widiastuti, 2006; Wahyunto, Ritung and Subagjo, 2003, 2004; Wijedasa *et al.*, 2012). The new generation of very high resolution (VHR) multispectral imagery (with resolution of ≤10 m; e.g. SkySat [Planet: 0.72 m], Doves [Planet: 3 m], WorldView [2 m], IKONOS [4 m], RapidEye [5 m]), and others might considerably enhance future peatland delineation. However, as these are commercial operations, they come at a price and may not be accessible to developing countries.

Optical sensors are limited by weather conditions and rely upon solar illumination or thermal radiation. To compensate for frequent cloud cover, especially in the tropics, satellite imagery with high temporal resolution should be used (e.g. Sentinel-2).

Radar satellite systems

Radar remote sensing from space has developed greatly over recent decades, in parallel with the development of radar sensors, but also with developments in space technology, computing capacity, image processing techniques and physical understanding of the interaction of radar waves with the terrain. Radar-based satellites are not affected by weather conditions and can penetrate clouds and, to some degree, vegetation.

In 1978, NASA launched SEASAT, equipped with the first space-borne synthetic aperture radar (SAR). This radar satellite used the so-called L-band wavelength of ± 25 cm. Radar wavelengths are much larger than wavelengths used for optical systems and have the capability to penetrate clouds, mist and rain. Moreover, radar is an active system, which means it has its own source of illumination and is independent of solar illumination, allowing imaging radar to observe 24 hours per day, each day of the year.

Besides L-band radar, other radar systems with shorter wavelengths exist, such as C-band and X-band radar (Table 1).

Table 1 **Remote sensing tools and their characteristics, useful for peatland mapping**

Satellites / sensors	Country	Period of operation	Band	Wave-length (cm)	Polarisation	Spatial resolution (m)	Orbital repeat (days)
ALOS / PALSAR	Japan	2006–2011	L	23.6	Single, Dual, Quad	10–100	46
ALOS-2 / PALSAR-2	Japan	2014–present	L	23.8	Single, Dual, Quad	1–100	14
NISAR	NASA, India	Start in 2021	L	23.8	Single, Dual, Quad	3–10	12
Sentinel-1	Europe	2014–present	C	5.6	Single, Dual, Quad	W–20	12 (6)
RADARSAT Constellation	Canada	2019–present	C	5.6	Single, Dual, Quad	1–100	12 (4)
TerraSAR-X TanDEM-X	Germany	2007–present 2010–present	X	3.1	Single, Dual	1-16	11
PAZ	Spain	2019–present	X	3.1	Single, Dual	1–16	11
COSMO-SkyMed	Italy	2007–present	X	3.1	Single, Dual	1–100	16

The longer the wavelength, the deeper the waves penetrate the forest canopy. L-band radar reflections are mainly caused by trunks and large branches, while the shorter C- and X-band radar are mainly reflected by the leaves of the upper canopy, which means they can help to observe peatland soil moisture only where there are no trees. Radar systems with short waves also have higher spatial resolution. This makes L-band radar more suitable for land cover and forest biomass monitoring, while X-band radar is better for detecting disturbances in the forest canopy at tree level.

Radar systems also differ in the polarization(s) of the waves used. There are systems with single polarization, dual polarization and full (quad) polarization. More polarizations allow better distinction between different types of land cover (Table 1).

Radar satellites are designed with specific applications in mind. The Japanese L-band systems PALSAR-1 and PALSAR-2 cover the entire world systematically, building large archives for the study of continental-scale land cover change and wetland dynamics. The European Sentinal-1 mission utilizes two identical satellites to provide free data at 20 m resolution. The systematic acquisition is done with an observation interval of six or 12 days, depending on geographic location. This interval will be improved into six days in the near future. The X-band satellites TerraSAR-X and COSMO-SkyMed provide images with much higher resolution but these images cover smaller areas. They are typically used where high or very high resolution is required (see also Lucas *et al.*, 2012; GOFC-GOLD, 2013; 2015; GFOI, 2013).

A multisensory[1] and iterative[2] approach that includes historical remote sensing (see next section) and field data is recommended[3]. This approach can be split into three phases: Phase 1 for collection and processing of input data; Phase 2 for peatland mapping (including peatland delineation and peat thickness modelling); and Phase 3 for possible interventions and restoration mapping. These phases are described below.

---

[1] Use of multiple remote sensing systems (including passive and active sensors) in combination (Lawson *et al.,* 2014).

[2] Peatland mapping based on remote sensing is an iterative process in which different sensor types are used (multisensory approach). The interpreter conducting the peatland mapping should preferably have a background in peatland ecology, local knowledge of the area of interest, and a profound understanding of the different remote sensing systems applied.

[3] As with every remote sensing approach, peatland distribution derived from remote sensing must be validated using *in situ* data.

Box 3

Definition of peat and peatland by the IPCC

There are no IPCC definitions for peat and peatland. In the IPCC 2013 Wetlands Supplement, the concept of peatland is considered to be included in "(land with) organic soil". The Supplement follows the definition of organic soils in the 2006 IPCC Guidelines (Annex 3A.5, Chapter 3 in Volume 4):

"Organic soils are identified on the basis of criteria 1 and 2, or 1 and 3, as listed below (FAO, 1998):

- *Thickness of organic horizon greater than or equal to 10 cm. A horizon of less than 20 cm must have 12 percent or more organic carbon when mixed to a depth of 20 cm.*
- *Soils that are never saturated with water for more than a few days must contain more than 20 percent organic carbon by weight (i.e. about 35 percent organic matter).*
- *Soils are subject to water saturation episodes and have either:*
    a. *at least 12 percent organic carbon by weight (i.e. about 20 percent organic matter) if the soil has no clay; or*
    b. *at least 18 percent organic carbon by weight (i.e. about 30 percent organic matter) if the soil has 60 percent or more clay; or*
    c. *an intermediate proportional amount of organic carbon for intermediate amounts of clay."*

According to the IPCC 2013 Wetlands Supplement, it is "good practice" that, when a country uses another definition of organic soil in accordance with its national circumstances, the concept of organic soil (and its possible subdivisions) applied is clearly defined, and that the definition is applied consistently across the entire national land area and over time. Research is continuously contributing to the harmonisation of definitions, however, further research is needed to clarify concepts for different applications. Establishing a national definition for peat and minimum thickness to define a peatland is a crucial step in the definition of mapping methodologies.

Types of radar data

Different types of radar input data are beneficial for peatland mapping:

L-band data: the Japanese Space Agency JAXA acquired large archives of L-band data during the JERS-1 mission (1992–1998) and the PALSAR-1 mission (2006–2011). These data are available free of charge. For data from the current PALSAR-2 mission (from 2014 to the present), this is not (yet) the case. In the near future, free L-band data from the NISAR mission is expected to become available, with systematic coverage at high resolution (10 m), every 12 days.

C-band data: two C-band radar satellite constellations are currently operational. Both provide free data. The European Sentinel-1 covers the land surface regions systematically using one satellite (every 12 days) or combining both satellites, to reduce the observation interval to six days. The RADARSAT, with three satellites, can reduce the revisiting time to four days.

X-band data: the X-band missions (see Table 1) provide very high resolution, but cannot do this systematically. Acquisitions must be planned and are not free of charge.

PHASE 1: COLLECTION AND PROCESSING OF INPUT DATA

The following data should be considered in the course of mapping peatlands during the desktop study phase.

Historical and legal data

Many peatlands have a history of degradation, so are difficult to map with recent remote sensing data. In such cases, peat extent should be delineated from historical optical satellite imagery (e.g. Landsat archive) by interpreting historic drainage and vegetation patterns.

Historical land cover and land use maps may help to interpret historical satellite imagery. In cases where no local historical data on land cover and land use are available, global or regional land (and forest) cover and land use data may be considered as an alternative (e.g. Arino *et al.*, 2008; Bartholomé and Belward, 2005; Friedl *et al.*, 2010; Hansen *et al.*, 2000).

When using global maps and other data, find out the source of the global product and which data have been used to validate it, as this may have been done in a completely different area or climatic region than the country or region of interest, and as such may have a low accuracy. Regional land cover and land use data (e.g. Margono *et al.*, 2014; Miettinen, Shi and Liew, 2016) will probably be more accurate but should also be cross-checked against other data.

The legal status of land is registered in the cadastre of most countries. Spatial plans issued by the government provide information on what type of activity is planned or allowed, for example whether the land is designated as a conservation area, national park, or under a concession.

Current land cover, land use and changes

With the Sentinel satellite constellation with its unprecedented temporal (six days) and spatial (10–20 m) resolution in operation since late 2014, automatic land cover mapping is rapidly starting to become the standard at low cost, especially when utilizing the power of cloud computing platforms [e.g. FAO SEPAL (see Box 7), Copernicus Data and Access Information Services (e.g. Mundi Web Services), Google Earth Engine (Gorelick *et al*., 2017)] which contain much of the common satellite imagery as well as frequently used classification algorithms such as classification and regression trees, random forest (RF), and support vector machines. VHR satellite imagery may be used to delineate reference datasets to train these algorithms, reducing the need for field measurements and consequent cost and time. The quality of the maps depends on the ability to create a sufficiently cloud-free composite image, which may require at least a year of observations.

Once a good land cover or land use map has been created, disturbances can be monitored at regular intervals. Drainage canals or ditches, logging tracks and roads can be manually digitized from VHR (≤10 m) resolution optical imagery. Larger canals and logging tracks can be delineated from high resolution (10–30 m) Sentinel-2 and Landsat imagery, for example using the FAO Open Foris suite.

Elevation model

As peatlands develop under long-term water saturation of the soil, they are found in areas where large amounts of water are available (e.g. coastal environments) or flowing (e.g. depressions, rivers). Elevation models are useful to identify these hydrological landscape units. Further, elevation data help to identify the location of peat domes and to interpret the peat (dome) morphology, which is useful when designing field surveys (see next section). It is, however, important to recognize the limitations of elevation models in detecting peatlands that are not dome-shaped. The still frequently used shuttle radar topography mission (SRTM) data, collected in 2000, provide a surface elevation model – not a terrain model – as they include vegetation height. Furthermore, SRTM data are referenced to the geoid and not to local mean sea level (MSL).

Peat depth

Peat thickness, together with its carbon content, determines the carbon stock in a vertical peat column, and the potential duration of GHG emissions if this particular peatland is drained. Peat depth distribution data are therefore needed to understand the full carbon stock in a peatland landscape (Parry and Charman, 2013), which can be taken into account for land use planning and management. In many countries, peat depth is one of the key criteria, which defines an area as a peatland, and determines whether it can be converted or not. However, peat depth can vary considerably within and between peatlands, and they emit GHGs as long as the peat is exposed to air. Therefore, the depth of a peatland affects the potential period and total amount for GHGs. There is a considerable lack of peat depth data at local, national and global scales (Parry, Charman and Noades, 2012).

Peat depth strongly depends on the relief of the underlying material (such as rock, sand, clay). This presents a challenge to modelling and usually requires field measurements to establish an accurate estimate of peat carbon stocks. In case of limited resources, therefore, the assessment of peatland extent and status (drainage; plantation; and other activity data) should be prioritized, the more so because emissions depend mainly on the area affected by degradation (oxidation, erosion, fire), and much less on total peat depth.

Peat depth can be measured by (i) manual probing with a peat corer or metal rod to record the probable depth, and (ii) ground penetrating radar (GPR). In the field, manual augers or corers are used for measuring, as shown in Figure 7. Field surveys are recommended to be carried out along transects perpendicular to rivers. A detailed protocol as well as an approach to field survey design for an effective and cost-efficient peat thickness survey has been proposed (Vernimmen *et al.*, 2017, 2018). GPR is a non-invasive geophysical technique that uses radar pulses to image the subsurface base layer of peat (Parry *et al.*, 2014). A GPR unit consists mainly of transmitting and receiving antennas, a control unit and a display. The transmitting antenna produces short-pulse electromagnetic waves that penetrate the belowground substrate and will be reflected or scattered back to the receiving antenna over time. GPR has been applied successfully to the measurement of peat depth (see e.g. Lowry, Fratta and Anderson, 2009; Mellett, 1995; Murdiyarso *et al.*, 2017).

Where an accurate elevation model is available, peat thickness can be determined by identifying the peat bottom position that is the interface between the peat and the underlying mineral sediment, i.e. the difference between the peat surface and depth of the peat bottom. This is further illustrated in Figure 8, and examples are provided in Vernimmen *et al.* (2017, 2018). Belowground carbon stock of the peat can also be determined (see Key features of peatland delineation p.8). Peat samples at different depths can be taken at the same time as the peat thickness measurement, to determine carbon content and bulk density in the laboratory.

Figure 7 **Manual auger used for peat sampling in the field**

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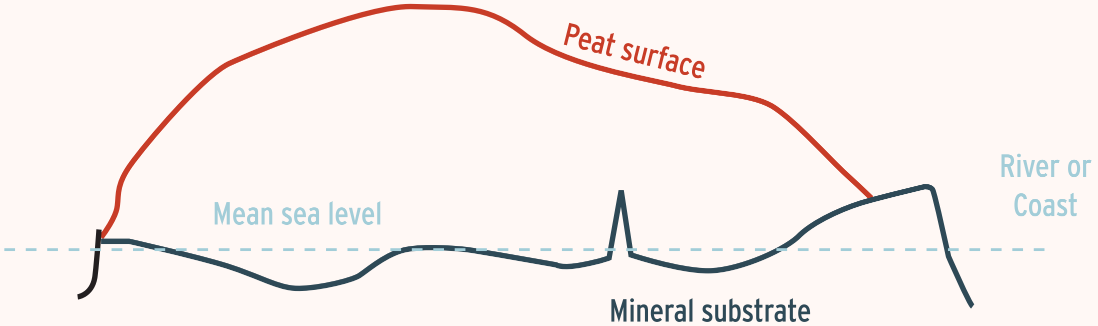
Figure 8 **How to determine total peat thickness in a domed peatland**



Source: Deltares 2017

© UN-REDD

Historical fire occurrence and burnt areas

Fires have been monitored routinely from space by the MODIS Aqua and Terra satellites since late 2000 and these data are freely available (Giglio *et al.*, 2003; Justice *et al.*, 2002; Kaufman *et al.*, 1998). Several data products exist including a burnt-area product derived from these satellite data (Giglio *et al.*, 2018). The MODIS hotspot data represent areas of 1 km^2 in which there is a fire, but this does not necessarily mean that the entire 1 km^2 is burning; the actual area on fire may only be a fraction of that (NASA 2020), leading to an overestimation of fire occurrence. On the other hand, MODIS burnt areas have also been found to underestimate actual burnt area (Gaveau *et al.*, 2014; Tansey *et al.*, 2008). Therefore it is preferable to compare with other maps of burnt area, such as those delineated from cloud-free optical or radar satellite imagery (e.g. Gaveau *et al.*, 2014; Lohberger *et al.*, 2018; Tansey *et al.*, 2008).

PHASE 2: PEATLAND MAPPING

Based on an iterative process, peatlands are delineated by an expert incorporating all the above-mentioned input data. More details on delineation methodologies have been developed by Barthelmes, Ballhorn and Couwenberg (2015), Gumbricht *et al.* (2017), and Bourgeau-Chavez *et al.* (2018) for tropical and boreal peatlands. Other methodologies are also widely available. Personnel mapping the peatlands will need to take the actions described below through field surveys, at least in the main types of peatlands.

Peatland status and socio-economic factors

It is important to map the peatland status, particularly if it has been drained and/or burnt and if different management or other activities are ongoing, and to divide it into different sections according to the type of management. To determine GHG emissions and carbon losses, it is also important to understand hydrological connectivity, i.e. if the effect of drainage extends beyond the area where the GWL has been directly lowered (see Figure 1 and Figure 2).

For reporting on socio-economic issues, as well as improving the sustainability of peatland management, it is important to understand the various ways that people use the peatlands – low-intensity activities such as hunting or gathering non-timber forest products, or activities involving fire or land clearing. It may be useful to disaggregate the collected data by gender and by stakeholder groups to allow a targeted approach, for example for development collaboration. Using geographic information systems it is possible to integrate socio-economic and other data in the peatland maps. National forest inventories (NFIs) are one possible source for land use and socio-economic data acquired through household surveys.

Biodiversity assessments

While accessing the peatlands, it is important to note at least the key plant species that are forming the peat, i.e. the dominant species in the vegetation, such as Sphagnum mosses, grasses, sedges or trees. For livelihood development, note any natural peatland species that could allow for non-invasive, non-drainage-based livelihood options, if needed. An example of biodiversity assessment for monitoring the United Kingdom's peatlands has been developed by Natural England (2011).

PHASE 3: INTERVENTION AND RESTORATION MAPPING

Through a combined assessment of the above input data (Phase 1: collection and processing of input data) and the results from the peatland mapping (Phase 2: peatland mapping), the areas requiring intervention, such as restoration, are mapped. There will be areas where it is best to only undertake hydrological restoration and allow natural vegetation to return naturally through (assisted) natural regeneration (FAO, 2018, 2019a) or ecological succession, and other areas where both hydrological restoration and planting of native vegetation (rehabilitation) are required (see Figure 9). Planting might be necessary, for example, when peatland fires have destroyed the seed bank, and there are no peatland species growing in the area allowing for natural expansion. Consequently, both rewetting and revegetation should always be planned together, with revegetation achieved either through natural regeneration or, depending on local environmental and socio-economic circumstances, through planting of trees. Increasing tree density by replanting peatland species can help reduce the loss of humidity through evapotranspiration (Limpens *et al.*, 2014).

Revegetation with native peatland tree species is especially applicable to tropical peatlands (see for more: Box 4 and Figure 9). On the other hand, in most temperate and boreal non-forested peatlands, which are dominated by mosses, the removal of tree plantations is, in fact, a restoration challenge on drained sites in the process of restoring native Sphagnum bogs (The Flow Country, 2019).

Box 4

Peatland restoration and rehabilitation

The terms peatland restoration and rehabilitation are frequently used and are often conflated. "Rehabilitation" refers to revegetation and is used for activities with the goal of repairing ecosystem processes, without necessarily reverting to the previous state (Society for Ecological Restoration International Science & Policy Working Group, 2004). Note however that without the raised water table, the wetland plants and trees would not be able to return. "Restoration" is mainly used to refer to hydrological restoration, such as canal blocking and associated measures, which would allow the peatland species to return. Peat restoration is best used as a single class to define areas where hydrological restoration is required (see Figure 9).

Figure 9 Decision-support tree for choosing whether rehabilitation through revegetation should be considered

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* Include fires due to lighting

** Threat by canal or road development or recent fire occurrences along forest edge within buffer zone of 5 km

Chapter 3

Peatland monitoring

by Ronald Vernimmen, Aljosja Hooijer, Hans Joosten,
Uwe Ballhorn, Maria Nuutinen and Hesti Tata

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Peatland monitoring is referred to here as the regular and systematic observation of specific variables and their changes over time, within a known peatland area. Monitoring is often used to inform and understand how peatland function and condition is evolving and to assess the effectiveness of water management strategies, restoration interventions, and the risk of fires. To achieve results, a true landscape approach is important:

> *"By adopting a landscape approach, we learn how to look at landscapes from a multi-functional perspective, combining natural resources management with environmental and livelihood considerations. People and their institutions are therefore perceived as an integral part of the system rather than as external agents operating within a landscape"*
>
> *(Global Partnership on Forest and Landscape Restoration, 2018)*

The landscape approach in the case of peatlands means, in particular, considering water flow and changes, people's livelihoods, and different sectors' impact and activities, sometimes located far from the peatlands but having an impact on them. Other factors to consider are, for example, the buffer zones around peatlands and practices using fire within the landscape.

Peatland monitoring is distinct from peatland mapping, which serves to determine the extent of the peat (see Chapter 2). The purpose of a peatland monitoring system defines the parameters and the relevant data sources and thus the monitoring approaches and tools. Common purposes set by governments are monitoring and reporting on peat-related GHG emissions under the GHG inventories and the MRV framework to the Climate Convention, as well as monitoring restoration efforts, and to observe and to be able to make appropriate decisions to control and prevent further deterioration of peatlands.

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Chapter 5 covers further frameworks to showcase different monitoring needs, and points out how monitoring could be harmonized to serve multiple reporting requirements.

MONITORING PARAMETERS

Monitoring needs differ depending on the peat condition and the required interventions, defined for example in the mapping phase (see Chapter 2). Examples of tools to measure these parameters are described in Chapter 4. The parameters in Table 2 should be measured to monitor the changing conditions of peatlands and estimate GHG emissions.

Table 2 Examples of parameters for monitoring different types of peatlands, suggested minimum frequency and utility for climate reporting indicators

Peatland's condition	Possible monitoring parameters	Suggested minimum frequency	For climate reporting, indicator of:
All peatlands	Area of peat	Annually	Potential GHG emissions
	Local climate and altitude	Rainfall regimes seasonally	Potential for GHG emissions
	Socio-economic factors	Annually	Sustainability of action
	Peat depth	Once	Carbon storage and potential duration of emissions
Peatlands in temperate and boreal regions	Fertility	Once at different peat depths	Potential for GHG emissions
Temperate peatlands	Vegetation	Regularly, e.g. every five or ten years	Proxy for GHG emissions
Pristine peatlands	Potential land cover or land use change	Annually	Need for preventive action
	Drainage-free land uses	Twice a year	Sustainability of action
	GWL (also through canal water depth)	Seasonally	Adaptive capacity
	Soil moisture	Seasonally	Fire risk in case of reduced moisture
	Fire risk and fire detection during dry periods	Daily	GHG emissions, haze and associated health, economic and political issues
Drained peatlands	Area of each drained peatland hydrological unit or area	Twice a year	GHG emissions
	Land cover change or development of drainage canals or ditches, logging tracks and roads (expansion of network)	Twice a year	Changes in above and below-ground carbon stock; Need for preventive action
	Surface level: subsidence and peat depth	Four times a year	GHG and other carbon loss
	Soil moisture and GWL	Seasonally, twice a year	Fire risk, disaster risk reduction
	Fire risk and frequency of fires	Daily during dry periods	GHG emissions, disaster risk reduction
	Area of burnt peat and frequency of fires	After the dry season	GHG emissions, disaster risk reduction
Restored peatlands	Land cover change: Return of native peatland species	Annually	Success indicator
	Management: Wet peatland uses	Annually	Sustainability of action
	Profitability and gender equity of wet livelihood options	Annually	Sustainability of action
	Fully rewetted area with the entire drainage system blocked	Twice a year	Avoided GHG emissions
	Location and status of dams and other restoration efforts (e.g. blocking of canals and ditches)	Twice a year	Success indicator
	Surface level: subsidence and peat depth	Four times a year	GHG emissions and success indicator
	Soil moisture and GWL (also through canal water depth)	Twice a year	Avoided GHG emissions; disaster risk reduction
	Fire risk and frequency of fires	Daily during dry season	GHG emissions; disaster risk reduction
	Area of burnt peat	After the dry season	GHG emissions, disaster risk reduction

Direct carbon loss measurements

Peat emissions are unique, as they are not calculated based on one off deforestation or degradation events, but when drained, they continue over longer periods until the organic material is fully decomposed (Hooijer *et al.*, 2010). Measuring GHG emissions (CO_2, CH_4 and N_2O) directly at field level has recently become less costly and accessible thanks to portable measurement devices with chamber measurements as well as with flux towers ("eddy covariance method") (FAO, 2014). In addition, losses of water-borne organic carbon (e.g. dissolved organic carbon) can be measured. Note, however, that the interpretation of such measurement data requires highly experienced personnel.

The requirement for long-term GHG measurements - two years are often required - over different seasons, as well as the need for better equipment, is hindering the development of Tier 2 emission factors that could help countries to estimate their specific GHG fluxes from peatlands. The IPCC 2013 Wetlands Supplement provides standard emission factors for different climatic zones and guidance on how to update the emission factors.

