© R. LINDSAY

Peatlands: the challenge of mapping the world's invisible stores of carbon and water

R. Lindsay, A. Ifo, L. Cole, L. Montanarella and M. Nuutinen

Peatlands have long been unrecognized or ignored, but they will play a crucial role in climate change and water security and must be a focus of policy and research.

Richard Lindsay is at the Sustainability Research Institute, University of East London, London, United Kingdom of Great Britain and Northern Ireland.
Averti Ifo is at the Université Marien Ngouabi Ecole Normale Supérieure, Département des Sciences et Vie de la Terre, Laboratoire de Géomatique et d'Ecologie Tropicale Appliquée, Brazzaville, the Congo.
Lydia Cole is at the School of Geography & Sustainable Development, University of St Andrews, St Andrews, Scotland, United Kingdom of Great Britain and Northern Ireland.
Luca Montanarella is at the European Commission, Joint Research Centre (JRC), Ispra, Italy.
Maria Nuutinen is Forestry Officer at the FAO Forestry Department, Rome, Italy.

When Apollo 13 suffered catastrophic failure during its flight to the Moon in 1970, initially there was confusion and uncertainty. Commander Jim Lovell spotted a "gas" leaking into space from the Command Module. An hour later, the Command Module had lost its entire oxygen supply. This caused its fuel cells to shut down, leaving it without power. If the crew had immediately been able to identify and plug the leak, the situation need not have become as critical as it did, but they couldn't see where the emissions were coming from, or why. It became clear that, if they were to survive, the Lunar Module (LM) must instead become their lifeboat – although the LM was designed to support two men for 45 hours, not three men for 90 hours. The next four days were to become an extraordinary exercise in radical thinking and finite resource management.

Given the current situation on Spaceship Earth, it is tellingly ironic that the greatest danger facing the Apollo 13 crew during their remarkable subsequent voyage was a buildup of carbon dioxide (CO_2) within their "lifeboat" because the LM's air filters were unable to process the additional burden of that gas. Spaceship Earth is also experiencing dangerous emissions and an alarming rise in CO_2 concentration. As with Apollo 13, however, even though the buildup of CO_2 in the Earth's atmosphere

Above: A University of East London research team monitors Plantlife's Munsary Peatlands blanket bog, Caithness, northern Scotland, United Kingdom of Great Britain and Northern Ireland

is well documented, the emissions leading to this Earth-bound crisis are proving just as difficult to track down.

GLOBAL CARBON EMISSIONS – ARE WE LOOKING IN THE RIGHT PLACE?

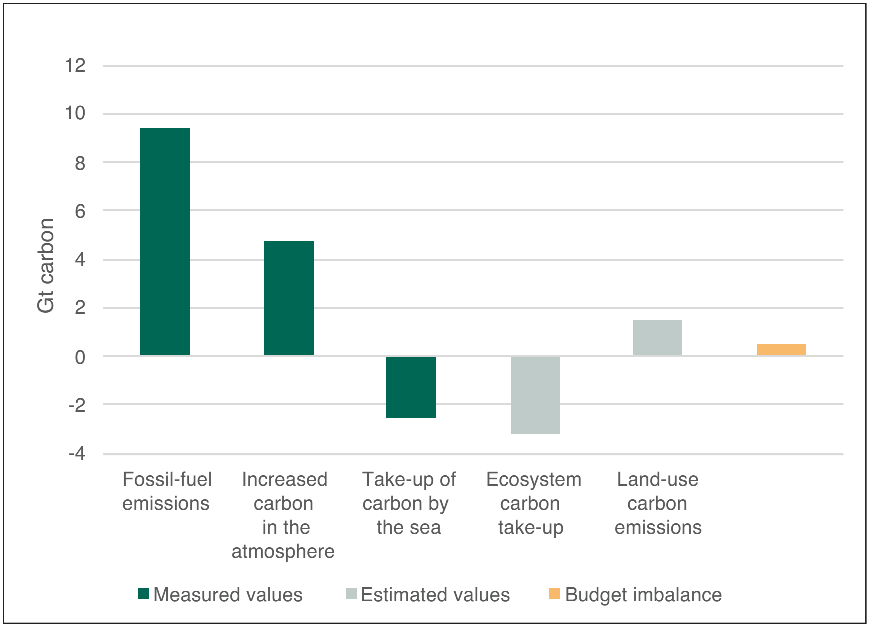
The headline figures are simply stated. According to the latest data from the Global Carbon Project (Le Quéré *et al*., 2018), which estimates carbon-flux pathways based on measured atmospheric values, the average annual increase in atmospheric carbon in the period 2008–2017 was 4.7 gigatonnes (Gt). Average annual fossil-fuel emissions in that period were 9.4 Gt of carbon, and the world's oceans absorbed some 2.5 Gt per year of this. Two other major pathways contribute to this picture of atmospheric carbon balance: carbon released by land-use change, estimated at around 1.5 Gt per year, and carbon absorbed by terrestrial ecosystems, estimated as 3.2 Gt, leaving 0.5 Gt unaccounted for (Figure 1).