Canal water depth and groundwater level

Measuring the level of the water table in peatlands (often below the peat surface) and in canals is a priority for assessing the changing conditions in the peat, the impact of drainage in various parts of the system (e.g. in a peat dome), and thus likely carbon emissions, restoration requirements and associated results.

GWL, due to its direct correlation with GHG emissions from peatland degradation, is the best parameter to estimate GHG emissions, as also recommended in the IPCC 2013 Wetlands Supplement (IPCC, 2014a). (See the section on Dipwells for water-table depth measurement p. 28.) Canal water depth, sometimes referred to as "freeboard" by water management practitioners, can be used as an indicator of GWL, and accessed directly using light detection and ranging (LiDAR). One of the limitations of LiDAR has traditionally been its high cost. Developments in 2019 allow expecting that the price of monitoring using LiDAR could be reduced in future, for example with the increased use of programmed unmanned aerial vehicles (UAVs) such as drones.

Subsidence

Peat subsidence is a serious issue associated with peatland drainage and often connected with other peatland problems. "Subsidence" means the gradual sinking of an area of land. Most peatland subsidence is associated with a massive and continual loss of carbon via both air and water (Couwenberg and Hooijer, 2013), with the intrusion of saltwater, and with an increased risk of flooding. If peat subsidence continues and global sea levels continue to rise, vast areas will become permanently flooded. Subsidence rates in drained boreal and temperate peatlands are typically in the range 1-3 cm per year, whilst in drained tropical peat rates are higher (3-6 cm per year) as a result of faster decomposition rates at higher temperatures (Evans *et al.*, 2019). Subsidence rates are generally higher in more deeply drained peat, and in the period immediately following drainage. Large areas of peat in some countries such as the Netherlands and Britain, where drainage began centuries ago, are now below sea-level and require energy-intensive pumped drained. This approach is unlikely to be feasible for the vast areas of coastal peatland in Southeast Asia that have been drained more recently, and if peat subsidence continues in these regions, and global sea levels continue to rise, these areas will be at increased risk of flooding. Loss of areas where people live (cities, villages) or work (forestry, cropping or grazing) through increased flooding and intrusion of saltwater may cause significant economic and social hardship, and force countries to take extensive adaptation and disaster risk reduction (DRR) action. Subsidence intensifies when proper management is lacking (Saputra, 2019) and often indicates the need for restoration.

Subsidence is also closely associated with carbon loss, with at least half of all subsidence typically resulting from the oxidation of aerated peat and resultant CO_2 emissions. In the IPCC 2013 Wetlands Supplement, subsidence measurements were recommended as a cost-effective method to estimate GHGs for reporting purposes in drained organic soils. As subsidence and raising of the peat surface vary according to the water content of the peat, it can also be used to estimate the success of peatland rewetting. For examples of measurement methods, see sections on Subsidence poles and Subsidence measurements, pages 27 and 28.

Fire occurrence

Fire monitoring is an area of work currently under development. Monitoring peatland condition is relevant for determining fire risk, likely causes, and the GHG emission associated. New emission factors should be available in the near future, making it possible to estimate, for example, emissions due to reduced fire load after several fire events. Fire monitoring should intensify during dry periods (see sections on Historical fire occurrence and burnt areas, p. 15 and on Fire monitoring initiatives, p. 42), and studies have shown the importance to monitor peatland status even after, and between, fire events, due to its relevance for GHG emissions calculations (Lupascu, 2020).

Different methods exist to monitor fire risk and fire events. In most cases, meteorological centres conduct fire danger monitoring, which is closely related to monitoring weather conditions, such as rainfall, wind, and thunderstorms. Large commercial enterprises often have their own fire risk monitoring systems and teams charged with extinguishing fire. Fire risk monitoring allows the setting of fire warnings, such as prohibiting the use of fire outdoors.

In the humid tropics, the majority of fires are anthropogenic, and – importantly – most fire events can be spotted, and their original location traced. Many countries have made rapid advances in identifying the culprits of intentionally lit fires. In this case, a timely monitoring system can contribute to emergency response and development of strategies to avoid intentional fires.

Canal blocks

Water loss can be controlled by canal blocking[4] leading to raised GWL and allowing peatlands to restore[5]. In some cases, canal blocks have been damaged[6] by people who prefer to use the canals for transportation or to keep the water levels low. Canal blocks are also often destroyed by natural causes, such as floods. Therefore, to ensure successful restoration, regular monitoring that the dams remain in place is required. For large areas, high-resolution imagery through remote sensing tools can verify the state of canal blocks, depending on their size.

Other monitoring parameters

Depending on the goal of the monitoring process, biodiversity (e.g. plant and animal species, vegetation structure, connectivity), and socio-economic factors (e.g. local livelihoods, profitability and gender equity of wet livelihood options) could be analysed in order to understand the evolution of peatland status and possible threats. In addition, climate reporting often requires socio-economic data, such as information on safeguards. The results of the mapping phase can be useful to determine which parameters to monitor, but note that any available information on peatland status can be used as a basis for peatland monitoring within a national system.

TAKING DECISIONS

The parameters to be monitored depend on the question the monitoring personnel has and may differ among countries. Monitoring requirements can be derived from international frameworks and conventions (see Chapter 5) and/or national legal frameworks or conservation goals and strategies. Table 2 shows possible monitoring parameters depending on the peatland state (for tools to measure these and other parameters see Chapter 4).

The scope of this report does not cover potential issues of data-sharing, institutional arrangements (such as mandates, coordination, capacities, legal basis, budgets, organizational development or other aspects) and processes (such as data handling, quality management, third-party reviews, archiving). In addition, the peatland information is best catered to various stakeholder groups in an approachable manner to allow for social debate, and fact-based decisions to be made. Much can be learned from the experience of countries that have been working on national forest monitoring systems (NFMSs) and GHG inventories as well as national adaptation plans (NAPs).

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[4] Canal block constructions have been built as compacted peat dams, cement structures, box dams, partial canal infilling, and peat dam cascades with positive and negative results (BRG, 2016). After collecting restoration experience from several countries in different climatic zones, the most positive experience has been reported with compacted peat dams. Their particular benefits are persistence even during peak flow, as well as the availability and sustainability of the raw material.

[5] To achieve full rewetting, stopping peat degradation, reducing fire risk as well as avoiding GHG emissions, the GWL needs to be raised to at least around the peat surface, preferably higher. Canal blockings should be constructed high enough, taking into account the rainy seasons and other periods when water easily breaks dams.

[6] Compacted peat dams have been noted to be the most difficult to break.

Chapter 4

Examples of monitoring tools and approaches

by Andrew Groom, Albert Sulaiman, Dirk Hoekman,
Laura Villegas, Kai Milliken, Ronald Vernimmen,
Laure-Sophie Schiettecatte, Maria Nuutinen and Erik Lindquist

Chapter 4

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This chapter provides examples of monitoring tools, i.e. those that are currently operational and those that are expected to become operational in the near future. As a key objective is to mitigate climate change by reducing GHG emissions, the descriptions extend beyond observational tools to include analytical tools. Analytical tools focus on those that enable the conversion of monitoring results into GHG emission metrics. The examples are not exhaustive, and only include tools that take into account the specificities of peatland landscapes.

Table 3 **Summary of tools for peatland monitoring**

Object of monitoring	Type of tool	Tool	Known or expected challenges
Peat surface motion	Ground monitoring	**Subsidence pole**	Provides limited spatial detail Impractical for monitoring large areas
Peat surface motion	Ground monitoring	**Integrated, autonomous subsidence measurement instruments**	Some additional cost Impractical for monitoring large areas
Sub-centimetre changes in surface level	Remote observational tool	**Interferometric SAR**	Variable results linked to vegetation characteristics Update frequencies
Water-table depth	Ground monitoring	**Dipwells**	Artificial disturbances of peat surface during installation
Canal water depth, ground surface level	Remote observational tool	**LiDAR**	Cost
Hydrological characteristics, fire, canal detection, forest degradation, etc.	Remote observational tool	**Synthetic aperture radar**	Cost
Detection of land-use changes, and landscape elements (e.g. canal blockings, deforestation, etc.)	Remote observational tool	**High resolution optical imagery**	Time needed for interpretation of satellite images
Net ecosystem CO_2 exchange	Ground monitoring	**Flux towers**	Cost
Emissions from peat soils under deforestation, fire, and logging	Carbon and GHG balance	**AFOLU Carbon Calculator**	Some updates needed

Object of monitoring	Type of tool	Tool	Known or expected challenges
GHG balance, temporal carbon trends, and estimation of other climate impacts	Carbon and GHG balance	**CarboScen**	Availability of GHG emission models
Impact of agriculture, forestry and fishery development projects, programmes and policies on the carbon balance	Carbon and GHG balance	**EX-Ante Carbon Balance Tool – EX-ACT**	Differentiation of emission factors for areas drained more than five years and less than five years
Carbon stock fluxes (above - and belowground) and GHG emissions derived from land cover change to oil palm	Carbon and GHG balance	**Palm GHG Calculator**	Identification of further reliable peat emission parameters

OBSERVATIONAL TOOLS AVAILABLE TODAY

Ground-based tools

Subsidence poles

Changes in peat surface elevation (e.g. subsidence) can be measured by inserting a pole made from long-lasting material (e.g. a thick PVC tube) vertically into the peat. It is important to ensure that the subsidence pole is installed firmly into the mineral substrate underlying the peat (to a minimum depth of 50 cm) to guarantee proper anchorage. Upon installation, a permanent marker (PVC collar or another permanent marking) allows a fixed recording of the height of the peat surface. It is relevant to secure that the permanent marker is light enough not to sink in the peat, but heavy enough not to float when flooded. In some instances, it is recommended to fence an area of 2 m × 2 m around the subsidence pole to prevent inaccurate measurements by disturbance of the peat surface, but care should be taken to avoid the fencing activity itself disturbing the measurements.

RSPO (Roundtable on Sustainable Palm Oil) highlights the importance of subsidence measurements, and recommends the installation of subsidence poles with a minimum density of at least one, and preferably two, poles for every 240 ha of oil palm plantations on peatlands for which surface elevation monitoring is required (RSPO, 2018). Subsidence poles should be placed in a representative location (i.e. not close to a ditch or canal) and across a range of representative land use types. Densities may need to be finer for areas with a variety of peat types, depths and drainage conditions.

The RSPO best practice manual requires the peat surface elevation to be recorded at least every quarter year, to adequately capture wet and dry season variability (RSPO, 2018). Regular measurements over a minimum of three years provide reliable subsidence rates.

Dipwells for water-table depth measurement

Dipwells are PVC tubes which may be joined in length depending on the depth of the peat in which they are installed. They enable the measurement of water-table depth below the peat surface. When a dipwell is embedded into the mineral substrate underlying the peat it can function at the same time as a subsidence pole, allowing the observation of change in peat surface elevation.

To maximize robustness and lifespan potential, the PVC tubes (with an inside diameter of e.g. 3.80 cm or 1.5 inch) should be of the highest quality available, with a preferred wall thickness of 3 mm, as these are more resistant to UV radiation than thin-walled PVC tubes.

Dipwells should be placed at a minimum distance of 10 m from the main transect access path to avoid disturbance and compaction of the peat surface at the monitoring location. They are installed in the peat through boreholes and should be sunk a minimum of 50 cm into the mineral substrate to allow the dual monitoring of peat surface elevation. The top of the tube is sealed with a cap to prevent rainfall from entering the tube (Figure 10, right), while entrance of the groundwater is enabled through a "filter" of 1 mm holes drilled manually into the tube located 5 cm apart (Figure 10, left). During installation, workers should stand on wooden planks to avoid artificial disturbance of the peat surface (Figure 10, right). Installation also provides an opportunity to record peat depth.

Figure 10 **Dipwells for water-table depth measurement**

Thick-walled PVC pipes with holes to measure groundwater table and an installed dipwell, covered by a removable cap and a PVC collar on the surface of the peat.

© Ronald Vernimmen

Depth to water table is monitored by routinely measuring the distance from the water table in the dipwell to the top of the dipwell. Measuring from the top of the dipwell to the peat surface records any changes in peat surface elevation. Because the peat surface around the dipwell is irregular, the height of the dipwell above the peat surface should be measured to a PVC collar placed on the ground around it (Figure 10, right). As noted above, the material used for the collar should be light enough to float on the peat surface, and heavy enough not to float when the peat surface is flooded.

Good practice also involves photographing the site conditions when readings are taken. These pictures can reveal possible data irregularities that may relate to the conditions of the transect, the equipment, or the data entry.

Figure 11 **Automated groundwater level, rainfall and wind measurement point**

Automated groundwater level, rainfall and wind measurement point with a solar panel visited by Congolese researcher Dr. Ifo Suspense in Indonesia

© FAO / Maria Nuutinen

Subsidence measurements

Observing changes in peat surface elevation entirely manually and with sufficient frequency is a challenge using subsidence poles or dipwells, particularly on extensive peatlands. Peat surface motion is highly dynamic and thus temporally frequent observations are preferred to understand drainage regimes and related GHG emissions, also to calibrate and validate remote observations.

Automatization reduces the need to access the measurement devices. The Centre for Ecology and Hydrology in the United Kingdom has developed a time-lapse camera system that provides daily observations of peat surface elevation with no requirement for a daily manual reading. The system is designed to be low-cost and easily constructed from materials that can be locally sourced. The tools are robust under field conditions (there are no external moving parts, and similar cameras are widely used in wildlife camera-traps in the region) and able to operate autonomously for long periods (batteries and data storage should allow the system to operate unattended for months).

The British system includes a time-lapse camera mounted on a lightweight platform which "floats" on the peat surface and takes a daily photograph of a target attached to a metal subsidence pole embedded in the mineral substrate underlying the peat. The daily photograph provides a high-resolution (millimetre-scale) measurement of the relative displacement of the camera relative to the target. Software is available to automatically extract these readings from the received photographs.

Greenhouse gas measurements

GHG exchanges between the land surface and atmosphere can be quantified using a variety of methods. The FAO report (2014) describes a variety of methods for direct measurements, summarized here:

CO_2 air-soil measurement: *the eddy covariance or "flux tower" method is a micro-meteorological technique employed on a tower with instrumentation typically located above the vegetation. This method determines the surface-atmosphere flux from source areas (hectares to square kilometres) by measuring the covariance between fluctuations in the gas mixing ratio and the vertical wind velocity. A flat, homogeneous topography is a pre-requisite for undertaking these measurements, and steady atmospheric conditions are desirable for more accurate results. In contrast to closed chambers, this method provides continuous, whole ecosystem gaseous flux measurements over relatively large areas.* (See for more: FAO, 2014.)

Waterborne carbon: *the DOC content is determined by measuring the oxidation of organic matter to CO_2, which is generally accomplished using high-temperature combustion or persulfate oxidation. The spectrophotometric method is used as a complementary method for determining DOC content in the water. To estimate the total loss of DOC, the total discharge also needs to be measured and the catchment area defined.* (FAO, 2014.)

In addition, GHGs can be estimated using proxies, as described in the Box 5.

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Box 5

Central European vegetation as a proxy for greenhouse gas fluxes

by John Couwenberg

Vegetation is well suited to indicating GHG fluxes (Couwenberg *et al.,* 2011) because:

- it is a good indicator of the water table, which in turn strongly correlates with GHG fluxes;
- it is controlled by various other site factors that determine GHG emissions from peatlands, including nutrient availability, soil reaction (pH) and land use (history);
- it is itself directly and indirectly responsible for the predominant part of the GHG emissions by regulating CO_2 exchange, supplying organic matter (including root exudates) for CO_2 and CH_4 formation, reducing peat moisture, and providing possible bypasses for methane fluxes via gas conductive plant tissue, or "aerenchymous shunts";
- it reflects long-term water-table conditions and thus provides indication of average GHG fluxes on an annual time scale; and
- it allows fine-scaled mapping, e.g. 1:2 500–1:10 000.

The approach of estimating GHG emissions through vegetation is currently being applied in the United Kingdom, Germany (Bonn *et al.,* 2014) and the Baltic countries (Sendžikaitė *et al.*, 2018).

In a recent study, the results of a meta-analysis of GHG fluxes were combined with a matrix system of all vegetation types that may occur in Central European peatlands. The analysis then allows for extrapolation and interpolation of measured flux data along various axes of site characteristics (Couwenberg *et al.,* 2011). The resulting greenhouse gas emission site types are currently mainly based on water-table class, vegetation and land use, but also nutrient status and acidity (pH). Additional measurement data are regularly integrated to increase the accuracy of GHG emission estimates.

In order to estimate emission reductions, scenarios of vegetation development must be formulated for the situation with rewetting ("project scenario") and the situation without rewetting ("baseline scenario"). Emission reductions can be conservatively estimated by applying low estimates for the baseline and by omitting emissions from ditches and of N_2O, while applying high estimates for the project scenario. CH_4 emissions from ditches can be particularly substantial, but are usually emitted from small areas that are expected to be overgrown after rewetting measures, thus reducing emissions. Disregarding emissions from ditches thus means reductions are underestimated. N_2O emissions are erratic, but always negligible when peatlands are wet. Leaving N_2O out of the assessment will result in an underestimation of emission reductions.

Remote observational tools

Changes in peatlands can be increasingly monitored using remote sensing tools (see also Box: 6) and platforms (see e.g. Box 7).

Synthetic aperture radar

Space-borne radar observation is not hindered by adverse atmospheric conditions, such as clouds, smoke and haze, and can be made frequently and repetitively, including in the rainy season. Because of a certain penetration level of the radar waves, observation below the canopy is also possible. Particularly the L-band sensors on board the former JERS-1 and ALOS-1 satellites (Rosenqvist *et al.*, 2007) are superior to all other space-borne sensors for assessment of flooding and drought conditions and thus hydrological cycles.

Moreover, radar signals are sensitive to forest structure and biomass level (Hoekman and Quiñones, 2002; Hoekman, Vissers and Wielaard, 2011; Lohberger *et al.*, 2012; Schlund *et al.*, 2014). This offers unique opportunities for applications such as monitoring peat swamp forest conditions, hydrological integrity and fire susceptibility, as well as fast response to illegal tree logging and canal construction (Hidayat *et al.*, 2011; Hoekman, 2018; Schlund *et al.*, 2015). A near real-time system based on free Sentinel-1 C-band data has recently been demonstrated, allowing forest degradation, deforestation and new canal detection to be monitored. For more accurate information related to hydrology, it is better to integrate these C-band data with L-band data.

Figure 12 is an apt example of the use of SAR data, which illustrates that temporal dynamics in flooding intensity can be related to the hydrology of ombrogenous[7] peat swamp forests and indirectly to peat depth (Hoekman, 2007). Light blue areas show flooded parts of the relatively flat tops of two peat domes ("A"); "B" indicates a central depression with a river; and "C": relatively flat and wet fringe of a

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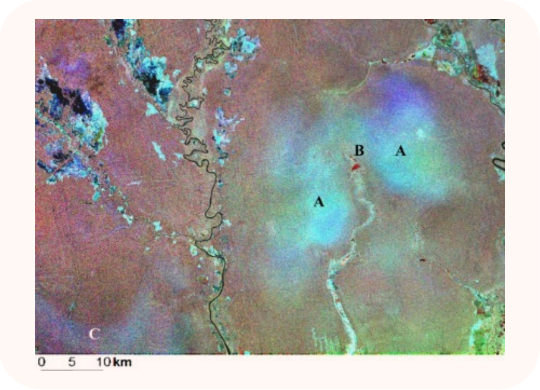
[7] A peat-forming vegetation community lying above groundwater level: it is separated from the ground flora and the mineral soil, and is thus dependent on rainwater for mineral nutrients.

dry peat dome, which can be better seen in Figure 13. The red area dates back to 7 September 1994, with green and blue representing 12 July 1995 and 4 January 1996 respectively.

Figure 12 Example of SAR data on flooded areas within a complex peat dome in Mawas area, Central Kalimantan and JERS-1 SAR multi-temporal composite image



Source: Hoekman, 2007.

In Figure 13, the time-series of JERS-1 SAR exemplifies the deleterious impacts of underground peat fires and the fast succession of events that resulted in trees falling down at a central area of peat swamp forest. This forest collapse can be accurately depicted, using time-series data to highlight the logical sequence of events. Until 1996, the dome was hydrologically intact, however, in 1997, the construction of a wide canal through the dome became apparent. In the third image of the sequence (September), the canal becomes filled with water and becomes black and distinguished with a small bright area. This bright area grows exponentially through time, until the forest completely collapses in January 1998. To note, the images of figure 13 are from the location “C” in Figure 12.

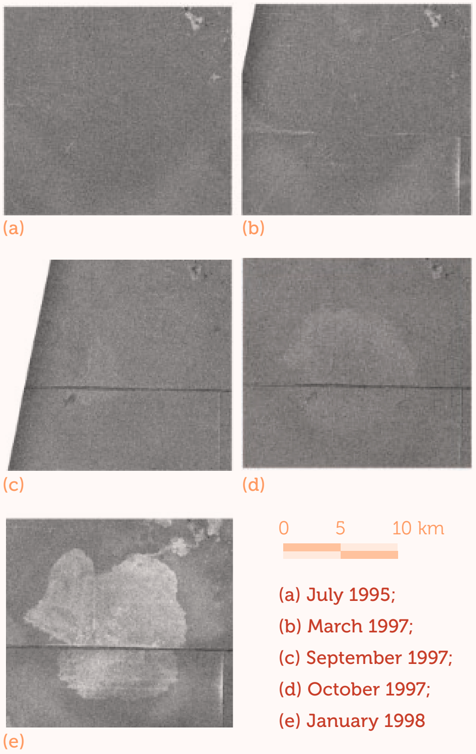
Soil surface subsidence for this dome was estimated to be approximately two meters (Kool, Buurman and Hoekman, 2006). A pivotal cause of the collapse was the intense drainage caused by the wide canal. That said, the coinciding ENSO period at the time, may have accelerated the process (Hoekman, 2007).

Interferometric SAR

High-precision mapping and monitoring of changes in land surface elevation are also possible using satellite-based techniques, the most common of which is differential interferometric synthetic aperture radar. These techniques exploit subtle changes in the radar signal phase to identify sub-centimetre changes in the line-of-sight position of targets. The two most common times series InSAR methods are PSInSAR (persistent scatterer) and SBAS (small baseline subset), both of which can typically produce very accurate deformation profiles for urban or rocky, sparsely vegetated areas. However, both methods are considered to be severely challenged over vegetated terrain due to uncertainty of signal penetration - depending on vegetation density and height - and high variability incoherence of the measured signal (Figure 14).

Recent studies have shown that all SAR wavelengths are able to penetrate a forest canopy to some extent. The challenge is to develop a technique that can effectively filter out and exploit the high coherence points and produce meaningful observations of changes in surface elevation. Such a technique, known as ISBAS (intermittent small baseline subset), was developed at the United Kingdom’s Nottingham University in 2012 (Sowter *et al.*, 2013).

Figure 13 JERS-1 SAR time series of the collapse of the peat dome in 1995–1998 in Kahiyu, Central Kalimantan, Indonesia



(a) July 1995;
(b) March 1997;
(c) September 1997;
(d) October 1997;
(e) January 1998

Source: Hoekman, 2007.

ISBAS is imagery intensive, requiring a dense time series of SAR observations in order to allow for the capture of sufficient numbers of high coherent points. The operational Sentinel-1 mission (a two-satellite constellation) captures a new image at least every 12 days over all global landmasses.

This temporal capability, combined with the partial canopy penetration (Sentinel-1 is C-band), enables the generation of land motion measurements over both vegetated and non-vegetated surfaces.

Figure 14

Illustration of radar backscatter from a typical forest element

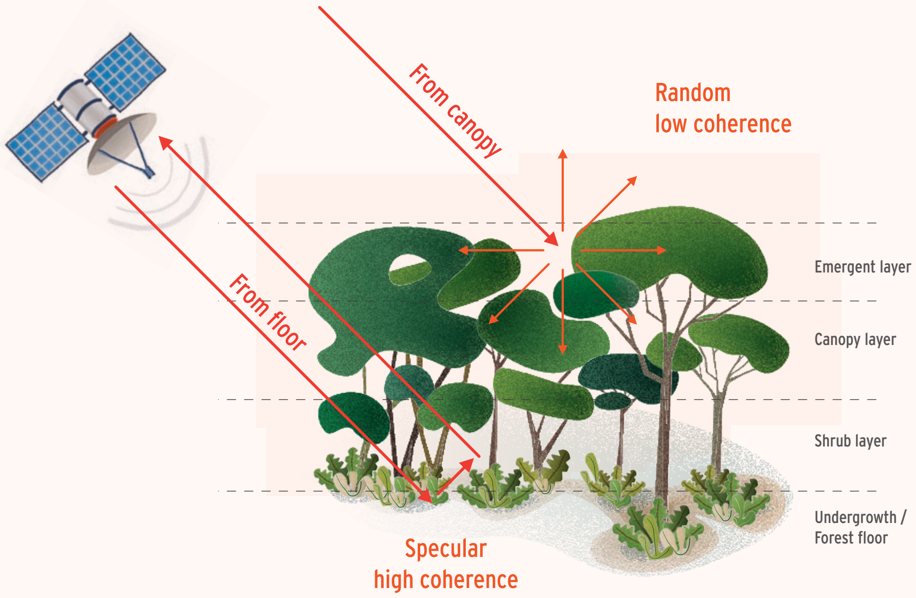


Illustration of radar backscatter from a typical forest element, showing incoherent (diffuse) scattering from the canopy and coherent (specular) scattering from targets on the forest floor

Source: European Space Agency and Dr Andrew Sowter/Personal communication.

This means ISBAS can be used for almost complete coverage of any landscape, including peatlands.

The technique is able to generate average rates of motion, with 12-month update frequencies, and has been demonstrated to work in all peatland contexts (arctic permafrost, temperate, Neotropical and tropical) (Alshammari *et al.*, 2018; Cigna *et al.*, 2014). It can be used for wide-area surveys of peat surface motion to select priority restoration areas, as well as routine, ongoing monitoring of peat surface motion to test the effectiveness of restoration interventions.

Peat surface elevation changes are known to be linearly related to water-table depth. As water-table depth is also related to GHG emissions, the technique can also be applied to:

- plantation-scale observations to test the effectiveness of water table management strategies;
- regional-scale observations to demonstrate compliance with water table depth regulations; and
- regional-scale observations to inform calculations and monitor GHG emissions in response to land management actions.

Box 6

Landscape-scale observation of peat surface elevation change

LiDAR (light detection and ranging) uses a laser to produce and emit pulses of light, and measures the time it takes for a reflection of this pulse to return. Most commonly, the LiDAR system is carried by a fixed-wing aircraft, and in addition to the laser-emitter-receiver scanner, LiDAR systems are also connected to a global positioning system (GPS), and an inertial measurement unit (IMU). The GPS constantly measures the position of the laser scanner, which is crucial for knowing the location where the light pulses are emitted. The IMU measures the tilting of the aircraft (roll, pitch, yaw), which is crucial for calculating the directionality of the aircraft and hence the directionality of the emitted pulses of light.

The easiest way to understand how LiDAR works is to examine the life of a single emitted pulse of light. The pulse of light is a clump of time-stamped photons emitted with known directionality. As this pulse contacts a surface (e.g. a leaf in the forest canopy), a portion of those photons is reflected back towards the laser. The laser-emitting device recognizes these time-stamped, reflected photons and calculates the time between their initial emission and their reflected return, alternatively called their echo (i.e. an echo was received from the emitted pulse). Next, the device calculates the location from where the echo originated. This is possible because pulse speed (i.e. the speed of light), pulse origin (location of emission), pulse directionality, and pulse travel time are known values, making it a simple geometry problem to calculate the location of the echo.

Light pulses frequently yield multiple echoes because not all of the photons are reflected by the first surface they contact. Instead, some continue through semi-transparent surfaces before contacting something else and delivering another echo. Therefore, whereas the first echo comes from the highest surface encountered by the pulse, for example the top of the canopy, the final echo from a given pulse comes from the last surface hit by the remaining photons. Most often, this is the ground, but in a dense forest, such as in the tropics, the last pulse can come from inside the canopy as well.

In addition to the location, the device also records the intensity of the returning echo. The intensity is higher if the pulse hits a solid surface, because more photos reflect back (ground vs forest canopy). Modern LiDAR systems can emit up to 800 000 pulses per second. Each pulse can yield multiple echoes, and for each of these locations the echo is recorded. The result is generally referred to as point cloud data; a cloud of points, all of which have an XYZ-location (coordinates). When the data are plotted, the structure of the scanned target can be visualized.

LiDAR has the capability to detect both surface water level in canals and ground surface level near canals, allowing the canal water depth to be determined below the land surface. Although water typically absorbs the LiDAR near-infrared wavelength of 1 064 nm (Höfle *et al.*, 2009; Roelens *et al.*, 2016), reflections of the pulse do occur on the water surfaces caused by low incidence angles and water turbidity among other factors, but also by floating debris and/or plants.

Detection of water surfaces is an essential step in many classification workflows for LiDAR, often to remove them from the dataset to create a digital terrain model that should present the land surface only. In a few cases, point cloud LiDAR data have also been used for surface water level measurement in ditches and rivers (Höfle *et al.*, 2009; Hopkinson *et al.*, 2011; Roelens *et al.*, 2016).

These principles can be applied to determine the absolute water surface elevation above MSL, as well as the level below the surrounding soil surface, i.e. the "freeboard" that is a common target parameter in lowland water management.

ANALYTICAL TOOLS TO ESTIMATE CARBON BALANCE AND GREENHOUSE GASES

All the following tools have parts and/or potential applications for different types of peatlands.

AFOLU Carbon Calculator

The AFOLU Calculator by USAID employs IPCC-based accounting methods that allow users to estimate the CO_2 fluxes of eight types of land-based activities: forest protection, forest management, afforestation, reforestation, agroforestry, cropland management, grazing land management, and forest degradation by fuelwood, in order to develop and support policies. The calculator is designed for forested landscapes with potentially decreasing carbon stock.

The calculator has several parts, and one of them, "AFOLU carbon calculator – The Forest protection tool: underlying data and methods" (Winrock International, 2014), when used for peatlands, computes emissions from deforestation, fire and logging that can then be compared with, for example, a REDD+ conservation scenario. Activity data used for calculations include, as appropriate, annual area deforested or burnt (ha), annual volume of wood illegally extracted (cubic metres/hectare), percentage area of peat, depth of peat drainage (metres) and depth of peat burning (metres). The carbon stocks include the live tree biomass (above and belowground) and soils (including peat). The technical area of peatland monitoring has developed rapidly since the calculator was published, and therefore some updates would be needed. As two areas for development, the tool should take into account the soil carbon stock after deforestation, as well as including soil carbon in belowground carbon counting.

CarboScen

CarboScen simplifies the quantification of GHG fluxes and allows the study of temporal carbon trends based on land-use data only. CarboScen has a comparative advantage in landscapes with rapid land use change but gradual changes in carbon density, such as in soil carbon if biomass change is sudden, as typically occurs during deforestation. Distinct uses range from educational to rapid expert assessments, typically simulating future carbon stocks in a landscape. CarboScen could be used in future carbon calculations when planning or releasing advance payments in REDD+ or other programmes aiming to increase ecosystem carbon. The main payments are then typically released only after results are documented in the field. CarboScen could naturally also be used to compute prior landscape carbon dynamics. CarboScen has been used to simulate various land use scenarios for peatland activities in Indonesia.

Access the tool online: *www.cifor.org/gcs/toolboxes/carboscen*

EX-Ante Carbon Balance Tool

The Ex-Ante Carbon-balance Tool (EX-ACT) is an appraisal system developed by FAO, providing estimates of the impact of agriculture, forestry and fishery development projects, programmes and policies on the carbon balance. The carbon balance is here defined as the net balance of all GHGs from peatlands (CO_2, CH_4, N_2O and DOC), expressed in carbon dioxide equivalent (CO_2eq) that are emitted or sequestered due to project implementation, as compared with a business-as-usual scenario.

Box 7

SEPAL — platform for land monitoring

The System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) is an online, open-source platform that allows users to query and process satellite data and undertake a range of geospatial analyses tailored for different needs. Field monitoring data can be processed through SEPAL's integrated tools by combining optical satellite-based time series analysis with radar-based soil moisture estimates and trends. Specific state-of-the-art peatland restoration monitoring modules are being developed by FAO and partners and are accessible in SEPAL.

SEPAL is a powerful cloud-computing platform for autonomous land monitoring, which uses remotely sensed data to readily process satellite data efficiently to generate advanced geospatial and statistical analyses (e.g. uncertainty). Notable innovations of the platform include:

- improved data access;
- system for rapid and standardized image processing;
- cloud-based processing capacity;
- powerful and useful open-source tools; and
- effective user interface that operates smoothly without the latest computers or high-speed internet connection.

Given that SEPAL is based on open-source code, it can easily be tailored for different users and countries, with their own working areas. In Indonesia, tailored modules are integrated into and accessible through SEPAL. The modules include the following workflows based on up-to-date, scientific methodology:

- dam detection with high-spatial resolution optical imagery;
- time-series analysis of field-based observations;
- time-series analysis of optical spectral indices; and
- radar-based surface soil moisture estimates and trends over time.

Access the tool online: *https://sepal.io*

EX-ACT is a land-based reporting system, estimating emissions or sinks of CO_2 in all five carbon[8] pools as well as GHG emissions per unit of land, expressed in tonnes of CO_2eq per hectare and year. The tool helps project designers to estimate and prioritize project activities with the greatest economic benefit and potential for climate change mitigation.

The tool can be applied to a wide range of land-based developments, as well as other projects concerned with climate change mitigation, watershed development, production intensification, food security, livestock, forest management or land use change. It is cost-effective, requires a comparatively small amount of data, and is equipped with useful resources such as tables, maps and FAOSTAT data. While EX-ACT is mainly used at the project level, it can easily be scaled up to programme or sector level and can also be used for policy analysis. The World Bank and International Fund for Agricultural Development already use EX-ACT to estimate the carbon balance of projects prior to their implementation. For emission factors and carbon stock, EX-ACT primarily incorporates the IPCC 2006 Guidelines, augmented by the 2013 Wetlands Supplement (IPCC, 2014a) and complemented by other methodologies.

Palm GHG Calculator

The Roundtable on Sustainable Palm Oil (RSPO) has guidelines to estimate the carbon stock changes (above and belowground) and GHG emissions that occur with land cover change to oil palm, peat drainage, and emissions from mills and operations. The guidelines see land use, peat oxidation, and chemical fertilizers as the largest sources of GHG emissions in a plantation.

The tool, known as the RSPO PalmGHG Calculator (version reviewed: 2018) is used to quantify annual net GHG emissions in CO_2eq per hectare and per unit of product and is a crucial component of the RSPO GHG Assessment process. It allows oil palm growers to identify crucial areas in their production chain and thereby guide emission reduction opportunities. The tool's manual does not mention emissions from fires on oil palm plantations on peatlands.

All important GHGs (CO_2, CH_4 and N_2O) from peatland degradation are included in the RSPO calculator. Sources of quantified emissions in this tool include peat decomposition, land conversion, manufacture of fertilizers and transport to the plantation, fertilizer application, fossil fuel combustion in the field and mill and palm oil mill effluent. Three classes of emission reduction are addressed: (i) carbon sequestration by oil palm growth; (ii) carbon sequestration by forest/vegetation growth in conservation areas; and (iii) avoided GHG emissions when mill energy by-products are sold to cement industries to displace fossil fuels.

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[8] The five pools include: aboveground biomass, belowground biomass, dead wood, litter and soil organic carbon.

Chapter 5

Existing frameworks for peatland reporting and verification

by Julian Fox, Kai Milliken, Maria Nuutinen,
Esther Mertens and Marieke Sandker

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Several global frameworks, conventions and multilateral environmental agreements (MEAs) require, or at least encourage, national and other stakeholders to monitor and report on their peatlands. This chapter gives an overview of the specific parameters, indicators and/or reporting requirements of these frameworks. It illustrates the cross-cutting nature of peatlands: nearly all the frameworks overlap, so that the so-called “integrated frameworks” (here covering SDGs, DRR and the Ramsar Wetland Convention), encourage the monitoring of many climate-related peatland topics, as well as the means to tackle fire. Although this report focuses on mapping and monitoring for climate purposes, biodiversity indicators are listed to show the overlaps with both climate change mitigation and adaptation indicators. The multitude of data requirements demonstrates the need for integrated and harmonized mapping and monitoring, which would allow for cost-effective, targeted reporting on peatlands without unnecessarily burdening countries and other stakeholders.

Figure 15 **The Sustainable Development Goals that require peatland monitoring**

INTEGRATED ASSESSMENT FRAMEWORKS

Sustainable Development Goals: indicators and reporting

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, including a set of 17 aspirational SDGs to eradicate poverty, protect the planet, and ensure prosperity for all (UN, 2019b). Peatland monitoring for appropriate management and conservation overlaps with many of the SDGs, but is particularly relevant to:

- **Goal 6:** Ensure availability and sustainable management of water and sanitation for all;
- **Goal 12:** Ensure sustainable consumption and production patterns;
- **Goal 13:** Take urgent action to combat climate change and its impacts;
- **Goal 15:** Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (Figure 15).

The 17 SDGs encompass 169 targets with 232 indicators monitored through the SDG Tracker (Ritchie *et al.* 2018). The UN invites Parties to collaboratively develop “the most complete and up-to-date sources for tracking global progress to 2030”.

Table 4 gives some examples of SDGs targets, definition of goals, indicators and monitoring parameters that can be fulfilled through peatland mapping and monitoring.

Table 7 (Annex) summarizes how peatland degradation and restoration can hinder or advance the achievement of selected SDGs.

Table 4 Examples of SDG targets, definition of goals, indicators and potential monitoring parameters related to peatlands

SDG	Target	Definition of the goal	Indicators	Potential peatland monitoring parameters
13 Take urgent action to combat climate change and its impacts.	13.1: Strengthen resilience and adaptive capacity to climate-related disasters.	By 2030, strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.	Number of deaths, internally displaced persons, missing persons, and total numbers affected by natural disasters.	Losses caused by peatland fires and flooding.
15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.	15.1: Conserve and restore terrestrial and freshwater ecosystems.	By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.	The proportion of total terrestrial area designated as protected; The proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type.	The proportion of all peatlands that is conserved. The proportion of all degraded peatlands that is restored.
	15.3: End desertification and restore degraded land.	By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world.	Proportion of total land area that is degraded.	Proportion of the total original peatland area that is degraded. No data available for monitoring the indicator.

The Sendai Framework for Disaster Risk Reduction

Floods and fires on peatlands are often manufactured issues caused by unsustainable management, particularly drainage. The Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) (UNDRR, 2020) is a voluntary, non-binding agreement that aims to achieve a substantial reduction of disaster risk and losses in lives, livelihoods and health, and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries within 15 years. Related to peatlands, the framework recognizes that:

- poor land management, unsustainable use of natural resources and degrading ecosystems are driving forces of natural disaster risk;
- disasters cause environmental impacts and loss of natural capital; and
- countries should bolster the sustainable use and management of ecosystems for building resilience to disasters.

The SFDRR underlines the need to safeguard and restore ecosystems as a vital strategy to offset natural disasters. Strengthening country capacity to use ecosystems in DRR and management is particularly pertinent to peatlands and other wetland ecosystems, as 90 percent of disasters are induced by water-related hazards (UNDRR, 2015).

Between 1979 and 2015, the area of marine, coastal and inland natural wetlands declined 35 percent (Ramsar, 2018). Loss of peatlands, as well as most other wetland areas, aggravates the risks from storms and floods, whereas well-managed peatlands help to minimize such damage. Coastal peatlands, such as mangroves, protect against flooding and serve as buffers against saltwater intrusion and erosion. Inland wetlands such as floodplains, lakes and peatlands absorb and store excess rainfall, which reduces flooding and delays the onset of drought by storing water (UNDRR, 2017). Peatland fires, in particular, underline the necessity for peatland mapping and monitoring to assess whether the global targets of the Sendai Framework are being reached. The SFDRR is expected to be renewed after 2019.

The Ramsar Convention on Wetlands

The purpose of the Ramsar Convention on Wetlands (Ramsar, 1971) is to ensure "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world". Currently, the Convention has 170 contracting parties and 2 331 designated wetlands of international importance, which cover approximately 2.1 million km^2 (Ramsar, 2018). The Convention recognizes the importance of peatlands for climate change mitigation and calls upon countries to minimize degradation and promote restoration and wise management of peatlands and other wetland types that are significant long-term carbon stores or have the ability to sequester carbon. Under the fourth strategic plan, Ramsar Parties are committed to:

- addressing the drivers of wetland loss and degradation;
- effectively conserving and managing the Ramsar Site Network;
- wisely using all wetlands; and
- enhancing implementation.

As a potential start to a peatland monitoring framework, the Parties to the Ramsar Convention approved detailed Guidelines for Global Action on Peatlands (Ramsar, 2002). Related to peatland mapping and monitoring, their recommendations are:

- to establish a global database containing ecological and carbon-related information on peatlands and mires;
- to monitor the quantity and quality of the peatland resources;
- to develop a globally standardized peatland terminology and classification; and
- to review national networks of peatland protected areas to guarantee the conservation of all peatland biodiversity.

The Ramsar Convention offers a framework for describing wetlands, carrying out inventories, assessment, and monitoring and reporting activities for designated Ramsar sites. Its implementation promotes the conservation and wise use of wetlands, as well as cross-border collaboration. The Convention's integrated framework for wetland inventory, assessment and monitoring (Ramsar, 2010) contains very similar monitoring parameters for climate purposes, and mapping is a cross-cutting activity:

- establishing the **location** and **ecological characteristics** of wetlands (baseline inventory); and
- assessing and monitoring over time the **status, trends and threats** to wetlands.

In addition, the framework encourages action to halt negative changes. Parties to the Convention submit national reports once every three years, including information on changes (condition, area, role in adapting to or mitigating climate change) in wetlands (Ramsar, 2016).

THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

The main objective of the United Nations Framework Convention on Climate Change is to Iprevent dangerous anthropogenic interference with the climate system within a time frame sufficient to allow ecosystems, food and economic systems to adapt to climate change (UNFCCC, 1992). The Convention requires Parties to report on anthropogenic emissions, adaptation actions, as well as the technical and scientific support to other countries in a transparent manner[9] under a framework of monitoring and reporting requirements that is evolving (UNFCCC, 2019b).

Under the Paris Agreement (Article 5.1), the signatory parties have agreed to "take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases". One significant way for countries to integrate peatlands into their climate action is to add them to their nationally determined contribution (NDC) report, which is updated regularly. To date, only a few countries have explicitly integrated peatlands in NDCs: their next revision in 2020 will offer an opportunity to enhance ambition.

Reporting

The IPCC, an independent United Nations body for assessing climate change science, cooperates with the UNFCCC in preparing guidance on reporting methodologies. Regarding peatlands, the key document guiding countries in GHG reporting is the IPCC 2013 Wetlands Supplement (IPCC, 2014a).

The IPCC has suggested that the category of agriculture, forestry and other land use (AFOLU) should be used to report carbon removal as well as reduction of GHG emissions. The AFOLU category would, therefore, cover the majority of peatland-related emissions. Countries are, however, currently reporting their peatland emissions under various means, through yearly GHG inventories under AFOLU, agriculture, or energy categories, or under the REDD+ framework.

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[9] The reporting procedures are being developed in an Enhanced Transparency Framework.

Many, if not all, REDD+ countries contain peatlands, and only a few have reported GHGs attributable to their peatlands either through REDD+ or NDC frameworks (e.g. Burundi, Indonesia, Rwanda, Uganda, and Uruguay). The REDD+ reporting framework requests Parties to also cover economic and social matters through safeguards (e.g. concerning gender and indigenous peoples), as well as environmental co-benefits such as biodiversity conservation and water resource preservation. By 2019, 40 countries had submitted a forest reference (emission) level (FREL/FRL) to the UNFCCC, but only two of these countries, Indonesia and Malaysia, report on emissions from peatland drainage (FAO, 2019). Indonesia reports emissions for the year 2012 at 47 percent of total CO_2 emissions from deforestation and forest degradation, including peatland drainage (MoEF and Government of Indonesia, 2016), illustrating how significant these emissions can be.

The annual emissions from drained organic soils under different land use are estimated to be responsible for 1–2 gigatonnes of CO_2eq, including emissions from microbial oxidation and fires (IPCC, 2014a; Joosten *et al.*, 2016; Leifeld and Menichetti, 2018). However, an update of these data is urgently needed. Following the IPCC 2013 wetlands supplement, the reporting scope includes GHG emissions from drainage-induced peat oxidation[10], erosion, peat extraction and fires, as well as emission reductions achieved through peatland restoration.

The IPCC 2013 wetlands supplement provides:

- a summary of emission factors and supplementary guidance for drained organic soils that can occur under all six IPCC land use categories, as well as an update for fire on organic soils; and
- guidance and emission factors for rewetted organic soils used for forestry, crop production or other purposes. The emission factors are generally stratified by climate (boreal, temperate, and tropical), peat type separated between "nutrient-rich" fen peat and "nutrient-poor" bog peat; drainage level (deep or shallow) and inland and coastal organic soils.

As a major difference to deforestation, peat emissions are unique, as they are not calculated based on a one-off deforestation or drainage event. Rather they continue emitting over longer periods until either the peatland reverts to a water-saturated wetland condition, or the peat material is completely lost to oxidation.

Adaptation and resilience

National Adaptation Plans (NAPs) allow Parties to the Convention on Climate Change to identify medium and long-term adaptation needs and to develop and enact strategic programmes and related budgets to address these needs.

While there are no established indicators under the UNFCCC, for example, to measure vulnerability, adaptive capacity or resilience, the NAP framework contains guidance on how to "monitor and evaluate" the NAPs to ensure that they are addressing key issues in different sectors, including land use, land use change and forestry (LULUCF). Given that peatlands can support ecosystem-based adaptation (EbA), recent developments in EbA monitoring can be helpful to countries, although monitoring is not obligatory.

EbA encompasses the use of biodiversity and ecosystem services into an overall strategy to help society adapt to the deleterious impacts of climate change. It incorporates a variety of ecosystem management activities to increase resilience and reduce vulnerability of people and the environment, including the following, which can include activities on peatlands:

- sustainable water management to provide water storage and flood regulation services;
- disaster risk reduction, such as restoration of coastal peatlands as a buffer against storms and erosion; and
- strategic management of shrublands and forests to limit the frequency and size of fires.

Challenges

Climate reporting is a challenging task and wide capacity-development is ongoing for most sectors for harmonized reporting (FAO, 2020a). Many countries have therefore requested to make the IPCC guidelines more accessible. In addition, the Tier 1 emission reference figures for tropical countries in the IPCC 2013 wetlands supplement were based on relatively few studies[11].

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[10] In the first few months or years after drainage, the peat surface subsides rapidly through peat compression (compaction and consolidation) and oxidation. During this transition phase, emissions are far higher than the default emission factors stipulated by the IPCC (Hooijer *et al.,* 2012).

[11] Different methods can be used to estimate emissions or removals from most source and sink categories. The selection of a particular method will depend on the desired degree of estimation detail, the availability of activity data and emission factors, and the financial and human resources available to complete the inventory. In IPCC terminology, the lowest ranking or simplest method is "Tier 1", while more elaborate methods are "Tier 2" and "Tier 3".