Atmospheric CO_2 concentrations, fossil-fuel emissions and ocean uptake are now relatively well documented, but global estimates of carbon emissions from land-use change and carbon absorbed by terrestrial ecosystems are both subject to considerable uncertainty (Hansis, Davis and Pongratz, 2015). This is because both are extremely difficult to measure across all the various forms of land-use intervention and ecosystem response. As a pragmatic consequence, the carbon balance of land-use change, in assessing these global fluxes, has largely been estimated by quantifying changes in forest cover on the assumption that, compared with the conversion of grasslands to pastures or croplands, conversion from forest to open land results in far more significant losses of both biomass and soil carbon (Houghton, 1999).

Although this assumption may hold true for most environments, it is certainly not the case for peatland ecosystems. The largest expanses of peatlands occur as open landscapes, and many naturally forested peatlands have been drained to increase timber production. The World Reference Base for Soil Resources (WRB) soil classification (IUSS Working Group WRB, 2015) shows the extraordinary carbon content of the soils (termed histosols) that characterize peatlands (Figure 2). Based on this carbon content, a peat depth of only 30 cm contains 327 tonnes of carbon per ha; in comparison, primary tropical rainforest contains 300 tonnes per ha in soil and biomass combined (Blais *et al*., 2005). This is because the carbon store in peat is continuous whereas a forest has gaps between trees – it is said, therefore, that you can walk through a forest but only on a peatland.

Carbon density varies between peatland types, as well as between different peatland conditions and even with peat depth. Generally, the deeper the peat and the less disturbed a peatland system, the less dense its carbon content, although this is relative. For example, Warren *et al*. (2012) recorded a fairly consistent value of around 60 tonnes of carbon per m^3 for three types of Indonesian tropical peatland systems ranging in depth from 2.5 m to 12 m, and similar carbon densities can be found in temperate-zone peat bogs in Scotland possessing several metres of peat in good condition. Even with these lower carbon densities, a peat thickness of just 50 cm is required at such sites to match the carbon content of tropical rainforest (compared with the 30 cm thickness required for thinner, denser peat deposits). Moreover, given the depth of most peatlands (peat depth can extend as much as 60 m below the surface), recent assessments have estimated that, globally, peatland systems contain an average of 1 375 tonnes of carbon per ha – more than four times the carbon stored in an equivalent area of tropical rainforest (Yu *et al*., 2010; Crump, 2017).

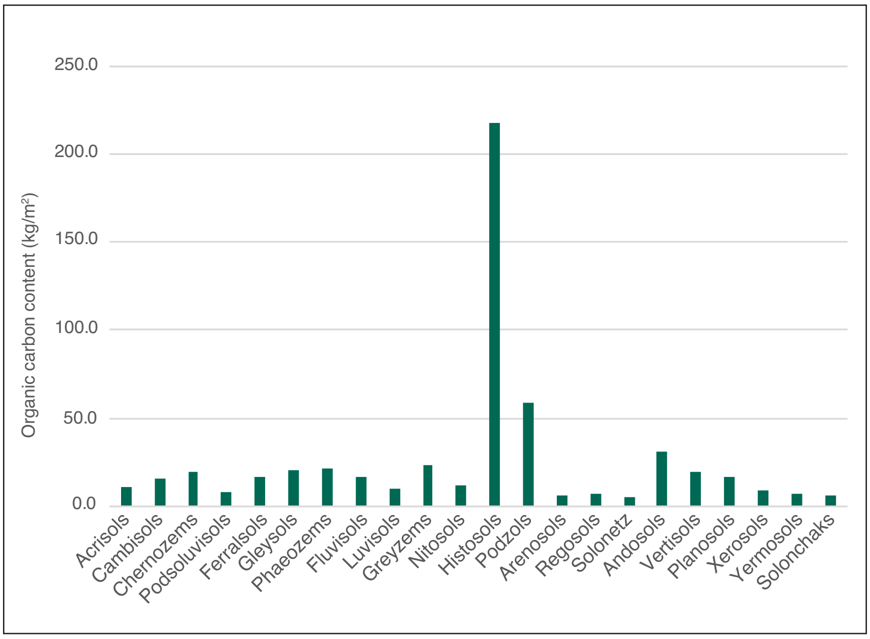
Carbon density is one source of variation, but peat depth gives rise to yet further levels of uncertainty. The Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) takes



1
Estimated annual carbon fluxes to and from the atmosphere, 2008–2017

Note: Based on documented fossil-fuel emissions, measured atmospheric carbon concentrations, measured carbon concentrations in the oceans, and the estimated take-up by terrestrial ecosystems and emissions from land-use activities; 0.5 Gt carbon is unaccounted for in current measurements and estimates.

Source: Global Carbon Project (Le Quéré *et al*., 2018).



2
Organic carbon content for FAO-UNESCO soil units to 2 m depth

Note: Peatland soils are histosols, and many extend to significantly greater depths than 2 m.
Source: Batjes (1996).