There is an urgent need to support countries in (I) measuring GHG emissions to establish relevant reference emissions levels for different areas, and (II) defining national peatland parameters (e.g. drainage levels) to calculate emissions (e.g. using the 2013 wetlands supplement). Simple guidelines, manuals and training materials should be prepared to enhance understanding of the IPCC guidance, and to provide options to move to Tier 2 reporting (which is mandatory when peatland emissions are one of the key categories). Currently, most countries do not report peatland emissions at all, and the latest estimations by Annex I countries[12] vary in approach (see e.g. Barthelmes *et al.*, 2018).

FIRE MONITORING INITIATIVES

There are no specific international agreements on fire. However, given significant peatland fire challenges faced by several countries, different monitoring approaches have been developed over some decades. This section summarizes some potential frameworks and considerations related to the mapping and assessment, as well as monitoring and reporting, approaches.

At the global level, institutionalized frameworks in which peatlands could be incorporated include the Global Fire Monitoring Centre and the Global Wildlife Fire Network, both voluntary networks that provide policy advice and facilitate technology transfer to enable nations to effectively:

- reduce the negative impacts of landscape fires on the environment and humanity; and
- advance knowledge and application of the ecologically and environmentally benign role of natural fire in fire-dependent ecosystems, and sustainable application of fire in land use systems.

The Southeast Asia region (see Case study: Southeast Asian Nations and regional haze monitoring case below), as well as Indonesia, have paved the way. Indonesia coordinates an International Peatland Fire Network under the Regional Fire Management Resource Centre. The overarching aim of the centre is to contribute to evidence-based political decisions and the development of relevant fire policies for Indonesia.

It is important to note that fire on peatlands is not restricted to tropical countries; fires on peat are a widespread occurrence in high-latitude peatlands. Although partly natural, their frequency and severity are predicted to increase as a result of climate change and the increasing presence of humans within many landscapes (Turetsky *et al.*, 2014). Fire is also used as a land-management tool in some Northern peatlands, such as those in Britain, although this is becoming increasingly controversial (Baird *et al.*, 2019; Marrs *et al.*, 2019).

Fire monitoring needs

The surface of an intact, undrained peatland has a lower probability of sustaining a fire, because it is usually too wet. However, loss of moisture from the upper peat layer, both by natural climatic variation and anthropogenic disturbance, increases the risk of fires. In various peatland locations, fire is used as a management tool, but many peatland fires are a direct consequence of land use change and disturbance of the natural ecosystem, including drainage and land clearing by fire. Drainage, deforestation and abandonment (stopping of active management) greatly increase the risk of ignition and severe burning of both vegetation and peat. Some of the most extensive peatland fires of the past two decades have occurred on peatlands that were either being used for agriculture, or were in the process of being converted to agricultural use – e.g. Russian Federation (UNFCCC, 2020), Canada (McMaster University, 2018) and Indonesia (Page *et al.*, 2002).

Research and observation have already characterized risk factors in peat igniting. The GWL needs to be sufficiently low, and a low rainfall period needs to be sufficiently long, for the surface layer (0–20 cm) of peat to dry out. Fires rarely if ever start deeper in the peat layer. Surface fires burning in heavier and coarser fuels with slower rates of spread and longer (one to two hours) residence times allow fire to move from above ground into the peat (Adinugroho *et al.*, 2005; ASEAN, 2009; Frandsen, 1997; Rein *et al.*, 2008; USUP *et al.*, 2004).

Peat fires are a particularly large source of carbon emissions into the atmosphere when compared with the combustion of aboveground vegetation, because they can persist for long periods (weeks to months) and consume a considerable thickness of peat (0.5 m thick block of peat contains more carbon per square metre than an equivalent area of pristine tropical rain forest on mineral soil, i.e. around 25 kg carbon per m^2)[13]. Also important for the type of emission is whether the fire is flaming on the surface or smouldering within the peat. Smouldering fires are particularly difficult to extinguish as they can burn even under snow.

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[12] Annex I Parties to the UNFCCC include the industrialized countries that were members of the Organization for Economic Co-operation and Development in 1992, plus countries with economies in transition (EIT), including the Russian Federation, the Baltic States, and several Central and Eastern European states. Most non-Annex I Parties are developing countries.

[13] Assuming 50 percent carbon content by dry weight and a bulk density of 0.1 g per cm^3.

GHG emissions from peat have added complexity due to the way peat burns, what is burnt and what is emitted. The parameters to assess GHG emissions from fires are (i) the area burnt, (ii) the patchiness of the burn, (iii) the fuel load, (iv) the combustion factor (fire intensity), and (v) the emission factors for GHG emitted per unit of dry matter combusted (i.e. actually burnt) (IPCC, 2014a). Fire emissions estimates tend to be simplistic, applying conservative default values for the data required.

Peat fire emissions may pose significant health risks, even at a regional level. Tropical peat fires emit per unit of carbon combusted as much as three to six times more fine, unhealthy particulate matter ("black carbon") than fires on grasslands and forests (Turetsky *et al.*, 2014), and have been implicated in large numbers of premature deaths from respiratory illnesses (Koplitz *et al.*, 2016). This emphasizes why peatlands should be incorporated in national and international fire frameworks and management programmes to coordinate efforts to prevent peat-related fire hazards and emissions (see more on fire monitoring on p. 42).

Case study: Southeast Asian Nations and regional haze monitoring

In 1997, forest and peatland fires were widespread across Southeast Asia. Around 24 000 km^2 of peatland were burnt, releasing an estimated 2.9–3.5 gigatonnes of CO_2eq (Page *et al.*, 2002). These fires were the result of the interference of a prolonged period of drought, driven by El Niño-Southern Oscillation (ENSO), with the presence of drained and deforested peat swamp forests. In response to this widespread environmental crisis, the ASEAN Agreement on Transboundary Haze Pollution (AATHP) was signed in 2002 by ASEAN Member States to reduce haze pollution in the region.

The Regional Haze Action Plan calls for measures to prevent and monitor land and forest fires and increase fire-fighting capacity. It requires neighbouring countries to assist with the mobilization of personnel and equipment to combat ongoing fires and obliges countries where fires originate to respond promptly and provide information and data to other countries.

The ASEAN Specialized Meteorological Centre (ASMC), has been supporting fire monitoring since 1993. Under the ASEAN Regional Haze Action Plan, the ASMC was tasked to monitor and assess land and forest fires and the occurrence of transboundary smoke and haze affecting the region. Peatlands that occur within these nations are particularly vulnerable to fires, under the influence of prolonged drought induced by the El Niño climate cycle and/or in combination with a positive Indian Ocean dipole, which also triggers extended periods of low rainfall in parts of the region (Abram *et al.*, 2008). This highlights the importance of ASMC, in conjunction with national and local meteorological agencies, to identify incipient fires and map high-risk zones using (drained) peat area as a predictive proxy.

The indicators of the implementation of the ASEAN "Haze-free roadmap" consist of:

- an increase in the number of days with good or moderate air quality in terms of defined pollutant standard or air quality index;

Table 5 Peat-related components of the Association of Southeast Asian Nations' roadmap

Strategy 1	Implementation of the ASEAN Agreement on Transboundary Haze Pollution (AATHP)
Strategy 2	Sustainable management of peatlands for peatland fire prevention
Strategy 3	Sustainable management of agricultural land and forest for large-scale forest and/or land fires prevention
Strategy 4	Strengthening policies, laws, regulations and their implementation, including facilitating exchange of experience and relevant information among enforcement authorities of the parties
Strategy 5	Enhancing cooperation, exchange of information and technology, and strengthening of the capacity of institutions at all levels
Strategy 6	Enhancing public awareness and cross-sectoral and stakeholder participation
Strategy 7	Securing adequate resources from multi-stakeholders for transboundary haze preventionW
Strategy 8	Reducing health and environmental risks and protection of the global environment

Source: ASEAN Secretariat, 2017.

- a reduction in the number of hotspots that are below a defined alert level under the ASEAN standard operating procedure on haze; and a decrease in the area subject to transboundary haze pollution.

These indicators are framed in the following strategic components that translate the principles of the AATHP into specific collective actions under a roadmap (Table 5).

Focus of monitoring

The standard operating procedure provides guidelines for the implementation of monitoring and assessment and joint emergency response under the AATHP. Monitoring is focused on (i) all fire-prone area; (ii) all land and/or forest fires; (iii) environmental conditions conducive to such land and/or forest fires; and (iv) haze pollution arising from such land and/or forest fires, following respective national procedures.

Early warning, early action

To mitigate fire-related problems and fire-suppression costs, forest and land management agencies, including landowners and communities, require early warning systems of extreme fire danger conditions that may lead to uncontrolled wildfires. Early warning allows fire managers to systematically implement prevention, detection and suppression before the fire appears. Fire danger information is provided by satellite data that identify hotspots for early detection, in conjunction with spectral data on land cover and fuel conditions. Such information is particularly relevant to peatlands as they hold a combustible fuel load that may support devastating fires and should be incorporated into early action frameworks in countries where peatlands are prevalent.

THE CONVENTION ON BIOLOGICAL DIVERSITY

The Convention on Biological Diversity (CBD) currently monitors the implementation of a Strategic plan for Biodiversity for the 2011–2020 period, including the Aichi Biodiversity Targets. The Strategic plan provides an overarching framework for all biodiversity-related conventions, including the entire United Nations system and all other partners engaged in biodiversity management and policy development. Parties to CBD will negotiate new targets before the end of 2020.

Peatland mapping and monitoring can contribute to monitoring the current Aichi Biodiversity Targets as well as the future framework. Table 6 shows the main indicators that can help to design peatland mapping and monitoring activities.

FOREST AND LANDSCAPE RESTORATION INITIATIVES

There are several initiatives encouraging countries to advance forest and landscape restoration, such as the African Forest Landscape Restoration Initiative; Initiative 20x20 for Latin America and the Caribbean; the UN Decade on Ecosystem Restoration (2021–2030) and the Bonn Challenge. All these initiatives promote the monitoring of landscapes throughout the restoration process, including their ecological and socio-economic characteristics.

The Bonn Challenge is a global initiative to restore 150 million hectares of the world's degraded and deforested lands by 2020, and 350 million hectares of degraded ecosystems by 2030, as well as mitigating climate change. It is underpinned by the forest landscape restoration (FLR) approach that aims to restore ecological integrity while improving human well-being using multifunctional landscapes. Restored peatlands were acknowledged as one of the ecosystems that could be forested under the Bonn Challenge (Besseau, Graham and Christophersen, 2018).

FLR is being monitored using a variety of indicators. Using the Bonn Challenge Barometer, IUCN and partners are looking at a certain set of indicators to monitor restoration, ranging from policies and institutional arrangements to financial flows and planning, and suggest a monitoring and evaluation framework defined by the stakeholders. This might include remote-sensing tools or national restoration monitoring platforms within a national forest monitoring system (NFMS).

Related to peatland restoration monitoring, the Bonn Challenge uses the following indicators of results and benefits achieved:

- hectares under restoration;
- climate impacts both in terms of mitigation[14] and adaptation;
- biodiversity impacts following the Aichi Targets and the World Database of Key Biodiversity Areas and other protected areas where FLR activities take place; and
- socio-economic impacts with a focus on jobs created.

The Bonn Challenge barometer also underlines synergies with existing reporting requirements, aiming to reduce the reporting burden on countries (Dave *et al.*, 2019).

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[14] Note that the monitoring and evaluation framework currently considers only cumulative tonnes of CO_2 sequestered through FLR activities since 2010, thereby excluding emissions avoided through peatland restoration.

Table 6 Peat-related Aichi biodiversity targets and relevant indicators

Aichi biodiversity target	Peat-related indicator, trends in:
Target 5: By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation are significantly reduced.	The extent of natural habitats other than forest
	Degradation of forest and other natural habitats
	Extinction risk and populations of habitat specialist species in each major habitat type
Target 11: By 2020, at least 17%of terrestrial and inland water, and 10%of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes	Area of terrestrial and inland water areas conserved
	Area of coastal and marine areas conserved
	Areas of particular importance for biodiversity conserved
	Areas of particular importance for ecosystem services conserved
	Ecologically representative areas conserved
	Areas with effective and/or equitable management conserved
	Connectivity and integration of conserved areas
Target 14 - By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable	Safeguarded ecosystems that provide essential services
	Benefits from ecosystem services
	Restoration of ecosystems that provide essential services
	The degree to which ecosystem services provide for the needs of women, indigenous and local communities, and the poor and vulnerable
Target 15 - By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks have been enhanced, through conservation and restoration, including restoration of at least 15% of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification	Carbon stocks within ecosystems.

Source: CBD, 2016.

The UN Decade on Ecosystem Restoration 2021-2030 is likely to use many approaches currently developed being for FLR, including peatland restoration monitoring and land degradation neutrality (LDN), a new concept introduced by the UNCCD in 2015.

The UNCCD is a legally binding international agreement linking the environment and development to sustainable land management. The Convention specifically focuses on arid, semi-arid and dry sub-humid zones (drylands). The UNCCD 2018-2030 Strategic Framework is a comprehensive global commitment to achieve LDN to avoid new degradation as well as restore the productivity of large areas of degraded land, including all land types while improving livelihoods.

A set of countries are restoring previously drained peatlands as part of their voluntary commitment to achieving LDN. The LDN reporting indicators were still to be finalized at the time of writing, but a draft version contains the indicators and associated GHG emission metrics. The following are related to peatlands: land cover (assessed as land cover change), and carbon stocks (assessed as soil organic carbon, SOC), as in Parties' regular reporting to the UNCCD. In addition, Parties are requested to identify ongoing land degradation, including gullying and coastal inundation, for example, and the drivers of land degradation, including unsustainable land use practices, such as overgrazing - both also relevant to peatlands (GEF, 2019).

Chapter 6

Country case studies

by Maria Nuutinen, Felix Beer
and Laura Villegas

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Various countries have advanced with mapping and monitoring peatlands. Progress with peatland mapping methodologies has helped in the discovery and mapping of new peatlands - especially in the tropics - that are significant for climate change mitigation and adaptation efforts. Peatland monitoring, on the other hand, is being explored by a small number of countries that have started the integration of peatlands into national monitoring systems. However, in most cases it is still a work in progress to further define monitoring needs and objectives and choose the most appropriate tools that would allow the continuous improvement of management and restoration strategies.

The country case studies are useful for understanding different approaches to the use of existing peatland information, as well as identifying needs and challenges to be faced while dealing with climate change action in peatland landscapes.

1 INDONESIA: NEW MONITORING METHODS AND CHALLENGES

*by Bambang Arifatmi, Muhammad Askary Masjkur, Maria Nuutinen,
Adam Gerrand and Laure-Sophie Schiettecatte*

Highlights of peatland mapping and monitoring in Indonesia

- Establishment of an institutional framework for peatland monitoring
- Indonesia has made international commitments, reported to the UNFCCC and has developed policies at various levels.
- The “One Map” policy intends to harmonize different maps into a set of officially acknowledged national maps, including a peatland layer.
- The Indonesian Peat Prize was given in 2018 to a team that had developed a method to map the extent and depth of the country’s peatlands. This method is ready to be applied across all peatlands to support the government to achieve restoration and fire reduction goals.
- Development of the Peatland Ecosystem Protection and Management Plan that guides peatland protection and monitoring.
- Implementation of the peatland monitoring platform to monitor GWL and rainfall, and to understand the progress of peatland restoration.
- Establishment of the Peatland Restoration Agency (BRG) to coordinate and facilitate the restoration.
- BRG is developing the online peat restoration information and monitoring system for its mandate area in 7 Indonesian provinces to both guide restoration activities implemented by various stakeholders and to report the progress transparently and reliably.

Indonesia holds an estimated peatland area of between 149 300 km^2 and 270 000 km^2, with the latest area in public sources being 246 700 km^2 (BBSDLP, 2013; Ministry of Environment and Forestry, 2018; Page, Rieley and Banks, 2011). Southeast Asia contains the world's largest tropical peat carbon store (66–70 gigatonnes) (Warren *et al.*, 2017), with Indonesia accounting for 57 gigatonnes of this estimate.

In Indonesia, and Southeast Asia generally, growing agricultural needs have led to the exploitation of lowland peat swamps, especially since the 1990s, by large companies as well as smallholders. A large proportion of these peatlands have thus become degraded with negative environmental and socio-economic consequences. Digging drainage canals to prepare the land for logging, palm oil or industrial forest plantations, and rice farming, have resulted in subsidence and land loss to flooding on the one hand, and dryer peatlands and increased fires on the other. Indonesian peat landscapes have suffered from extensive peat fires since the 1990s. In 2015, 2.6 million ha of land in Indonesia was burnt, including estimated 1.7 million ha of forest and 0.89 million ha of peatland, with related emission estimates varying from 0.71 and 1.75 gigatonnes CO$_2$eq (Ministry of Environment and Forestry, 2018; Randerson *et al.*, 2017). In response to this disaster, Indonesia has reinforced its governmental commitments to reduce peatland deforestation and fires as well as to rewet and restore degraded peatlands. Government policy mandates concession-holders, in particular, to fully restore peatlands in defined priority areas, and to increase the water table in the peatlands they manage.

Monitoring of peatlands

Indonesian peatland monitoring is guided by a variety of commitments to international conventions, particularly the 2015 Paris Climate Agreement and the NDC under the UNFCCC, other international commitments, such as the Bonn Challenge on Forest and Landscape Restoration, presidential decrees, and policies released by ministries as well as provincial and district administrations. The main responsibility for peatland monitoring lies within the public sector, while many international and private entities have over the years supported the technical development of tools, approaches and systems. Plantation companies are also mandated to monitor and report the GWL in peatlands that have been drained.

Indonesian efforts to improve the management of the country's peatlands have been delayed by the lack of an agreed map. Since 2016, a "One Map" policy[15] has been implemented to integrate different national maps into a set of officially approved maps, including the peatlands. To advance a scientifically solid method to consolidate the peatland layer of the One Map, the Indonesian Peat Prize was awarded in 2018 for the development of a method to measure the extent and depth of the country's peatlands (Ballhorn *et al.*, 2018). This method is expected to be progressively applied across all peatlands to help the government to protect and manage peatlands, accelerate their restoration and support Indonesia's development goals (World Resources Institute, 2018).

As one of the key guiding policies, a Peatland Ecosystem Protection and Management Plan was established by the Ministry of Environment and Forestry to guide peatland protection and management (MoEF, 2018). The plan is improved and revised based on data-driven approaches that help to coordinate restoration efforts by different stakeholders.

A groundwater level and rainfall monitoring database called SiMATAG (MoEF, 2019) in both concession and community areas was presented by the Indonesian Ministry of Environment and Forest (MoEF) in 2019. SiMATAG-0.4m ("information system for peat groundwater level") is a platform to monitor GWL and rainfall and to understand the progress of restoration activities.

The SiMATAG database displays over 10 300 compliance points across Indonesia, which are updated in real time through a mobile app. SiMATAG is connected to other databases such as the Forest and Land Fire Database, the Database of Meteorology, Climatology, the Geophysics Agency and the National Agency for Disaster Management (MoEF, 2018). The database can be used to determine compliance of concession-holders in adhering to the required water management regulations, and whether the peat is being damaged. Monitoring of parameters such as groundwater table depth (Bechtold *et al.*, 2018) in peatlands is an important process that can point to the state of a system while playing a role in fire prevention by providing the basis for an early warning, early action system for officials to act upon.

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[15] Presidential Regulation No. 9/2016 on the acceleration of one map policy implementation at 1:50.000 in scale. Compilation and integration under BIG and synchronization under the Coordinating Ministry of Economic Affairs.

Monitoring of restoration priority areas

In January 2016, the Peatland Restoration Agency (Badan Restorasi Gambut, BRG), was established under the first Presidential Regulation after the Paris Climate Summit in 2016. BRG's mandate is to coordinate and facilitate the restoration of 2.4 million ha of degraded and burnt peatlands by 2030 in seven key provinces (Riau, South Sumatra, West Kalimantan, Central Kalimantan, South Kalimantan, East Kalimantan and Papua). Based on the indicative map of restoration priority, the targeted priority areas for BRG's restoration activities consist of (i) the area burnt in 2015[16], (ii) peat domes with canals (for protection), (iii) peat domes without canals (for protection), and (iv) peatlands with drainage system (canals). BRG supervises, facilitates, assists and coordinates peat rewetting in concession areas and outside of them. BRG must monitor and report its results regularly to the President of the Republic.

A peat restoration information and monitoring system (PRIMS) is being developed by BRG to update and report the progress of peat restoration activities transparently and reliably and provide timely feedback to land managers and policy-makers alike, as well as to facilitate coordination across provinces and institutions. It is a prototype web-based mapping system aided by the World Resources Institute and the Agency for the Assessment and Application of Technology (BPPT) and supported by FAO's land use monitoring tools and systems, such as SEPAL, and other tools within the Open Foris suite (FAO, 2020b). Although still under development, PRIMS has key features that can provide insight into restoration activities, peat degradation indices, peat emission and fire hotspot monitoring, and assess the impacts of restoration efforts, including canal blockings, deep wells, canal backfilling, revegetation, and the economic revitalization of communities.

Challenges and opportunities

Although Indonesia has made important steps to construct various tools for peatland monitoring by different agencies, many challenges persist. In Indonesia's latest forest reference emission level (FREL) submission in 2016, the analysis of peat emissions included only account for drainage, which deals with emissions from peat decomposition. Peatland fire data were not included in the FREL – combustion through fire causes major GHG emissions – as historical activity data were not available. It was also stated that the development of comprehensive emissions factors for fire is complicated and subject to high uncertainties (Agus, Hairiah and Mulyani, 2011). Peatland fire emissions need to be addressed and calculated more accurately to build one functional and holistic system for monitoring and reporting on peatlands for various purposes, including improving MRV for various types of GHG (including REDD+) reporting.The MoEF, tasked on GHG reporting, is working with various partners to further develop the inclusion of peatland emissions in national GHG inventories and update reports.

The lack of an agreed map of Indonesian peatlands negatively affects many efforts not only to monitor but also to restore the target amount of remaining peatlands.

The complexity and cost of peatland monitoring over a large area are important challenges that Indonesia is facing. High temperatures and humid conditions, as well as the risk of fire, pose a threat to the reliability of automatic systems. Collaboration and sharing experiences, data, ideas and methodologies are crucial in overcoming many challenges. The use of satellite data for monitoring peatlands over large areas and with higher frequency is an opportunity that is being explored by the Indonesian Government with support from many of the organizations contributing to this report. These techniques have potential – e.g. on soil moisture (Greifeneder *et al.*, 2019) – but are in relatively early stages of development. All remote sensing tools need to be well-calibrated and validated with field data and have limitations, as outlined in Chapter 4.

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[16] Due to the high risk of new fires in the previously burnt areas.

Peat landscape in Indonesia
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Peat landscape in the Republic of the Congo

© FAO / Maria Nuutinen

2 THE DEMOCRATIC REPUBLIC OF THE CONGO

by Jean-Jacques Bambuta Boole, Cleto Ndikumagenge, Amélie Arquero, and Rémi d'Annunzio

Highlights of peatland mapping and monitoring in the Democratic Republic of the Congo

- The Ministry of Environment and Sustainable Development has established a Peatland Unit.
- The Unit has started consulting stakeholders to define priority needs for peatland mapping and monitoring, including assessments of extent, carbon storage, ecosystem services, and institutionalization of monitoring approaches.
- Different organizations, including national academia, have advanced with peatland mapping and data generation mainly in the Cuvette area (see Map 1), including peat soil sampling.
- The capacity of national institutions has been developed with a pilot integration of a few peatland sites into the national forest inventory.

The Central Congo Basin peatlands are estimated to be the world's most extensive, continuous peatland complex[17] in the tropics. They are also among the most carbon-dense ecosystems, with an average of 2 186 tonnes of carbon per hectare. Approximately 29 percent of the total tropical peat carbon stock is currently estimated to be found within the Cuvette Centrale (Map 1). In terms of both peat area and peat carbon stock, the Democratic Republic of the Congo (90 800 km^2 of peat equivalent to 19.1 Pg C) and the Republic of the Congo (54 700 km^2 of peat equivalent to 11.5 Pg C) become the second and third most important countries in the tropics for peat areas and carbon stocks, after Indonesia. It is estimated that there are also other peatland areas around the Cuvette region in the northeast of the DRC (see e.g. Map 1).

Map 1 The extent of peatlands in the Cuvette Centrale, Congo Basin

Source: Dargie *et al.* (2017).

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[17] Note that Indonesian peatlands have a larger area, but are divided between different islands, and therefore not connected to each other like the peatlands within the Cuvette Centrale.

Most of these peatlands remain pristine and undrained. However, they also face various threats: drainage for various types of economic activities, mainly oil concessions, cropping, and potential infrastructure development, as well as declining regional precipitation with more extensive dry periods among them. The drainage and/or poor management of these extensive areas of carbon-rich soils can lead to the release of one of the biggest carbon stocks in the tropics. Therefore, the peatland system in the Congo Basin plays a key role in the global carbon cycle. (Dargie *et al.*, 2018)

Urgent need for peatland monitoring

The Peatland Unit and stakeholders have defined four priority needs for peatland action

- identify the distribution, status (pristine, drained, burnt, cropped, and grazed) and carbon storage of peatlands, including an approximate assessment of the depth of these deposits and their concentration of soil carbon;
- assess the importance of the identified peatlands' ecosystem services, such as sheltering unique biodiversity, water regulation, provision of food and other socio-economic and cultural benefits;
- develop and institutionalize a stakeholder engagement process, and
- integrate peatlands into the country's national monitoring system utilizing state-of-the-art peatland monitoring tools and approaches.

(ministerial source, private communication, July 2019.)

Monitoring is justified for a fundamental reason – peatlands in the Democratic Republic of the Congo are hitherto intact and protected because they are regularly flooded and difficult to access. However, they remain fragile over time, particularly if regional rainfall changes or hydrology is affected by land conversion.

Land use monitoring system and peatlands

At the time of writing, no countrywide peatland maps exist at the national level in the Democratic Republic of the Congo. However, with international support, efforts have been made to rectify this, including peat soil sampling and a pilot integration of some peatland sites into the NFI, including household surveys inquiring about potential drainage practices.

As a result of the activities under the REDD+ framework, the country has an NFMS (Democratic Republic of the Congo, 2020), accessible online and currently being operationalized, which requires capacity-development activities. The NFMS, managed by government agencies[18], aims at assessing the state and evolution of forest resources, as well as meeting the requirements of the UNFCCC for participation in REDD+. With the support of FAO, the satellite land monitoring system will assess land use and land cover changes, and the NFI will measure forest carbon stock and the GHG inventory to report GHG emissions from the AFOLU sector. The collected data, as well as the analyses and results will be published online on the NFMS web portal.

Challenges of peatland management

Stakeholders are asking how peatlands can contribute to the country and its people, including sustainable livelihoods. The Democratic Republic of the Congo is looking forward to finding answers and value its peatlands but the country must overcome various challenges. The first challenge relates to the establishment of financial mechanisms to generate benefits from peatlands with special regard to economic development at national and provincial levels, including local communities and indigenous peoples, and the definition of different stakeholder roles. The second challenge is linked to the analysis of the desirability of fostering jurisdictional interventions at the provincial level, building also on the country's experience in REDD+. Finally, the third challenge will pertain to the demand and need for capacity-building on peatlands, covering mapping, monitoring and approaches to sustainable management. (Ministerial source, private communication, July 2019.)

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[18] Direction des Inventaires et Aménagement Forestiers (DIAF); Ministère de l'Environnement et du Développement Durable (MEDD).

Figure 16

Peat landscape in Peru
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3 PERU

by Pedro Raul Tinoco Rodriguez

Highlights of peatland mapping and monitoring in Peru:

- Multiple researcher teams have used remote sensing and field data to map several peatland complexes throughout the country.
- Several mapping and monitoring initiatives are underway
- Peruvian government is coordinating actions and harmonizing the recommended peatland mapping methodology into national guidelines for peatland identification.

Thanks to its varied geography, three types of peatlands can be found in Peru: coastal, Andean and Amazonian. Peat extraction, mining activities and grazing are threatening peatlands in the Andes (Maldonado, 2014). The Amazonian peatlands are mainly threatened by infrastructure for transportation, agriculture, unsustainable forms of *Mauritia flexuosa* palm fruit harvesting, charcoal production, mining, oil, gas, and hydropower production.

National mapping and monitoring approaches

The national Peruvian Amazon Research Institute and a team of researchers have recently mapped the largest peatland complex in the Loreto department of the Peruvian Amazon. They used a combination of probability map constructed with the help of remote sensing (both optical and radar data) and soil measurements in the field.

Peru has prepared a national ecosystem map that includes palm swamps, herbaceous-shrub swamps, mangroves, bofedales (a special type of highland peatland) (Figure 16) – all these ecosystems are considered to potentially form peat – estimating a total area of 77 800 km^2 (7 780 824 ha). In addition, the National Wetland Inventory is being developed within the framework of the National Wetlands Committee, chaired by the Peruvian Ministry of Environment (MINAM). Other institutions have carried out various investigations on the country's peatlands (Chimner *et al.*, 2019; CIFOR, 2017; The Mountain Institute, 2016).

Political frameworks and peatland monitoring

At the time of writing, Peru does not have a nationwide policy framework regulating or protecting all types of peatlands (CIFOR, 2017). Within the framework of the Ramsar Convention for Wetlands, the country has adopted recommendations for the management and monitoring of peatlands. In addition to the multilateral environmental agreements, Peru has several laws, policies and strategies that, although they do not emphasize peatlands, regulate the conservation and sustainable management of the ecosystems that support them[19]).

Next steps for peatland mapping and monitoring

At the time of writing, several mapping initiatives are underway and the government is coordinating actions and harmonizing the recommended peatland mapping methodology. This process will define the scope of the country's peatlands considered in the map, and in longer-term monitoring, and it is expected to include the state of the peatlands and their estimated peat depth. In general, there is information on the distribution of wetland ecosystems. The greatest information gaps are related to peatlands' state, the depth of peat in different wetland types and their carbon content, which will require direct assessments and measurements in the field.

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[19] These legal and policy frameworks include: the General Environment Law; National Environment Policy; Organic Law for the Sustainable Use of Natural Resources (1997); National Biodiversity Strategy to 2021 and its 2014–2018 Action Plan (2014); National Water Resources Policy and Strategy of Peru (2009); Forestry and Wildlife Law (2015); and National Wetland Strategy (2015).

4 THE UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

by Rebekka R.E. Artz, Ian Crosher, Andrew Coupar, Emma Goodyear and Chris Evans

Highlights of peatland mapping and monitoring in the United Kingdom:

- The United Kingdom's has mostly over 30 years old peat maps using different mapping methodologies and peat definitions.
- Most recent efforts aim using satellite-data derived models in combination with ground observations to improve the mapping of peat extent.
- Assessment of restored peatland areas have provided evidence of the immediate climate mitigation benefits of peatland restoration efforts.
- Research on GHG emissions from peatlands has increased awareness of the condition and climate impact of country's peatlands, increasing public funding for restoration measures.
- Work is ongoing to incorporate full peatland GHG emissions reporting.
- Current initiatives aim to develop standardized, cost-efficient monitoring methods for evaluating restoration impacts.
- A new citizen monitoring initiative monitors the condition and long-term changes of peatlands and facilitates data collection and sharing through a web application.

Peatland extent and status

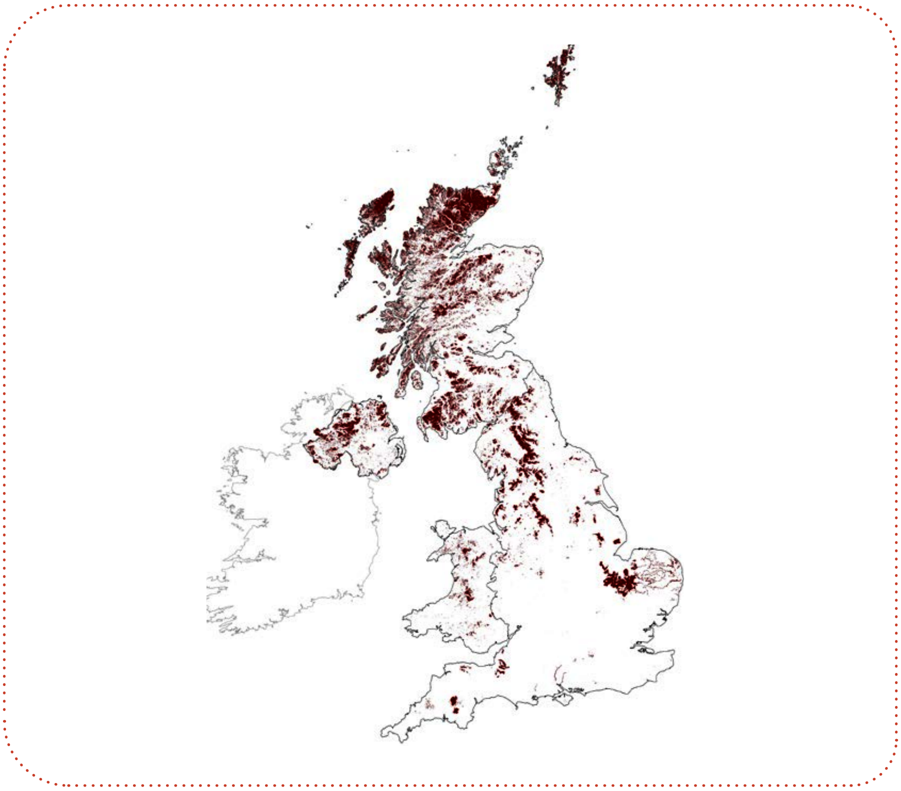
Peatlands in the United Kingdom extend from coastal lowland regions to the uplands. The most extensive peatland type is blanket bog, which forms in high-rainfall regions. Blanket bogs have been affected by drainage, grazing, managed burning, conifer plantation forestry, air pollution and erosion. Lowland peats, particularly fen peats, have been progressively drained and converted to agricultural use over centuries, to the extent that most of them are now under cultivation, and large areas have been reduced to thin ("wasted") peat. Lowland raised bogs are less extensive and have been affected by horticultural peat extraction as well as agricultural drainage. The most recent estimated extent of the United Kingdom's peatlands is 2.9 million ha (29 000 km^2) (Map 2).

The latest country-wide update on trends in condition on peatland habitats was published in 2013 (Joint Nature Conservation Committee, 2013). This report paints a largely bleak picture of the condition of peatland habitats under nature designation, with the overall assessment of condition status being considered bad across all nine reported peatland habitat types, although six of these habitats showed an overall improving trend in condition status. In both bog and fen, marsh and swamp habitats, a decline in species richness was noted.

National reporting on the condition of the United Kingdom peatlands is largely based on extrapolation of data from designated site monitoring. Various pilot projects have attempted to model peatland condition at local to national scale using satellite-derived data combined with ground observations (see below). There is an ongoing need for traditional field-survey data to support and provide meaningful quantification of remote-sensed and modelled peatland condition assessments at the national scale.

Peatlands undergoing active restoration management largely show significant improvements in ecological conditions, although most sites have been restored only recently and only a handful of publications from early restoration projects exist. However, a recent compilation of the current scientific evidence suggests that halting emissions from degraded peatlands now will have immediate climate mitigation benefits in the short to medium term, with potential long-term benefits for carbon, water and biodiversity (Günther *et al.* 2019).

Map 2 Updated map of the extent of peat in the United Kingdom



Source: James Hutton Institute, 2017.

Mapping and monitoring activities

The United Kingdom's peat maps are reliant on interpolated ground surveys, most of which were undertaken 30 or more years ago, and mapping methodologies (and even peat definitions) vary among the four devolved administrations (England, Northern Ireland, Scotland, Wales). Recent efforts aim to use satellite-data derived models in combination with ground observations to improve the mapping of peat extent.

Peatland mapping and national reporting have traditionally been achieved through upscaling from field-based surveys such as the UK's Common Standards Monitoring programme (Joint Nature Conservation Committee, 2004; 2009). The Programme, however, was not specifically designed to assess peat condition, and only covers legally protected sites so it does not provide a sufficient basis for national-scale assessment of peatland status, function or emissions. Evans *et al.* (2017) combined data from land cover and soil data sources to map peatland extent and provide a broad, habitat and soil-based, condition classification. They used the associated GHG emissions (also compiled in the same report) for these condition categories to estimate current GHG emissions from the country's peatlands. This report was used by the 2018 British Committee on Climate Change report to estimate that 4–11 Mt CO_2eq per annum could be mitigated by restoring peatlands by 2050 (Committee on Climate Change, 2018). Work is ongoing to incorporate full peatland GHG emissions reporting in the British national emissions inventory. Increased awareness of the condition of British peatlands and the emissions arising from them has led to an increase in public funding since 2012, which has resulted in a corresponding increase in the implementation of restoration measures on the ground.

Peatland monitoring is focused on reporting under international biodiversity obligations. Monitoring is carried out using ground-based surveys but is confined to (largely vegetation-based) habitat monitoring and assessments for a limited list of protected species. Remote surveillance options are being tested as lower-cost options. For example, there has now been a sizeable number of efforts to remotely assess the condition and/or degradation features in British peatlands, using aerial photography (Scholefield *et al.*, 2019) or in combination with LiDAR (Carless *et al.*, 2019). Water table and surface elevation fluctuations have been monitored using interferometric synthetic aperture radar (InSAR) from satellite sources (Alshammari *et al.*, 2018). This method has the potential to provide high-frequency monitoring of peat conditions and a proxy for CO_2 emissions and removals.

At a lower resolution, the condition across the whole of Scotland's peatlands was recently modelled using a time series of satellite data (Artz *et al.*, 2019). Sentinel-1 radar and Sentinel-2 spectral data could be used to produce higher-resolution and repeatable assessments of peatland condition to support national peatland GHG emissions reporting (Lindsay *et al.*, 2019). However, none of these remote techniques has yet been tested at the national scale.

Restoration is not monitored under any formal programme, in spite of its multiple societal benefits. Most, if not all, restoration monitoring includes some form of hydrological monitoring, often combined with assessments of vegetative change. In some cases, changes in GHG emissions or aqueous transport of carbon are being assessed. A review of the state of this monitoring evidence is currently being compiled for the IUCN UK Peatland Programme (unpublished). Current initiatives aim to develop standardized, low-cost monitoring methods for evaluating restoration outcomes and to verify the anticipated emissions reductions, to implement consistent national restoration monitoring systems in the future.

Future initiatives

There are potential benefits in using the power of modern remote-surveillance techniques to implement national peatland monitoring, but further testing of these methods is required to ensure they are fit for purpose for national reporting. Eyes on the Bog (Lindsay *et al.*, 2019), for example, is a newly launched citizen science monitoring initiative for British peatlands. It aims to engage the wider community in monitoring the condition and long-term changes of peatlands and provides a robust, repeatable and accessible monitoring methodology to harmonize basic data-collection across a network of long-term peatland monitoring sites.

The initiative employs cost-effective and simple techniques as well as modern technology to enable useful monitoring information to be collected by peatland community employees or volunteers. The information may be used to inform management interventions and test long-term climate predictions and assumptions about the condition and function of British peatlands. Data collected across multiple independently established sites within the Eyes on the Bog network can be collated in a standardized format by an open-access data hub. For example, PeatDataHub (https://peatdatahub.net/) is an emerging peatland-specific web application and database that allows the uploading and sharing of site metadata, datasets, files and images from peatlands around the world.

The aim is to facilitate the collaborative use of shared datasets to address both British and global-scale questions about peatlands in much the same way that Forestplots (http://www.forestplots.net/) has been used for tropical forests.

LESSONS LEARNED BY DIVERSE COUNTRIES

While peatland mapping status varies from country to country, most mapping efforts are recognized by academia. Official, nationwide peatland maps are not usually available, especially in tropical countries, where existing gaps are evident. Surveys that support peatland monitoring need to not only consider habitat type, but also the underlying soil characteristics that use harmonized classification methods to support consistent peatland mapping and monitoring approaches. A standardized peatland definition and harmonized mapping approaches would facilitate the creation of one, nationally confirmed peatland map.

Peatland monitoring has also sparked the interest of governments and private organizations. A holistic land use and land use change monitoring system would take into account the diverse needs, goals and institutional frameworks in each country.

Experience on peatland restoration monitoring is increasing. Restoration monitoring has helped to demonstrate the impact of investment. In most cases, current funding for peatland restoration does not provide adequate resources for monitoring and data collection. More coordinated and harmonized approaches are needed to reduce research and monitoring wastage, and to make better use of satellite technologies and citizen science.

Chapter 7

Remaining questions and knowledge gaps

by Maria Nuutinen, Felix Beer,
Laure-Sophie Schiettecatte and Peter Moore

Chapter 7

Remaining questions and knowledge gaps

by Maria Nuutinen, Felix Beer,
Laure-Sophie Schiettecatte and Peter Moore

Mapping and monitoring peatlands can be a challenging task depending on the spatial scale to cover and the number and kind of parameters to be assessed. In the long term, it would be ideal to develop a fully automatic monitoring system – based on a robust and practical mapping procedure – that combines ground and remotely sensed observations providing information on all desired parameters. However, the automatic quantification and upscaling of factors over large areas is not yet fully achieved and requires sophisticated intermediate processing steps, and expert analyses tailored to specific peatlands – a challenge to a wide range of users. Additionally, some parameters cannot directly be derived from remote sensing but depend on ground-point measurements, especially peat occurrence and GWL – one of the most important conditioning factors in peatland GHG emissions. Mapping, modelling and the use of proxies thus require further research to strengthen the scientific basis of their assessment and application.

Mapping methods are already well developed, and research has been carried out on the delineation of almost all types of peatlands. The variety of conditions and characteristics of peatland occurrence makes it difficult to standardize methodologies for peatland mapping at global and even at national levels, which usually increases the cost of field mapping activities on a scale necessary for land planning and management. New approaches and advances with remote sensing technologies are benefiting peatland mapping in a variety of contexts. Continuing to map and develop research on mapping will not only help countries to realize and value their peatland resources, but could lead to efficient and accurate peatland monitoring for conservation and sustainable management. A coherent link between peatland mapping and monitoring needs to be established to avoid wasting resources and institutional capacity.

In addition to the research and data gaps elaborated below, and the general need for capacity-development, constant maintenance of ground equipment and access to data remain crucial in the robust setting up and running of peatland monitoring in countries.

GROUNDWATER LEVEL AND SOIL MOISTURE

Remotely sensed radar-based soil moisture, in combination with GWL field monitoring, can be used as a proxy for GWL modelling (Hashim *et al.*, 2002; Jaenicke, Lohberger and Siegert, 2010). This approach needs further elaboration, as surface soil moisture is quickly changed by events such as precipitation without affecting the GWL. Furthermore, strongly degraded peat at the surface can become hydrophobic, causing surface soil moisture to lose its correlation with the underlying GWL (Wösten *et al.*, 2008). Despite the ability to show trends, and the effect of rewetting activities over time, uncertainties in the consistency of the soil moisture-GWL link require further investigation to robustly quantify the GWL from soil moisture, particularly for emissions estimations.

The appropriate distribution and continuing maintenance of ground observation instruments, to verify soil moisture data from remote sensing and modelling, constitute one of the main challenges to the integration of peatlands into national land use monitoring systems.

RELIABLE SOIL MOISTURE DETECTION

Technically, soil-moisture detection with radar (microwave) satellite systems are based on robust methodologies and has advantages over optical satellite-based approaches (Wang and Qu, 2009). However radar waves can only penetrate ground covering objects up to the size of their wavelength. L-band data with a wavelength of 24 cm that can penetrate vegetation is considered most suitable for remotely sensed soil-moisture assessment regardless of vegetation cover, but needs to be purchased (JAXA, 2020). Freely available X- and C-band data (e.g. Sentinel-1 for C-band) with wavelengths of 3.1 cm and 5.6 cm respectively, can only be applied on bare soils or areas with very light ground cover (e.g. short vegetation).Limited and expensive access to relevant data is a major obstacle to soil-moisture monitoring, as in

the case of entire peat domes in Indonesia. The NASA-ISRO synthetic aperture radar satellite (NISAR) will, however, provide freely accessible L-band data from 2021.

The use of vegetation moisture based on optical sensors as a proxy for soil moisture indicates good results, but also requires further investigation into the moisture dynamics of the different vegetation types and their relation to soil moisture.

GREENHOUSE GAS EMISSION ESTIMATIONS

Integrated systems utilizing data from remotely sensed and field measurements appear to be the best options for estimating GHG emissions and the status of peatlands. However, further measurements would be beneficial to fill the data gaps.

Emissions from decomposition

GHG emissions from peat decomposition correlate well with the GWL and subsidence and depend on land use type, nutrient status and climate zone (IPCC, 2014a). In countries such as Indonesia, where the current peatland management policies favour only partial rewetting (GWL at −40 cm), GHG monitoring should be able to account for emissions from peatlands with different GWLs – to showcase the benefits from raising the water table, even only partially – and on the other hand to emphasize the potential of complete rewetting and restoration for climate change mitigation and disaster reduction. Outside Indonesia, especially in tropical regions, data and models for robust GHG emission accounting on different land use types are largely lacking and require intensive research.

To improve national reporting of emissions from organic soils, the recommendation is to seek the best possible data on activities in the landscape, preferably those that comply with IPCC land use categories, in a spatially all-inclusive ("wall-to-wall") approach (Barthelmes *et al.*, 2018). It is important to collate and integrate all available information for nationwide, comprehensive coverage of organic soils, use proxy sources to identify possible occurrences of organic soils, and conduct peatland surveys that include fallow land, protected or otherwise not actively used, in particular when it has been drained. Potential proxies can include for example vegetation data, high-resolution elevation data, and data on drainage networks.

Emission factors

Further GHG emission measurements and refinement of emission factors are still needed, particularly in subtropical Africa and Central and South America, including degrading and restored highland peatlands. Decision-makers could benefit from information on peatland emission dynamics to confront a changing climate in the permafrost regions and other potential hotspots.

Land conversion, mainly conversion of wetlands such as mangroves and peatlands, will not only lead to changes in GHG emissions on land once converted and managed but will also export organic and inorganic materials to adjacent water bodies. This material will eventually sustain inland water ecosystem production and ultimately lead to CO_2, CH_4 and N_2O emissions to the atmosphere. Therefore, further research should be conducted to close the carbon budget in the peatlands by investigating more on exported carbon, such as dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and particulate organic carbon (POC) in drainage canals or ditches. This was already anticipated by the IPCC 2013 Wetlands Supplement, which provides information on the emission factors for CH_4 in the canals. More recent scientific literature also show evidence of fluvial transfer of carbon from managed peatlands which lead to GHG efflux from adjacent water bodies (Cook *et al.*, 2018; Evans, Renou-Wilson and Strack, 2015; Manning *et al.*, 2019).

Gaps in peat fire monitoring and emissions

Estimation of GHG emissions from burning peat is difficult due to the challenge of measuring the variables of (1) burnt area and depth of burn, (2) fuel present on the site (peat as well as aboveground biomass and other surface fuels), (3) fire intensity, (4) amount of fuel (peat) consumed and (5) the GHGs emitted from the burnt peat. The gaps can be set out as follows:

- The difficulty of measuring burnt peat area, fire patchiness and burn depth, is compounded by the fact that fire often smoulders underground. Very little research has been published to evaluate methods of collecting these data[20].
- There is also lack of data on peat fuel load, although peat density is sometimes measured.
- Limited information exists on peat fire intensity and severity in smouldering fires. Temperatures are measured in experiments.
- Investigation is required on consumption of peat by fire, although there may not be a lot of variation between burned areas.

There is limited research of trace gases emitted during authentic (non-experimental) peat fires burning at various depths in different peat types (Stockwell *et al.*, 2016). While monitoring systems have been established to detect fires and assess the burnt area, other relevant factors require better understanding and intense research in all peatland regions.

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[20] One exception is the APFNet project, Improving capacities towards reducing greenhouse gas emissions from peat swamp forest fires in Indonesia.

Chapter 8

Recommendations

by Hans Joosten, Maria Nuutinen, Laura Villegas,
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Chapter 8

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Peatland mapping and monitoring need to be approached as a complex and nuanced exercise. The key attributes of an effective monitoring system that includes peatlands will need a synergistic combination of various remote-sensing techniques together with the application of ground-truthing and field measurements, not overlooking the socio-economic factors that remain largely outside the scope of this report. For example, there is evidence that established remote-sensing techniques can be used at a landscape scale to assess land use cover and vegetation conditions, while newer higher-resolution methodologies could monitor the ground water level by detecting soil moisture levels and rates of subsidence.

The following five areas for recommendations give overall suggestions for **national decision-makers and institutions**, in particular, the **ministries in charge of finance, planning, agriculture, environment and forestry, statistical agencies, bodies in charge of conservation, national forest and land use inventories**, as well as **funding, development, cooperation and research institutions**. Similarly, the **scientific community and civil society** can often take a clearer role in advancing peatland protection.

1 ADVANCING WITH PEATLAND MAPPING

Peatland mapping and monitoring should be a priority for all **countries** with peatlands to maintain their carbon and ecosystem services. The support of **research organizations** is needed for the proper integration of information on peatland distribution, extent and status into national maps and monitoring systems. **National governments**, through the relevant ministries or agencies, should focus on consolidating and agreeing national peatland map that can be consistently used by other institutions and stakeholders in territorial planning, land-use management and conservation laws compliance. For the **international community**, coordination and capacity development to construct a global peatland map are imperative for the future management of restoration and preservation for related resource needs, as well as to collect lessons learned for different peatland types across the globe.

The **national agencies in charge of national forest and other land use inventories** are advised to recall that a harmonized and unified peatland map, that includes location, extent, approximate depth of peat and management status, among other variables, is the basis of effective peatland monitoring. Monitoring focuses on the identification of change of the different variables identified in the mapping phase over time. Remote sensing is extremely helpful in identifying and estimating peatland occurrence, especially where access and information availability is limited (see Chapter 2), but the exact location and extent of peatlands still requires knowledge of ground conditions and soil sampling. Field missions are essential to draw accurate conclusions about the carbon content of the soil and hence better estimates of GHG emissions from peat degradation, so must be budgeted either through national or regional budgets or through research funding.

National academia is in a good position to promote the conservation of these important carbon pools, advocating for the inclusion of shallow peat (widely regarded as a layer less than 50 cm deep) into peatland maps. A peat layer of 15 cm thick – only half the 30 cm depth used by conservative approaches to peatland definition – already holds a larger carbon stock than a high-carbon-stock forest on mineral soil (Barthelmes, Ballhorn and Couwenberg, 2015). For historical reasons, thin peatlands are not classified as peat in many countries. Because of classification issues, shallow peatlands are more often drained and degraded. Their inclusion in national maps would help to ensure that all peatlands were better managed and their emissions accounted for (Lindsay *et al.*, 2019.). Peatlands could be endangered and emissions could considerably increase if monitoring systems were to rely on outdated or inconsequential definitions.

2 FOCUS ON AREA AND COUNTRY-SPECIFIC DEFINITION

The definition of soil carbon content and the minimum thickness necessary to define a peatland, crucial in mapping methodologies, varies between countries. The decisions made in the early stage of definitions through collaboration of the **academia and national institutions** – regarding soil types and classifications, ecological and physical conditions for the identification of an area as a peatland, and key factors for peatland monitoring – will greatly influence a country's peatland delineation methodologies, future conservation strategies and GHG emissions. **International technical agencies** and experts can advise on the standardisation of concept definitions and methods, as well as share technologies in order to speed up the peatlands preservation process.

Peat depth is often mentioned as a critical factor for deciding the conservation value a peatland. However, when deciding on the intervention areas, **national institutions** can find it helpful to consider that many of the most relevant variables to be monitored in peatlands, such as GHG emissions and biodiversity, are largely independent of depth, especially in the short term. Whereas most countries and scientific disciplines specify a minimum depth of peat for an area to be called a peatland, such definitions differ widely and the background to most of them does not relate to monitoring. If the main goal of current monitoring is, for example, to identify GHG emissions and how they change over time, but the peatland definitions are informed by practical agricultural considerations (such as rooting and plough depth) (see e.g. Lindsay *et al.* 2019), a discrepancy between goals and definitions might occur.

The 2006 IPCC Guidelines largely follow the FAO definition of "histosols"[21], but have omitted the thickness criterion to allow for often historically determined, country-specific definitions of organic soils. As a recommendation for the **IPCC working groups**, a conservative approach to the definition of peatlands, which would serve most monitoring aims, would use a minimum thickness of the organic horizon of 10 cm. (See IPCC, 2014a).

In soil science, a threshold of 18 percent carbon has been established as the boundary above which soils are considered to be organic (Figure 4). This value has been recognised to exclude some soils with high volumetric carbon content - i.e. causing potential high emissions when degraded. From a climate point of view, the boundary between organic and mineral soils could be better drawn at 5 percent carbon, and decided e.g. through **national academia and institutions**. The problem of low-percentage and high-density carbon soils, which has already been recognised by various countries reporting emissions from "peaty soils", needs more attention from the **scientific community** (Barthelmes *et al.*, 2018).

3 UPDATING PEATLAND EMISSION FACTORS

The IPCC 2013 wetlands supplement provides emission factors for land use on peatlands for different climate zones, land use types and nutrient status (for boreal and temperate zones). At the time of publishing the Supplement, data from the tropics were limited. An update of the IPCC emission factors is now required to include all measurement data since 2013. The data, as well as available capacity-development approaches, would allow the guidance given in the supplement to be updated and clarified. Also, the **scientific community** could be invited to update the peatland emission references on the *IPCC Emission Factor Database* more systematically. Countries can use those data to increase the accuracy of their inventories instead of using the most simple methods and Tier 1 emission factors.

The **scientific community** should be encouraged to cover gaps in peatland GHG emission factors with the support under various funding mechanisms. Investment in more GHG and other carbon loss measurements on certain peatland types, such as degrading highland peatlands, is recommended.

Peatland fire emissions need to be addressed and calculated more accurately by the **scientific community** to build one functional and holistic system for monitoring and reporting on peatlands for various purposes, including improving MRV for various types of GHG (including REDD+) reporting.

Some countries already have started to integrate peatlands into their national monitoring systems, while others have developed certain elements but still need technical support and capacity development to set up and fully implement integrated systems. Mapping and peatland status update would often require attention and funding from **the development partners**.

4 INTEGRATING PEATLANDS INTO MONITORING SYSTEMS

Countries are increasingly burdened by various types of reporting needs and requests for statistical analysis. The SDG process aims to help manage and prioritize various reporting requirements. For **country decision-makers**, prioritising high-carbon ecosystems, integrating them into existing frameworks, plans, policies and legislation, as well as budgeting, is essential to safeguard, for example, the water services provided by peatlands.

Given that most countries have some forest and agriculture monitoring and reporting frameworks and established processes in place, it is recommended to integrate peatland monitoring into these frameworks. Several gaps still need to be filled to allow countries to improve their peatland mapping, monitoring and reporting for multiple purposes:

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[21] A histosol is defined as a soil having a histic or folic horizon, either 10 cm or more thick from the soil surface to a lithic or paralithic contact, or 40 cm or more thick and starting within 30 cm from the soil surface.

- Awareness needs to be raised that peatland-related mitigation and adaptation actions can be significant, similar to action on forests.
- Resources need to be targeted to assess the extent and condition of peatlands, not only for climate purposes but for land use and management planning.

Guidance and capacity can and must be rapidly developed to achieve functional monitoring systems, where confidence is being increased with international harmonisation and mutual quality control, for example through South-South and Triangular Cooperation events with participation of peatland countries.

Peat in national forest monitoring systems

National forest monitoring systems (NFMSs) is an area of work in which countries have already been investing, and which may be able to accommodate peatland considerations. National forest monitoring is a comprehensive process that includes the systematic collection, analysis and dissemination of forest-related data, and the derivation of information and knowledge at regular intervals using both remote sensing and ground data to allow the monitoring of changes over time (FAO, 2017).

An NFMS is one of the elements used by developing country Parties to the UNFCCC implementing REDD+ activities (UNFCCC, 2019a). An NFMS fulfils their obligations to continually develop, monitor and report on forest resources, which may include various land cover classes and soil types, such as peatlands (FAO, 2017). Progress has been made in many countries in this respect (FAO, 2018). These systems and their associated institutional capacities can serve as a starting point when developing specific mapping, measurement and monitoring approaches for peatlands. Ongoing initiatives have gained a wealth of experience on good practices for integrated monitoring, institutional arrangements and data management, which can be adapted to a peatland context bearing in mind that the main ecological consideration of peatlands is that their wetness is the main indicator for degradation.

The information generated by the NFMS can support a variety of land use planning and reporting requirements. Should **countries** choose to voluntarily report REDD+ activities, their NFMS can support the measurement, reporting and verification (MRV) process, through data provision to demonstrate impacts and outcomes of national mitigation policies and measures. Also, the data collected can be useful for forest reference emission levels and/or forest reference levels (FRELs/FRLs) and countries can consider including peatlands in them. Similarly, for peatlands, information derived from an NFMS can serve planning and reporting needs.

However, peat landscapes are diverse and can occur as forested peatlands, as well as other vegetation covers such as herbs, mosses and small shrubs. Besides, when used for productive purposes, they can coincide with diverse categories of land use such as cropland, grazing land, energy sources. Due to intense soil management practices, such as tillage and fertilization, peatlands under crops are often the source of higher emissions than other land uses. For these reasons, peatland mapping and monitoring should often reach beyond NFMS and its MRV and monitoring processes and needs to rely on cross-cutting data sources from **various government institutions** (see Figure 17).

Mapping of peatlands can build upon tools and methodologies already used in the NFMS, such as the satellite land monitoring system (and national forest inventory (NFI) and its household surveys. Similarly, peatland monitoring can contribute to an NFMS's MRV component as well as national GHG inventories with data such as GHG emissions, emission reductions and enhancement of removals by sinks, as well as reporting on adaptation action such as reduction in vulnerability. In the case of forested peatlands, both mapping and monitoring can contribute to REDD+ reporting through the inclusion of peat emissions and removals originating from forest land (conversion) in the FREL/FRL. It is important for **national agencies** to align peatland monitoring to the existing NFMS for consistency and transparency and to take advantage of existing verification processes.

Learning from experience

Monitoring systems can act as effective mechanisms to learn from the results of interventions on peatlands, modalities of engagement of stakeholders, restoration activities, data collection, among other aspects. The country cases presented in this report are an example of diverse ways in which monitoring systems can provide data on a range of peatland status variables. **Government**-led, application-supported, or community monitoring strategies, among other types, can provide timely updates that can build up to feed international reporting requirements. Finally, ideal monitoring systems should be sufficiently robust to ensure that climate change mitigation efforts are measurable, reportable and verifiable so that emissions and emission reductions are adequately and transparently captured.

5 IMPROVING COORDINATION AND INSTITUTIONAL SETTING

Given the cross-cutting nature of peatlands, various institutions have to collaborate closely in gathering the relevant data through their current or enhanced monitoring practices and systems (Figure 17). A significant challenge is often to have a true and efficient collaboration comprising of data sharing and trust between institutions. For ecosystems that extend over numerous landscapes such as peatlands, improving collaboration across sectors and institutions is a true requirement. **Developing countries** can benefit from enhancing the collaboration, and exchanging best practice through South-South and Triangular cooperation activities.

An example of inter-agency collaboration is the integration of the peat fire monitoring component within the land use monitoring system.

This allows early responses but often requires enhanced governance and coordination. **Land use planners** as well as **units developing and coordinating disaster risk reduction and management plans, strategies, budgets and actions**, would benefit from efficient information sharing on peatlands, their location and drainage status.

As explained in this publication it is possible to build on the lessons learned in different countries regarding the responsibilities and potential support available for MRV, including its institutional setting. As illustrated in Figure 17, to be able to collect and report data on peatlands to different international conventions, **various institutions need to share data with the coordinating unit often located in the Ministry of Environment**. As peatlands are utilized for cropping, grazing, forestry, plantations, infrastructure and extractive industries, institutions in charge of collecting the data (on the right side of the figure) should have peatlands and other high-carbon ecosystems included in their mandates to allow for a country to report on them. **Space agencies and units in charge of disaster risk reduction** will also need to collaborate and offer support.

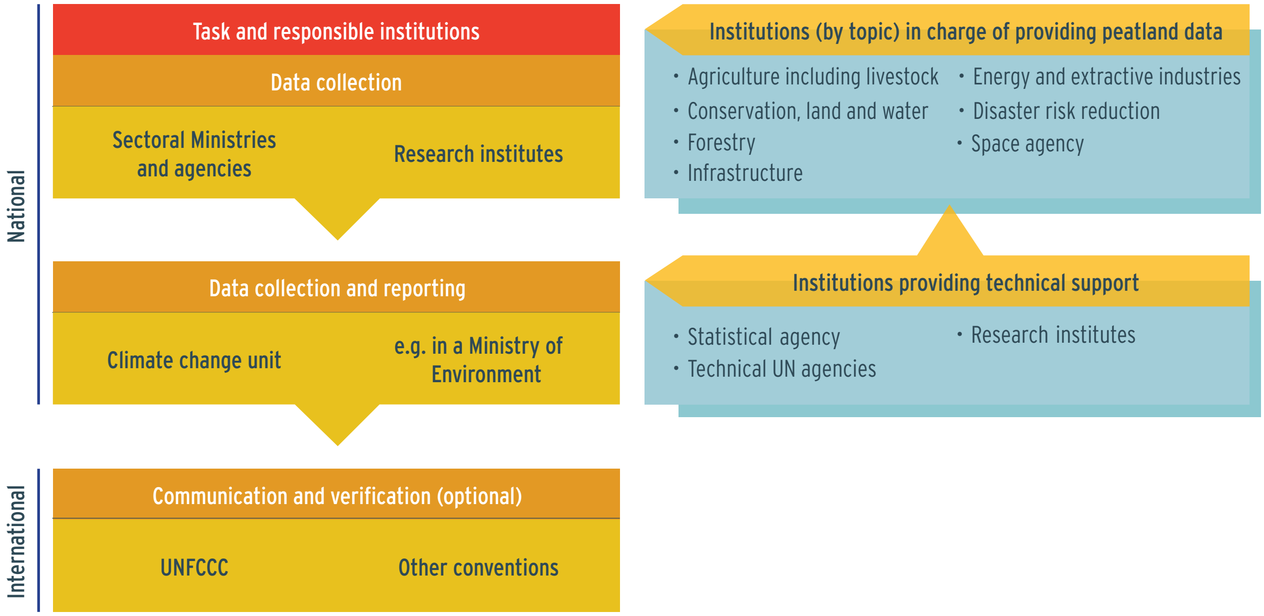
Capacity development and support on technical and institutional matters can and need to be provided by different **institutions both for collecting as well as combining data** and analysing information both for reporting and for improved management. Capacity should be understood here both as skills, knowledge and other capacities of individuals, organizations as well as their enabling environment, but also as hardware (tools, laboratories) and software, including land use monitoring and data processing platforms. A systematic review of approaches for covering peatlands within national coordination mechanisms as well as monitoring systems could be beneficial for countries now developing peatland monitoring.

CONCLUDING REMARKS

It is increasingly evident that mapping and monitoring of peatlands are crucial, particularly given the role of peatlands in climate change mitigation. Similarly, understanding the specific national context is critically important to integrate peatlands in the national institutional mandates and land use monitoring frameworks. The rapid development of peatland mapping and monitoring methodologies, guidance and capacity development approaches allow them to be tailored to country-specific context and needs.

As evidenced from the case studies in this publication, much remains to be done in particular to map peatlands before countries can develop reliable peatland monitoring and reporting systems. If resources can be systematically deployed to the work on peatlands, approaches described in this report can help conserve an array of peatland assets that in turn will help in adapting to and mitigating climate change.

Figure 17 Institutional setting and contribution to peatland monitoring and reporting



Annex I: Impacts of peatland degradation on selected SDGs

Table 7 The impacts of peatland degradation and restoration on selected SDGs

SDG	Impacts of peatland drainage and degradation	Impacts of peatland restoration
1. End poverty in all its forms everywhere.	Land subsidence and flooding: land loss, decreased productivity and income (Saputra, Spit and Zoomers, 2019).	Improved management of peatland ecosystems: sustainable livelihoods, alternative streams of income, and food and water security.
	Peatland fires: diminished income, decreased availability of fresh water, timber and non-timber forest products.	Increased resilience to economic, social and environmental disasters from fires, floods, and climate related shocks.
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.	Degrading water quality and quantity.	Restored water retention capacity with improved water availability and quality.
	Peat oxidation and land subsidence: flooding and exposed acid sulfate or organic soils decrease available agricultural land (Hoogland, Akker and Brus, 2012), agricultural yields, and food security.	Avoided land loss and better water availability: increased yields, resilient and sustainable food production, reduced hunger and malnutrition.
	Peat soil degradation: pressure on and scarcity of land prevent implementation of sustainable agriculture practices which reinforces monoculture plantation production (Sumarga *et al.*, 2016).	Sustainable biomass production on rewetted organic soils and peatlands "paludiculture" (Wichtmann, Schröder and Joosten, 2016).
3. Ensure healthy lives and promote well-being for all at all ages.	Reduced biodiversity and environmental quality: reduced food security and well-being.	Improved well-being and livelihoods by reducing risks of social and environmental hazards and diseases ensuring a cleaner environment, and water availability.
	Land subsidence: higher risk from flooding for coastal communities (Andreas *et al.*, 2018).	
13. Take urgent action to combat climate change and its impacts.	Drained peatlands are currently responsible for 5% of the global anthropogenic GHG emissions (Joosten, 2015).	Attenuated GHG emissions from fire and microbial oxidation.
	Continued drainage of already drained peatlands could leads to the release of 81 Gt of carbon and 2.3 Gt of nitrogen.	Intact peatlands are long-term carbon stores, holding an estimated 644 Gt of carbon globally.
	Peat erosion by wind, water and frost increases carbon losses and GHG emissions (Parry *et al.*, 2014).	High peatland water tables and revegetation reduce peat erosion.
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.	Peatland drainage and vegetation damage affect biodiversity and the provision of various ecosystem services (Dieleman *et al.*, 2015).	Peatland restoration restores the wide variety of ecosystem services that wet peatlands provide (Bonn *et al.*, 2016; Wichtmann, Schröder and Joosten, 2016).
	Continued drainage-based agricultural crop production leads to further land degradation.	Increased resilience reduces the impacts of environmental disasters and climate regime shifts.

References

Abram, N.J., Gagan, M.K., Cole, J.E., Hantoro, W.S. & Mudelsee, M. 2008. Recent intensification of tropical climate variability in the Indian Ocean. Nature Geoscience, 1(12): 849–853. https://doi.org/10.1038/ngeo357

Adinugroho, W.C., Nyoman, I., Suryadiputra, N., Saharjo, B.H. & Siboro, L. 2005. Manual for the control of fire in peatlands and peatland forest. Climate Change, Forests and Peatlands in Indonesia Project. Bogor, Indonesia, Wetlands International–Indonesia Programme and Wildlife Habitat Canada. 183 pp. https://indonesia.wetlands.org/publications/manual-for-the-control-of-fire-in-peatlands-and-peatland-forest/

Agus, F., Hairiah, K. & Mulyani, A. 2011. Measuring carbon stock in peat soils: practical guidelines. Bogor, Indonesia, World Agroforestry Centre (ICRAF). 60 pp. http://old.worldagroforestry.org/downloads/Publications/PDFS/MN17335.PDF

Alshammari, L., Large, D.J., Boyd, D.S., Sowter, A., Anderson, R., Andersen, R. & Marsh, S. 2018. Long-term peatland condition assessment via surface motion monitoring using the ISBAS DInSAR technique over the flow country, Scotland. Remote Sensing 10(7): 1103. https://doi.org/10.3390/rs10071103

Anderson, J. 1983. The tropical peat swamps of western Malaysia. Ecosystems of the World 4B: mires: swamp, bog, fen and moor, pp. 181–199. Amsterdam, Elsevier.

Andreas, H., Abidin, H.Z., Gumilar, I., Sidiq, T.P., Sarsito, D.A. & Pradipta, D. 2018. Insight into the correlation between land subsidence and the floods in regions of Indonesia. Natural Hazards – Risk Assessment and Vulnerability Reduction. https://doi.org/10.5772/intechopen.80263

Arino, O., Bicheron, P., Achard, F., Latham, J., Witt, R. & Weber, J. 2008. GLOBCOVER – The most detailed portrait of Earth. ESA Bulletin, 136. Frascati, Italy, European Space Agency Directorate of Earth Observation Programmes. https://earth.esa.int/web/guest/-/globcover-the-most-detailed-portrait-of-earth-5910

Artz, R.R.E., Johnson, S., Bruneau, P., Britton, A.J., Mitchell, R.J., Ross, L., Donaldson-Selby, G., Donnelly, D., Aitkenhead, M.J., Gimona, A. & Poggio, L. 2019. The potential for modelling peatland habitat condition in Scotland using long-term MODIS data. The Science of the Total Environment, 660: 429–442. https://doi.org/10.1016/j.scitotenv.2018.12.327

ASEAN. 2009. Report for peatland and fire management capacity building project. Jakarta, ASEAN Australia Development Cooperation Program. https://www.oecd.org/countries/fiji/48473742.pdf

ASEAN. 2017. Roadmap on ASEAN cooperation towards transboundary haze pollution control with means of implementation. In Haze Action Online [online]. [Cited 24 September 2019]. http://haze.asean.org/haze-free-roadmap/

Baird, A.J., Evans, C.D., Mills, R., Morris, P.J., Page, S.E., Peacock, M., Reed, M., Robroek, B.J.M., Stoneman, R., Swindles, G.T., Thom, T., Waddington, J.M. & Young, D.M. 2019. Validity of managing peatlands with fire. Nature Geoscience, 12(11): 884–885. https://doi.org/10.1038/s41561-019-0477-5

Ballhorn, U., Jubanski, J. & Siegert, F. 2011. ICESat/GLAS Data as a measurement tool for peatland topography and peat swamp forest biomass in Kalimantan, Indonesia. Remote Sensing, 3(9): 1957–1982. https://doi.org/10.3390/rs3091957

Ballhorn, U., Konecny, K., Prayitno, M., Joosten, H., Navratil, P., Setiadi, B. & Siegert, F. 2018. International Peat Mapping Team (IPMT) final report. Final Testing Phase (Kubu Raya District). Indonesian Peat Prize.

Barthelmes, A., Ballhorn, U. & Couwenberg, J. 2015. Consulting study 5: practical guidance on locating and delineating peatlands and other organic soils in the tropics. High Carbon Stock (HCS) Science Study. www.carbonstockstudy.com

Barthelmes, A., Connolly, J., Couwenberg, J., Hanganu, J., Heikkilä, R., Ivanovs, J., Joosten, H., Lazdins, A., Lupikis, A., Møller, A., Peters, J., Tanneberger, F., Turunen, J. & Wilson, D. 2018. Reporting greenhouse gas emissions from organic soils in the European Union: challenges and opportunities. Greifswald, Germany, Greifswald Mire Centre. https://www.euki.de/wp-content/uploads/2018/12/181211_PolicyBriefing_Paludiculture.pdf

Bartholomé, E. & Belward, A.S. 2005. GLC2000: a new approach to global land cover mapping from Earth observation data. International Journal of Remote Sensing, 26(9): 1959–1977. https://doi.org/10.1080/01431160412331291297

BBSDLP. 2013. Rencana Strategis: Penelitian dan Pengembangan Sumberdaya Lahan Pertanian 2015–2019, p. 98. No. 18. Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian, Badan Penelitaian dan Pengembangan Pertanian, Kementrian Pertanian. http://sakip.pertanian.go.id/admin/file/Renstra%202015-2019%20BBSDLP.pdf

Bechtold, M., Schlaffer, S., Tiemeyer, B. & De Lannoy, G. 2018. Inferring water table depth dynamics from ENVISAT-ASAR C-band backscatter over a range of peatlands from deeply-drained to natural conditions. Remote Sensing, 10(4): 536. https://doi.org/10.3390/rs10040536

Besseau, P., Graham, S. & Christophersen, T. 2018. Restoring forests and landscapes: the key to a sustainable future. Vienna, Global Partnership on Forest and Landscape Restoration. http://www.forestlandscaperestoration.org/sites/forestlandscaperestoration.org/files/resources/GPFLR_FINAL%2027Aug.pdf

Bonn, A., Reed, M.S., Evans, C.D., Joosten, H., Bain, C., Farmer, J., Emmer, I., Couwenberg, J., Moxey, A., Artz, R., Tanneberger, F., Unger, M. von, Smyth, M.-A. & Birnie, D. 2014. Investing in nature: Developing ecosystem service markets for peatland restoration. Ecosystem Services, 9: 54–65. https://doi.org/10.1016/j.ecoser.2014.06.011

Bonn, A., Allott, T., Evans, M., Joosten, H. & Stoneman, R. 2016. Peatland restoration and ecosystem services: an introduction. In A. Bonn, T. Allott, M. Evans, H. Joosten & R. Stoneman, eds. Peatland Restoration and Ecosystem Services, pp. 1–16. Cambridge, UK, Cambridge University Press. https://www.cambridge.org/core/product/identifier/CBO9781139177788A012/type/book_part

Bourgeau-Chavez, L.L, Endres, S.L., Graham, J.A., Hribljan, J.A., Chimner, R.A, Lilleskov, E.A. & Battaglia, M.J. 2018. Mapping peatlands in boreal and tropical ecoregions. Elsevier, Reference Module in Earth Systems and Environmental Sciences, 6.04. https://www.fs.fed.us/nrs/pubs/jrnl/2018/nrs_2018_bourgeau-chavez_001.pdf

Brady, M. 1997. Organic matter dynamics of coastal peat deposits in Sumatra, Indonesia. University of British Columbia, Canada. (PhD dissertation)

BRG. 2016. BRG's roadmap for peatland restoration. Paper presented at CBD & FAO workshop: "Forest Ecosystem Restoration", 27 June 2016, Bangkok. Badan Restorasi Gambut/Peatland Restoration Agency. https://www.cbd.int/doc/meetings/ecr/ecrws-2016-02/other/ecrws-2016-02-presentation-day1-03-en.pdf

Carey, P.D., Wallis, S., Chamberlain, P.M., Cooper, A., Emmett, B.A., Maskell, L.C., McCann, T., Murphy, J., Norton, L.R., Reynolds, B., Scott, W.A., Simpson, I.C., Smart, S.M. & Ullyett, J.M. 2008. Countryside survey: UK results from 2007. NERC Open Research Archive. 105 pp. http://nora.nerc.ac.uk/id/eprint/5191/

Carless, D., Luscombe, D.J., Gatis, N., Anderson, K. & Brazier, R.E. 2019. Mapping landscape-scale peatland degradation using airborne lidar and multispectral data. Landscape Ecology, 34(6): 1329–1345. https://doi.org/10.1007/s10980-019-00844-5

CBD. 2016. Decision adopted by the Conference of the Parties to the Convention on Biological Diversity XIII/28: Indicators for the Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets, p. 24. No. CBD/COP/DEC/XIII/28. Cancun, Mexico. https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-28-en.pdf

Chimner, R.A., Bourgeau-Chavez, L., Grelik, S., Hribljan, J.A., Clarke, A.M.P., Polk, M.H., Lilleskov, E.A. & Fuentealba, B. 2019. Mapping mountain peatlands and wet meadows using multi-date, multi-sensor remote sensing in the Cordillera Blanca, Peru. Wetlands. https://doi.org/10.1007/s13157-019-01134-1

CIFOR. 2017. Peru's peat. In CIFOR Forests News [online]. Bogor, Indonesia, Center for International Forestry Research. [Cited 20 July 2019]. https://forestsnews.cifor.org/49728/leveraging-peat-to-beat-the-heat?fnl=en

Cigna, F., Sowter, A., Jordan, C. & Rawlins, B. 2014. Intermittent Small Baseline Subset (ISBAS) monitoring of land covers unfavourable for conventional C-band InSAR: Proof-of-concept for peatland environments in North Wales, UK. Proceedings of SPIE – The International Society for Optical Engineering.

Committee on Climate Change. 2018. Land use: reducing emissions and preparing for climate change. [Cited 20 July 2019]. https://www.theccc.org.uk/wp-content/uploads/2018/11/Land-use-Reducing-emissions-and-preparing-for-climate-change-CCC-2018-1.pdf

Cook, S., Whelan, M., Evans, C., Gauci, V., Peacock, M., Garnett, M., Kho, L.K., Teh, Y.A. & Page, S. 2018. Fluvial organic carbon fluxes from oil palm plantations on tropical peatland. Biogeosciences Discussions: 1–33. https://doi.org/10.5194/bg-2018-417

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A. & Joosten, H. 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiology, 674(1): 67–89. https://doi.org/10.1007/s10750-011-0729-x

Couwenberg, J. & Hooijer, A. 2013. Towards robust subsidence-based soil carbon emission factors for peat soils in south-east Asia, with special reference to oil palm plantations. Mires and Peat, 12: 1–13. http://pixelrauschen.de/wbmp/media/map12/map_12_01.pdf

Dargie, G.C., Lawson, I.T., Rayden, T.J., Miles, L., Mitchard, E.T.A., Page, S.E., Bocko, Y.E., Ifo, S.A. & Lewis, S.L. 2018. Congo Basin peatlands: threats and conservation priorities. Mitigation and Adaptation Strategies for Global Change, 24(4): 669–686. https://doi.org/10.1007/s11027-017-9774-8

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T.A., Page, S.E., Bocko, Y.E. & Ifo, S.A. 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature, 542: 86. https://doi.org/10.1038/nature21048

Dave, R., Saint-Laurent, C., Murray, L., Antunes Daldegan, G., Brouwer, R., de Mattos Scaramuzza, C.A., Raes, L., Simonit, S., Catapan, M., García Contreras, G., Ndoli, A., Karangwa, C., Perera, N., Hingorani, S. & Pearson, T. 2019. Second Bonn Challenge progress report. Gland, Switzerland, International Union for Conservation of Nature. https://portals.iucn.org/library/node/48446

Democratic Republic of the Congo. 2020. National Forest Monitoring System. [online]. [Cited 16 March 2020]. http://www.rdc-snsf.org/

Dieleman, C., Branfireun, B., McLaughlin, J. & Lindo, Z. 2015. Climate change drives a shift in peatland ecosystem plant community: Implications for ecosystem function and stability. Global Change Biology, 21. https://doi.org/10.1111/gcb.12643

Draper, F.C., Roucoux, K.H., Lawson, I.T., Mitchard, E.T.A., Honorio Coronado, E.N., Lähteenoja, O., Torres Montenegro, L., Valderrama Sandoval, E., Zaráte, R. & Baker, T.R. 2014. The distribution and amount of carbon in the largest peatland complex in Amazonia. Environmental Research Letters, 9(12): 124017. https://doi.org/10.1088/1748-9326/9/12/124017

Evans, C., Renou-Wilson, F. & Strack, M. 2015. The role of waterborne carbon in the greenhouse gas balance of drained and rewetted peatlands. Aquatic Sciences, 78. https://doi.org/10.1007/s00027-015-0447-y

Evans, C., Artz, R., Moxley, J., Taylor, E., Archer, N., Burden, A., Williamson, J., Donnelly, D., Thomson, A., Buys, G., Malcolm, H., Wilson, D. & Potts, J. 2017. Implementation of an emissions inventory for UK peatlands, p. 88. Bangor, UK, Centre for Ecology and Hydrology. https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1904111135_UK_peatland_GHG_emissions.pdf

Evans, C.D., Williamson, J.M., Kacaribu, F., Irawan, D., Suardiwerianto, Y., Hidayat, M.F., Laurén, A. & Page, S.E. 2019. Rates and spatial variability of peat subsidence in Acacia plantation and forest landscapes in Sumatra, Indonesia. Geoderma, 338: 410–421. https://doi.org/10.1016/j.geoderma.2018.12.028

FAO. 1998. World reference base for soil resources. Rome, International Society of Soil Science ISSS-AISS-IBG. http://www.fao.org/3/w8594e/w8594e00.htm#Contents

FAO. 2014. Towards climate-responsible peatlands management. R. Biancalani & A. Avagyan, eds. Mitigation of Climate Change in Agriculture Series No. 9. Rome. 100 pp. [Cited 10 March 2020]. http://www.fao.org/documents/card/en/c/ed3a3b92-de47-4825-a417-f0daad81efb5/

FAO. 2017. Voluntary guidelines on national forest monitoring. Rome. 60 pp.

FAO. 2018. Advancing the role of natural regeneration in large-scale forest and landscape restoration in the Asia-Pacific region. Rome. http://www.fao.org/3/i8392en/I8392EN.pdf

FAO. 2019a. Restoring forest landscapes through assisted natural regeneration (ANR) – a practical manual. Rome. http://www.fao.org/3/ca4191en/ca4191en.pdf

FAO. 2019b. From reference levels to results reporting: REDD+ under the UNFCCC. Rome. http://www.fao.org/3/ca6031en/ca6031en.pdf

FAO. 2020a. Compliance with the Enhanced Transparency Framework under the Paris Agreement. [online]. Italy. [Cited 16 March 2020]. http://www.fao.org/climate-change/our-work/what-we-do/ndcs/transparency-framework

FAO. 2020b. Openforis. Free open-source solutions for environmental monitoring. [online]. Italy. [Cited 16 March 2020]. http://www.openforis.org/

FAO. 2020b. Openforis. Free open-source solutions for environmental monitoring. [online]. Italy. [Cited 16 March 2020]. http://www.openforis.org/

Frandsen, W. 1997. Ignition probability of organic soils. Canadian Journal of Forest Research, 27: 1471–1477. https://doi.org/10.1139/x97-106

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A. & Huang, X. 2010. MODIS collection 5 global land cover: algorithm refinements and characterization of new datasets. Remote Sensing of Environment, 114(1): 168–182. https://doi.org/10.1016/j.rse.2009.08.016

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. & Sheil, D. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Scientific Reports, 4(1): 6112. https://doi.org/10.1038/srep06112

GEF. 2019. Draft: guidelines for land degradation neutrality. No. GEF/STAP/C.56/Inf.02. Washington, DC, Global Environment Facility. https://www.thegef.org/sites/default/files/council-meeting-documents/EN_GEF.STAP_.C.56.Inf_.02_Guidelines%20for%20Land%20Degradation%20Neutrality.pdf

GFOI. 2013. Integrating remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests. Methods and Guidance from the Global Forest Observations Initiative, Geneva, Switzerland, Group on Earth Observations. https://unfccc.int/files/land_use_and_climate_change/redd/submissions/application/pdf/redd_20140218_mgd_report_gfoi.pdf

Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L. & Justice, C.O. 2018. The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment, 217: 72–85. https://doi.org/10.1016/j.rse.2018.08.005

Giglio, L., Descloitres, J., Justice, C.O. & Kaufman, Y.J. 2003. An enhanced contextual fire detection algorithm for MODIS. Remote Sensing of Environment, 87(2–3): 273–282. https://doi.org/10.1016/S0034-4257(03)00184-6

Global Partnership on Forest and Landscape Restoration. 2018. Our approach: the landscape approach [online]. [Cited 24 October 2019]. http://www.forestlandscaperestoration.org/our-approach-landscape-approach

GOFC-GOLD. 2013, 2015. A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation. Chapter 2.10.4: Forest monitoring using synthetic aperture radar (SAR) observations. Netherlands, GOFC-GOLD Land Cover Project Office, Wageningen University. http://www.gofcgold.wur.nl/redd/sourcebook/GOFC-GOLD_Sourcebook.pdf

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. & Moore, R. 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. Remote Sensing of Environment, 202: 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Greifeneder, F., Khamala, E., Sendabo, D., Wagner, W., Zebisch, M., Farah, H. & Notarnicola, C. 2019. Detection of soil moisture anomalies based on Sentinel-1. Physics and Chemistry of the Earth, Parts A/B/C, 112: 75–82. https://doi.org/10.1016/j.pce.2018.11.009

Gumbricht, T. 2012. Mapping global tropical wetlands from Earth Observing satellite imagery, p. 60. Working Paper 103. Bogor, Indonesia, Center for International Forestry Research. https://www.climatelinks.org/sites/default/files/asset/document/WP103CIFOR.pdf

Gumbricht, T., Roman-Cuesta, R.M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N. & Murdiyarso, D. 2017. An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. Global Change Biology, 23(9): 3581–3599. https://doi.org/10.1111/gcb.13689

Günther, Anke & Barthelmes, Alexandra & Huth, Vytas & Joosten, Hans & Jurasinski, Gerald & Koebsch, Franziska & Couwenberg, John. 2019. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. 10.1101/748830. https://www.biorxiv.org/content/10.1101/748830v1

Hansen, M.C., Defries, R.S., Townshend, J.R.G. & Sohlberg, R. 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. International Journal of Remote Sensing, 21(6–7): 1331–1364. https://doi.org/10.1080/014311600210209

Hashim, M., Busu, I., Sim, S., Jong, T., Kadir, W. & Salam, N. 2002. Soil moisture, depth of water table and peat decomposition in Sadong Simunjan river basin, Sarawak using AIRSAR/TOPSAR data. Paper presented at 3rd Malaysian Remote Sensing & GIS Conference and Exhibition "Spatial information Technology in the New Millennium", 2002, Kuala Lumpur.

Hidayat, H., Hoekman, D.H., Vissers, M. & Hoitink, A.J.F. 2011. Flood frequency mapping of the Middle Mahakam lowland area using satellite radar. AGU Fall Meeting Abstracts, 8: 0917. https://doi.org/10.5194/hessd-8-11519-2011

Hirano, T., Segah, H., Harada, T., Limin, S., June, T., Hirata, R. & Osaki, M. 2007. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Global Change Biology, 13(2): 412–425. https://doi.org/10.1111/j.1365-2486.2006.01301.x

Hirano, T., Segah, H., Kusin, K., Limin, S., Takahashi, H. & Osaki, M. 2012. Effects of disturbances on the carbon balance of tropical peat swamp forests. Global Change Biology, 18(11): 3410–3422. https://doi.org/10.1111/j.1365-2486.2012.02793.x

Hoekman, D. 2018. Remote sensing of wetland types: peat swamps. The Wetland Book: I: Structure and Function, Management, and Methods, pp. 1649–1657. https://doi.org/10.1007/978-90-481-9659-3_306

Hoekman, D.H. 2007. Satellite radar observation of tropical peat swamp forest as a tool for hydrological modelling and environmental protection. Aquatic Conservation: Marine and Freshwater Ecosystems, 17: 265–275. https://doi.org/10.1002/aqc.834

Hoekman, D.H. & Quiñones, M. 2002. Biophysical forest type characterization in the Colombian Amazon by airborne polarimetric SAR. Geoscience and Remote Sensing, IEEE Transactions on Geoscience and Remote Sensing, 40(6): 1288–1300. https://doi.org/10.1109/TGRS.2002.800242

Hoekman, D.H., Vissers, M. & Wielaard, N. 2010. PALSAR wide-area mapping of Borneo: methodology and map validation. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 3(4): 605–617. https://doi.org/10.1109/JSTARS.2010.2070059

Höfle, B., Vetter, M., Pfeifer, N., Mandlburger, G. & Stötter, J. 2009. Water surface mapping from airborne laser scanning using signal intensity and elevation data. Earth Surface Processes and Landforms, 34(12): 1635–1649. https://doi.org/10.1002/esp.1853

Hoogland, T., Akker, J.J.H. van den & Brus, D.J. 2012. Modelling the subsidence of peat soils in the Dutch coastal area. Geoderma, 171–172: 92–97. https://doi.org/10.1016/j.geoderma.2011.02.013

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H. & Jauhiainen, J. 2010. Current and future CO2 emissions from drained peatlands in Southeast Asia. Biogeosciences, 7(5): 1505–1514. https://doi.org/10.5194/bg-7-1505-2010

Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A. & Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands. Biogeosciences, 9(3): 1053–1071. https://doi.org/10.5194/bg-9-1053-2012

Hopkinson, C., Crasto, N., Marsh, P., Forbes, D. & Lesack, L. 2011. Investigating the spatial distribution of water levels in the Mackenzie Delta using airborne LiDAR. Hydrological Processes: n/a-n/a. https://doi.org/10.1002/hyp.8167

IPCC. 2014a. 2013 Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. Geneva, Switzerland, Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/wetlands/pdf/Wetlands_Supplement_Entire_Report.pdf

IPCC. 2014b. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx, eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IUCN. 2016. Securing the future for global peatlands. WCC-2016-Res-043-EN. Gland, Switzerland, International Union for Conservation of Nature. https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2016_RES_043_EN.pdf

IUCN UK Peatland Programme. 2020. Update: State of UK Peatlands. [online].The UK. [Cited 16 March 2020]. https://www.iucn-uk-peatlandprogramme.org/resources/commission-inquiry/commission-inquiry-peatlands-update/update-state-uk-peatlands

IUCN UK Peatland Programme. 2020. Update: State of UK Peatlands. [online]. The UK. [Cited 16 March 2020]. https://www.iucn-uk-peatlandprogramme.org/resources/commission-inquiry/commission-inquiry-peatlands-update/update-state-uk-peatlands

Jaenicke, J., Englhart, S. & Siegert, F. 2010. Monitoring the effect of restoration measures in Indonesian peatlands by radar satellite imagery. Journal of Environmental Management, 92(3): 630–638. https://doi.org/10.1016/j.jenvman.2010.09.029

Jaenicke, J., Rieley, J.O., Mott, C., Kimman, P. & Siegert, F. 2008. Determination of the amount of carbon stored in Indonesian peatlands. Geoderma, 147(3–4): 151–158. https://doi.org/10.1016/j.geoderma.2008.08.008

JAXA, 2020. About ALOS- PALSAR. [online]. Japan. [Cited 16 March 2020]. https://www.eorc.jaxa.jp/ALOS/en/about/palsar.htm

Joerg, R. & Körschens, M. 2009. Calculating the effect of soil organic matter concentration on soil bulk density. Soil Science Society of America Journal – SSSAJ, 73. https://doi.org/10.2136/sssaj2007.0149

Joint Nature Conservation Committee. 2004. Common Standards Monitoring Guidance for Lowland Wetland Habitats. Peterborough, UK. [Cited 20 July 2019]. https://hub.jncc.gov.uk/assets/2ca75082-4246-4ec3-9472-08fbc24165a3

Joint Nature Conservation Committee. 2009. Common Standards Monitoring Guidance for Upland Habitats. Peterborough, UK. [Cited 20 July 2019]. https://hub.jncc.gov.uk/assets/78aaef0b-00ef-461d-ba71-cf81a8c28fe3

Joint Nature Conservation Committee. 2013. Habitat Conservation Status Reports - 3rd UK Habitats Directive Reporting 2013. Habitat Reports. Peterborough, UK. http://archive.jncc.gov.uk/page-6563

Joosten, H. 2015. Peatlands, climate change mitigation and biodiversity conservation. An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots. Copenhagen, Nordic Council of Ministers. http://dx.doi.org/10.6027/ANP2015-727

Joosten, H. and Clarke, D. 2002. Wise Use of Mires and Peatlands. International Mire Conservation Group & International Peat Society, pp. 304. [Cited 10 March 2020]. http://www.imcg.net/media/download_gallery/books/wump_wise_use_of_mires_and_peatlands_book.pdf

Joosten, H., Sirin, A., Couwenberg, J., Laine, J. & Smith, P. 2016. The role of peatlands in climate regulation. Peatland Restoration and Ecosystem Services, pp. 63–76. New York, Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139177788.005

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F. & Kaufman, Y. 2002. The MODIS fire products. Remote Sensing of Environment, 83(1–2): 244–262. https://doi.org/10.1016/S0034-4257(02)00076-7

Kaufman, Y.J., Justice, C.O., Flynn, L.P., Kendall, J.D., Prins, E.M., Giglio, L., Ward, D.E., Menzel, W.P. & Setzer, A.W. 1998. Potential global fire monitoring from EOS-MODIS. Journal of Geophysical Research: Atmospheres, 103(D24): 32215–32238. https://doi.org/10.1029/98JD01644

Kool, D., Buurman, P. & Hoekman, D.H. 2006. Oxidation and compaction of a collapsed peat dome in Central Kalimantan. Geoderma 137, 1, 137. https://doi.org/10.1016/j.geoderma.2006.08.021

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M. & Myers, S.S. 2016. Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. Environmental Research Letters, 11(9): 094023. https://doi.org/10.1088/1748-9326/11/9/094023

Lähteenoja, O. & Page, S. 2011. High diversity of tropical peatland ecosystem types in the Pastaza-Marañón basin, Peruvian Amazonia. Journal of Geophysical Research, 116(G2): G02025. https://doi.org/10.1029/2010JG001508

Lähteenoja, O., Ruokolainen, K., Schulman, L. & Alvarez, J. 2009. Amazonian floodplains harbour minerotrophic and ombrotrophic peatlands. CATENA, 79(2): 140–145. https://doi.org/10.1016/j.catena.2009.06.006

Langner, A., Miettinen, J. & Siegert, F. 2007. Land cover change 2002–2005 in Borneo and the role of fire derived from MODIS imagery. Global Change Biology, 13(11): 2329–2340. https://doi.org/10.1111/j.1365-2486.2007.01442.x

Lawson, I.T., Kelly, T.J., Aplin, P., Boom, A., Dargie, G., Draper, F.C.H., Hassan, P.N.Z.B.P., Hoyos-Santillan, J., Kaduk, J., Large, D., Murphy, W., Page, S.E., Roucoux, K.H., Sjögersten, S., Tansey, K., Waldram, M., Wedeux, B.M.M. & Wheeler, J. 2014. Improving estimates of tropical peatland area, carbon storage, and greenhouse gas fluxes. Wetlands Ecology and Management, 23(3): 327–346. https://doi.org/10.1007/s11273-014-9402-2

Leifeld, J. & Menichetti, L. 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. Nature Communications, 9(1): 1071–1071. https://doi.org/10.1038/s41467-018-03406-6

Leifeld, J., Wüst-Galley, C. & Page, S. 2019. Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. Nat. Clim. Chang. 9, 945–947. https://doi.org/10.1038/s41558-019-0615-5

Limpens, J., Holmgren, M., Jacobs, C., van der Zee, S., Karofeld, E. & Berendse, F. 2014. How does tree density affect water loss of peatlands? A mesocosm experiment. PLoS ONE, 9. https://doi.org/10.1371/journal.pone.0091748

Lindsay, R., Clough, J., Clutterbuck, B., Bain, C. & Goodyer, E. 2019. Eyes on the bog manual: long-term monitoring network for UK peatlands. Gland, Switzerland, International Union for Conservation of Nature. [Cited 21 October 2019]. https://www.iucn-uk-peatlandprogramme.org/sites/default/files/header-images/Eyes%20on%20the%20Bog%20Manual.pdf

Lohberger, S., Franke, J., Keuck, V. & Siegert, F. 2012. Aboveground biomass estimation of tropical peat swamp forests using SAR and optical data. Paper presented at International Geoscience and Remote Sensing Symposium (IGARSS), Munich, Germany. http://www.grss-ieee.org/event/igarss-2012/

Lohberger, S., Stängel, M., Atwood, E.C. & Siegert, F. 2018. Spatial evaluation of Indonesia's 2015 fire-affected area and estimated carbon emissions using Sentinel-1. Global Change Biology, 24(2): 644–654. https://doi.org/10.1111/gcb.13841

Lopez Izquierdo, N. 2017. Congo Basin: extent of peatlands and threats. Cambridge, UK, UN Environment World Conservation Monitoring Centre, University of Leeds and University College London. [Cited 23 September 2019]. http://www.grida.no/resources/12534

Lowry, C.S., Fratta, D. & Anderson, M.P. 2009. Ground penetrating radar and spring formation in a groundwater dominated peat wetland. Journal of Hydrology, 373(1): 68–79. https://doi.org/10.1016/j.jhydrol.2009.04.023

Lucas, R., Rosenqvist, A., Kellndorfer, J., Hoekman, D., Shimada, M., Clewley, D., Walker, W. & Navarro de Mesquita Junior, H. 2012. Chapter 4: Global forest monitoring with radar (SAR) data. Global Forest Monitoring from Earth Observation, p. 347. CRC Press, Taylor & Francis Group.

Lupascu, M. 2020. Post-fire carbon dynamics in peat swamp forests and the application of remote sensing with artificial intelligence in peatland fire prediction - results from Brunei and Indonesia. Presentation in the Food and Agriculture Organization of the United Nations. Rome, Italy.

Maldonado, M. 2014. An introduction to the bofedales of the Peruvian High Andes. Mires and Peat, 15. http://www.mires-and-peat.net/

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. & Hansen, M.C. 2014. Primary forest cover loss in Indonesia over 2000–2012. Nature Climate Change, 4(8): 730–735. https://doi.org/10.1038/nclimate2277

Marrs, R.H., Marsland, E.-L., Lingard, R., Appleby, P.G., Piliposyan, G.T., Rose, R.J., O'Reilly, J., Milligan, G., Allen, K.A., Alday, J.G., Santana, V., Lee, H., Halsall, K. & Chiverrell, R.C. 2019. Experimental evidence for sustained carbon sequestration in fire-managed, peat moorlands. Nature Geoscience, 12(2): 108–112. https://doi.org/10.1038/s41561-018-0266-6

McMaster University. (2018). Simple key to risk of severe peat fires: Larger trees point to driest peat and greatest danger. [online]. ScienceDaily. [Cited 9 March, 2020]. www.sciencedaily.com/releases/2018/01/180117164013.htm

Medicine, T., Davis, F., Burdick, D., Coen, L., Doering, P., Gulland, F., Heck, K., Howard, M., Kearney, M., Montagna, P., Plotkin, P., Rose, K., Smith, E., Tallis, H., Thom, R., Woodrey, M., Mengelt, C., Johnson, S., Coleman, H. & Kulina, P. 2017. Effective monitoring to evaluate ecological restoration in the Gulf of Mexico. Washington, DC: The National Academies Press. https://doi.org/10.17226/23476

Mellett, J.S. 1995. Profiling of ponds and bogs using ground-penetrating radar. Journal of Paleolimnology, 14(3): 233–240. https://doi.org/10.1007/BF00682425

Miettinen, J. & Liew, S.C. 2010. Degradation and development of peatlands in Peninsular Malaysia and in the islands of Sumatra and Borneo since 1990. Land Degradation & Development: n/a-n/a. https://doi.org/10.1002/ldr.976

Miettinen, J., Shi, C. & Liew, S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Global Ecology and Conservation, 6: 67–78. https://doi.org/10.1016/j.gecco.2016.02.004

Miles, L., Ravilious, C., Garcia-Rangel, S., de Lamo, X., Dargie, G. & Lewis, S. 2017. Carbon, biodiversity and land-use in the Central Congo Basin Peatlands. pp. 8. Cambridge, UK, United Nations Environment Programme, University of Leeds and University College London. https://www.unep-wcmc.org/system/comfy/cms/files/files/000/001/153/original/Congo_peatland_20170303_wt.pdf

MoEF. 2018a. Corrective action on peatland management in Indonesia: Toward Sustainable Peatland Ecosystem. Jakarta, Ministry of Environment and Forestry Directorate General for Environmental Pollution and Degradation Control, Directorate of Peat Degradation Control. [Cited 20 July 2019]. https://gambut.oirto.com/wp-content/uploads/2019/04/Book.Gambut.20APR2019.pdf

MoEF. 2018b. The state of Indonesia's forests 2018. Jakarta, Ministry of Environment and Forestry, Republic of Indonesia. 196 pp. http://perpustakaan.bappenas.go.id/lontar/file?file=digital/191959-%5B_Konten_%5D-Konten%20E2337.pdf

MoEF & Government of Indonesia. 2016. National Forest Reference Emission Level for Deforestation and Forest Degradation: In the Context of Decision 1/CP.16 para 70 UNFCCC (Encourages developing country Parties to contribute to mitigation actions in the forest sector), Directorate General of Climate Change. pp. 113. No. version 2, revised final submission to UNFCCC. Jakarta, Directorate General of Climate Change, Ministry of Environment and Forestry. https://redd.unfccc.int/files/frel_submission_by__indonesia_final.pdf

MoEF. 2020. Informasi Peta Dasar dan Tematik. [online]. Indonesia. [Cited 17 March 2020].http://pkgppkl.menlhk.go.id/v0/

Murdiyarso, D., Kurnianto, S., Hergoualc'h, K., Sasmito, S. & Hanggara, B. 2017. Using ground penetrating radar: assessing the depth of tropical peatlands. Bogor, Indonesia, Center for International Forestry Research. http://www.cifor.org/publications/pdf_files/factsheet/6443-factsheet.pdf

NASA. 2020. MODIS Data Product Non-Technical Description- MOD 14 [online]. The USA. [Cited 16 March 2020]. https://modis.gsfc.nasa.gov/data/dataprod/nontech/MOD14.php

Natural England. 2011. Guidelines for monitoring peatland restoration. Natural England. http://publications.naturalengland.org.uk/publication/24008

Page, S.E., Rieley, J.O. & Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. Global Change Biology, 17(2): 798–818. https://doi.org/10.1111/j.1365-2486.2010.02279.x

Page, S.E., Rieley, J.O., Shotyk, Ø.W. & Weiss, D. 1999. Interdependence of peat and vegetation in a tropical peat swamp forest. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 354(1391): 1885–1897. https://doi.org/10.1098/rstb.1999.0529

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.-D.V., Jaya, A. & Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature, 420(6911): 61–65. https://doi.org/10.1038/nature01131

Parry, L. & Charman, D. 2013. Modelling soil organic carbon distribution in blanket peatlands at a landscape scale. Geoderma, 211–212: 75–84. https://doi.org/10.1016/j.geoderma.2013.07.006

Parry, L., Charman, D. & Noades, J. 2012. A method for modelling peat depth in blanket peatlands. Soil Use and Management, 28: 614–624. https://doi.org/10.1111/j.1475-2743.2012.00447.x

Parry, L.E., West, L.J., Holden, J. & Chapman, P.J. 2014. Evaluating approaches for estimating peat depth. Journal of Geophysical Research: Biogeosciences, 119(4): 567–576. https://doi.org/10.1002/2013JG002411

Phillips, S., Rouse, G.E. & Bustin, R.M. 1997. Vegetation zones and diagnostic pollen profiles of a coastal peat swamp, Bocas del Toro, Panamá. Palaeogeography, Palaeoclimatology, Palaeoecology, 128(1–4): 301–338. https://doi.org/10.1016/S0031-0182(97)81129-7

Phua, M.-H., Tsuyuki, S., Lee, J.S. & Sasakawa, H. 2007. Detection of burned peat swamp forest in a heterogeneous tropical landscape: a case study of the Klias Peninsula, Sabah, Malaysia. Landscape and Urban Planning, 82(3): 103–116. https://doi.org/10.1016/j.landurbplan.2007.01.021

Prager, A., Barthelmes, A. & Joosten, H. 2006. A touch of tropics in temperate mires: on Alder carrs and carbon cycles. Peatlands International (2): 26–29.

Ramsar. 1971. Convention on Wetlands of International Importance especially as Waterfowl Habitat. Paris, United Nations Educational, Scientific and Cultural Organization. [Cited 20 July 2019]. https://www.ramsar.org/sites/default/files/documents/library/scan_certified_e.pdf

Ramsar. 2002. Resolution VIII.17 Guidelines for Global Action on Peatlands. [Cited 24 September 2019]. https://www.ramsar.org/sites/default/files/documents/pdf/res/key_res_viii_17_e.pdf

Ramsar. 2010. Inventory, assessment, and monitoring. 4th edition. Ramsar Handbook 13. Gland, Switzerland. https://www.ramsar.org/sites/default/files/documents/pdf/lib/hbk4-13.pdf

Ramsar. 2016. International cooperation on wetlands. 5th edition. An introduction to the **Ramsar** Convention on Wetlands, Sub-series I: Handbook 1. Gland, Switzerland, Ramsar Convention Secretariat. https://www.ramsar.org/sites/default/files/documents/library/handbook1_5ed_introductiontoconvention_final_e.pdf

Ramsar. 2018. Global wetland outlook: state of the world's wetlands and their services to people 2018. N. Dudley, ed. Gland, Switzerland. https://www.ramsar.org/sites/default/files/flipbooks/ramsar_gwo_english_web.pdf

Randerson, J.T., van der Werf, G.R., Giglio, L., Collatz, G.J. & Kasibhatla, P.S. 2017. Global fire emissions database, Version 4.1 (GFEDv4). Oak Ridge, Tennessee, USA, ORNL Distributed Active Archive Center. https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1293

Rein, G., Cleaver, N., Ashton, C., Pironi, P. & Torero, J.L. 2008. The severity of smouldering peat fires and damage to the forest soil. CATENA, 74(3): 304–309. https://doi.org/10.1016/j.catena.2008.05.008

Renou-Wilson, F., Bolger, T., Bullock, C., Convery, F., Curry, J.P., Ward, S., Wilson, D. & Müller, C. 2011. Bogland: sustainable management of peatlands in Ireland. STRIVE Report No. 75. Johnstown Castle, Co. Wexford, Environmental Protection Agency.

Ritchie, Roser, Mispy, Ortiz-Ospina. Measuring progress towards the Sustainable Development Goals. [Cited 17 March 2020]. SDG-Tracker.org

Rieley, J. & Page, S. 2005. Wise use of tropical peatlands: focus on Southeast Asia. Wageningen, Netherlands, ALTERRA Wageningen University and Research Centre and the EU INCO-STRAPEAT and RESTORPEAT Partnership. http://www.alterra-research.nl/pls/portal30/docs/FOLDER/RESTORPEAT/download/wug.pdf

Roelens, J., Dondeyne, S., Van Orshoven, J. & Diels, J. 2016. Extracting cross sections and water levels of vegetated ditches from LiDAR point clouds. International Journal of Applied Earth Observation and Geoinformation, 53: 64–75. https://doi.org/10.1016/j.jag.2016.08.003

Rosenqvist, A., Shimada, M., Ito, N. & Watanabe, M. 2007. ALOS PALSAR: a pathfinder mission for global-scale monitoring of the environment. Geoscience and Remote Sensing, IEEE Transactions on, 45: 3307–3316. https://doi.org/10.1109/TGRS.2007.901027

Roßkopf, N., Fell, H. & Zeitz, J. 2015. Organic soils in Germany, their distribution and carbon stocks. Catena 133: 157–170. http://dx.doi.org/10.1016/j.catena.2015.05.004.

RSPO. 2018. RSPO peat audit guidance. Roundtable on Sustainable Palm Oil. https://rspo.org/news-and-events/announcements/rspo-peat-inventory-template-and-peat-audit-guidance

Saputra, E. 2019. Beyond Fires and Deforestation: Tackling Land Subsidence in Peatland Areas, a Case Study from Riau, Indonesia. Land, 8(5): 1–24. https://doi.org/10.3390/land8050076

Saputra, E., Spit, T.J.M. & Zoomers, A. 2019. Living in a Bottomless Pit: Households' Responses to Land Subsidence, an Example from Indonesia. Journal of Environmental Protection, 10: 1–21. https://doi.org/10.4236/jep.2019.101001

Schlund, M., Von Poncet, F., Hoekman, D.H., Kuntz, S. & Schmullius, C. 2014. Importance of bistatic SAR features from TanDEM-X for forest mapping and monitoring. Remote Sensing of Environment, 151: 16–26. https://doi.org/10.1016/j.rse.2013.08.024

Schlund, M., Von Poncet, F., Kuntz, S., Schmullius, C. & Hoekman, D.H. 2015. TanDEM-X data for aboveground biomass retrieval in a tropical peat swamp forest. Remote Sensing of Environment, 158. https://doi.org/10.1016/j.rse.2014.11.016

Scholefield, P., Morton, D., McShane, G., Carrasco, L., Whitfield, M.G., Rowland, C., Rose, R., Wood, C., Tebbs, E., Dodd, B. & Monteith, D. 2019. Estimating habitat extent and carbon loss from an eroded northern blanket bog using UAV derived imagery and topography. Progress in Physical Geography: Earth and Environment, 43(2): 282–298. https://doi.org/10.1177/0309133319841300

Sendzikaite, J., Truus, L., Strazdina, L., Jarašius, L., Herrmann, A., Pajula, R., Kirschey, T., Zableckis, N., Pakalne, M., Sinkevičius, Ž. & Pakalnis, R. 2018. First data on application of GEST approach in the Baltic region: vegetation mapping of pilot peatlands. Paper presented at Vegetation of Mires. Current Research on classification, mapping, use and conservation, 2018, Minsk/Grodno.

Society for Ecological Restoration International Science & Policy Working Group. 2004. The SER international primer on ecological restoration. [Cited 17 September 2019]. https://www.ctahr.hawaii.edu/littonc/PDFs/682_SERPrimer.pdf

Sowter, A., Bateson, L., Strange, Ambrose, K. & Syafiudin, M.F. 2013. DInSAR estimation of land motion using intermittent coherence with application to the South Derbyshire and Leicestershire coalfield. Remote Sensing Letters, 4. https://doi.org/10.1080/2150704X.2013.823673

Stockwell, C., Jayarathne, T., Cochrane, M., Ryan, K., Putra, E., Saharjo, B., Dwi Nurhayati, A., Albar, I., Blake, D., Simpson, I., Stone, E. & Yokelson, R. 2016. Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia during the 2015 El Niño. Atmospheric Chemistry and Physics Discussions: 1–37. https://doi.org/10.5194/acp-2016-411

Sumarga, E., Hein, L., Hooijer, A. & Vernimmen, R. 2016. Hydrological and economic effects of oil palm cultivation in Indonesian peatlands. Ecology and Society, 21. https://doi.org/10.5751/ES-08490-210252

Tansey, K., Beston, J., Hoscilo, A., Page, S.E. & Paredes Hernández, C.U. 2008. Relationship between MODIS fire hot spot count and burned area in a degraded tropical peat swamp forest in Central Kalimantan, Indonesia. Journal of Geophysical Research, 113(D23): D23112. https://doi.org/10.1029/2008JD010717

The Flow Country. 2019. Publications. In: The Flow Country Peatlands Partnership [online]. [Cited 19 December 2019]. https://www.theflowcountry.org.uk/learning-and-teaching/research/publications/

The Mountain Institute. 2016. Andes Program. In Dedicated to the Andes since 1996 [online]. [Cited 7 November 2019]. http://mountain.org/where-we-work/andes/

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van der Werf, G.R. & Watts, A. 2014. Global vulnerability of peatlands to fire and carbon loss. Nature Geoscience, 8: 11. https://doi.org/10.1038/ngeo2325

UN. 2019a. Mid-Term Technical Segment of the 25th Senior Officials Meeting. Environment Management Group. [Cited 20 November 2019]. https://unemg.org/wp-content/uploads/2019/09/INF_5_UN-Decade-Ecosystem-Restoration.pdf

UN. 2019b. About the Sustainable Development Goals – United Nations Sustainable Development [online]. [Cited 27 September 2019]. https://www.un.org/sustainabledevelopment/sustainable-development-goals/

UNCCD. 2015. Land matters for climate: reducing the gap and approaching the target. United Nations Convention to Combat Desertification. [Cited 24 September 2019]. https://www.unccd.int/sites/default/files/documents/2015Nov_Land_matters_For_Climate_ENG_0.pdf

UNDRR. 2015. The human cost of weather related disasters 1995–2015. Brussels, United Nations Office for Disaster Risk Reduction. https://www.unisdr.org/2015/docs/climatechange/COP21_WeatherDisastersReport_2015_FINAL.pdf

UNDRR. 2017. Protect wetlands to reduce disaster risk. In UN Office for Disaster Risk Reduction [online]. [Cited 24 September 2019]. https://www.unisdr.org/archive/51764

UNDRR. 2020. The Sendai Framework [online]. [Cited 17 March 2020]. https://www.undrr.org/

UNFCCC. 1992. United Nations Framework Convention on Climate Change. [Cited 17 October 2019]. https://unfccc.int/resource/docs/convkp/conveng.pdf

UNFCCC. 2019a. National forest monitoring system. In REDD+web platform [online]. [Cited 4 November 2019]. https://redd.unfccc.int/fact-sheets/national-forest-monitoring-system.html

UNFCCC. 2019b. FAQ's on the operationalization of the Enhanced

Transparency Framework. United Nations Climate Change Secretariat. [Cited 14 November 2019]. https://unfccc.int/sites/default/files/resource/FAQs_ETF.pdf

UNFCCC. 2020. Restoring Peatlands in Russia I Russia. [online]. Germany. [Cited 16 March 2020]. https://unfccc.int/climate-action/momentum-for-change/planetary-health/restoring-peatlands-in-russia-i-russia

Usup, A., Hashimoto, Y., Takahashi, H. & Hayasaka, H. 2004. Combustion and thermal characteristic of peat fire in tropical peatland in Central Kalimantan, Indonesia. Tropics, 14: 1–19. https://doi.org/10.3759/tropics.14.1

Vernimmen, R., Akmalia, R., Fitranatanegara, N., Artiyan, E., Febrianto, T., Yuherdha, A., Andreas, H. & Hooijer, A. 2018. Peatland mapping for Kubu Raya, West Kalimantan, using limited LiDAR data and peat thickness field measurements. Team Deltares report to the Indonesian Peat Prize – Final Phase. https://www.deltares.nl/app/uploads/2019/04/Peatland-mapping-for-Kubu-Raya-Team-Deltares.pdf

Vernimmen, R., Hooijer, A., Akmalia, R., Mulyadi, D., Syahrozi, O., Anugrah, I., Visser, M., Yuherdha, A. & Andreas, H. 2017. Peatland mapping for Bengkalis Island, Riau, using limited LiDAR data and peat thickness field measurements. Team Deltares report to the Indonesian Peat Prize – Solution Development Phase. https://www.deltares.nl/app/uploads/2019/04/Peatland-mapping-for-Bengkalis-Island-Team-Deltares.pdf

Wahyunto, Heryanto, B. & Widiastuti, H. 2006. Peta-peta sebaran lahan gambut, luas dan kandungan karbon di Papua/Maps of peatland distribution, area and carbon content in Papua, 2000–2001. Bogor, Indonesia, Wetlands International–Indonesia Programme and Wildlife Habitat Canada. https://www.wetlands.or.id/PDF/buku/Atlas%20Sebaran%20Gambut%20Papua.pdf

Wahyunto, Ritung, S. & Subagjo, H. 2003. Peta-peta sebaran lahan gambut, luas dan simpanam/kandungan karbon di Sumatra/Maps of peatland distribution and carbon content in Sumatra, 1990–2002. Bogor, Indonesia, Wetlands International–Indonesia Programme and Wildlife Habitat Canada.

Wahyunto, Ritung, S. & Subagjo, H. 2004. Peta-peta sebaran lahan gambut, luas dan kandungan karbon di Kalimantan/Maps of peatland distribution and carbon content in Kalimantan, 2000–2002. Bogor, Indonesia, Wetlands International–Indonesia Programme and Wildlife Habitat Canada.

Wang, L. & Qu, J. 2009. Satellite remote sensing applications for surface soil moisture monitoring: a review. Frontiers of Earth Science in China, 3: 237–247. https://doi.org/10.1007/s11707-009-0023-7

Warren, M.W., Kauffman, J.B., Murdiyarso, D., Anshari, G., Hergoualc'h, K., Kurnianto, S., Purbopuspito, J., Gusmayanti, E., Afifudin, M., Rahajoe, J., Alhamd, L., Limin, S. & Iswandi, A. (2012) A cost-efficient method to assess carbon stocks in tropical peat soil. Biogeosciences, 9, 4477–4485. http://dx.doi.org/10.5194/bg-9-4477-2012

Warren, M., Hergoualc'h, K., Kauffman, J.B., Murdiyarso, D. & Kolka, R. 2017. An appraisal of Indonesia's immense peat carbon stock using national peatland maps: uncertainties and potential losses from conversion. Carbon balance and management, 12(1): 12–12. https://doi.org/10.1186/s13021-017-0080-2

Wichtmann, W., Schröder, C. & Joosten, H., eds. 2016. Paludiculture – Productive Use of Wet Peatlands. Stuttgart, Germany, Schweizerbart Science Publishers. 272 pp. http://www.schweizerbart.de//publications/detail/isbn/9783510652839/Wichtmann_Schroder_Joosten_Paludicu

Wijedasa, L.S., Sloan, S., Michelakis, D.G. & Clements, G.R. 2012. Overcoming limitations with Landsat imagery for mapping of peat swamp forests in Sundaland. Remote Sensing, 4(9): 2595–2618. https://doi.org/10.3390/rs4092595

Winrock International. 2014. AFOLU Carbon Calculator series. The forest protection tool: underlying data and methods. United States Agency for International Development. [Cited 19 November 2019]. http://www.afolucarbon.org/static/documents/AFOLU-C-Calculator-Series_FP.pdf

World Resources Institute. 2018. Press release: Indonesian Peat Prize. In RELEASE: Indonesian Peat Prize Announces Winner of $1 million: International Peat Mapping Team (IPMT): Remote Sensing Solutions GmbH (RSS), the Agency for the Assessment and Application of Technology (BPPT) and Sriwijaya University [online]. [Cited 11 September 2019]. https://www.wri.org/news/2018/02/release-indonesian-peat-prize-announces-winner-1-million-international-peat-mapping

Wösten, H., Clymans, E., Page, S., Rieley, J. & Limin, S.H. 2008. Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia. CATENA, 73: 212–224. https://doi.org/10.1016/j.catena.2007.07.010

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Peatland mapping and monitoring
Recommendations and technical overview

Peatlands have a naturally accumulated peat layer at their surface. In their natural state, peatlands store large amounts of carbon, which is released into the atmosphere if they dry out.

This report gives an overview of key elements for developing peatland maps and integrating them into national land use monitoring systems and reporting processes, describes the advantages and limitations of different choices, and offers practical guidance to facilitate decision-making.

Mapping and monitoring methods are explored to ensure that emissions and emission reductions are measurable, reportable and verifiable. Information is given on other benefits from peatland conservation, restoration, rehabilitation and sustainable management. Country case studies present current achievements. Finally, recommendations are made for the development of robust peatland mapping and monitoring.

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