1 m depth as its reference depth for each soil unit because many of the national soil surveys that contribute data to the harmonized database have adopted this threshold. Consequently, the HWSD is severely constrained in its capacity to provide estimates of peat depth and carbon storage for the global peatland resource. The HWSD is further limited in accurately identifying the true extent of the global peat resource because of the relatively coarse scale of mapping and the often small number of field samples used to generate the soil survey data. Indeed, if there is a consistent theme running through the underpinning literature of peatland extent and global carbon flux, it is acknowledgement that peatland extent and depth are not well documented, and the land-use changes associated with peatlands are mostly not included in current global atmospheric assessments (Houghton, 1999; Houghton, 2003; Houghton *et al*., 2012). There are many reasons for this, but the underlying cause is that peatlands are "invisible" – both physically and culturally. They have been dubbed the "Cinderella habitat" because they provide so many ecosystem services yet continue to go largely unrecognized (Lindsay, 1993). The soils that characterize peatlands are hidden below the ground, making it difficult to distinguish between peatland and non-peatland. In addition, the reputation of peatlands as unproductive and dangerous wastelands, good only for conversion to productive uses, has meant that peatlands have also tended to vanish from our collective cultural consciousness and so have become more difficult to recognize. Thus, peatlands are often labelled as something other than peatland, with the result that their management causes harm that may not even be observed. This is dangerous because the failure to recognize an area as a peatland can lead to unexpected and sometimes very costly consequences.

THIN PEAT – PERIPHERAL BUT CRUCIAL

The issue is particularly crucial for thinner peats, essentially those with depths of 20–60 cm, not only because they tend to cover significantly more area than deep peat but also because they are more easily confused with other habitats and more easily destroyed. Thin peat deposits are consequently more challenging to map, and their shallow nature renders them more amenable to exploitation, degradation and wholesale loss. Tanneberger *et al*. (2017) sought to produce a harmonized map of peatlands in Europe based on data presented in the first complete review of peatlands across the continent (Joosten, Tanneberger and Moen, 2017). Both Tanneberger *et al*. (2017) and Joosten, Tanneberger and Moen (2017) chose, however, not to specify a minimum depth of peat for the definition of peatland because it was recognized that different thresholds of peat depth had been applied in different countries, with some ignoring thin peat altogether. In the United Kingdom of Great Britain and Northern Ireland, for example, the figure given by Tanneberger *et al*. (2017) for that country's contribution to the European peat map is 2.6 million ha, but the relevant chapter in Joosten, Tanneberger and Moen (2017) gives a figure of 7.4 million ha for "peat and peaty soils" (Lindsay and Clough, 2017). Thus, in the United Kingdom of Great Britain and Northern Ireland alone, the area of uncertainty concerning the true extent of peatlands amounts to around 4 million ha, almost wholly associated with thin peat. Assuming a depth of 30 cm for this peat, the quantity of carbon stored within this single example of uncertainty in one nation's peatland resource approaches the total estimated annual global emissions of 1.5 Gt of carbon resulting from land-use change.

Such uncertainty is far from unique to the United Kingdom of Great Britain and Northern Ireland – it is a global issue. What does it imply for the extent, condition of, and possible emissions from, the global peatland resource? Yu *et al*. (2010) gave widely quoted estimates of 4.4 million km^2 (3 percent of the global land surface) and around 600 Gt of stored carbon for the known extent of the global peat resource, based largely on documented areas of deep peat. These estimates alone mean that the

© R. LINDSAY

One hectare of peat only 30 cm deep holds as much carbon as 1 hectare of primary tropical rainforest, yet it may be mistaken for other habitats such as heathland and so managed inappropriately. Such a thin layer of peat is more easily destroyed by inappropriate management – the single pass of a plough, for example – than is the case for the loss of the carbon store held in a tropical rainforest, where, even after felling and burning, the roots and stumps of the forest remain. The loss of thin peat does not attract as much world attention as the loss of tropical rainforest, however

known global peatland resource contains more carbon than all the world's vegetation combined (Scharlemann *et al*., 2014). The fact that even thin peats (i.e. those peats most vulnerable to land-use change) have the potential to release as much carbon per unit area as the clearing of primary tropical forest lends particular urgency to the need for accurate mapping of these mostly overlooked but potentially very large areas of thinner peat. Even small changes in the mapped extent of national and global peat resources could mean substantial changes to the picture of associated carbon fluxes – whether negatively, in terms of emissions resulting from destruction through lack of awareness, or positively, by halting emissions, preserving the carbon, bringing back other ecosystem services and, eventually, over longer timescales, restoring the systems once more to carbon sinks.

THE CONSEQUENCES OF PEATLAND MISMANAGEMENT

The release of carbon

Peatlands are wetlands of major significance in terms of carbon storage and release because waterlogging preserves dead plant matter. When wetland plants die, their remains accumulate *in situ* because waterlogging slows decomposition to such an extent that a proportion of this plant material and its associated carbon is preserved in what becomes peatland, often on millennial timescales. Its waterlogged state means that peat is commonly as much as 95 percent water by weight and 85 percent by volume, meaning that peatlands are significant contributors to water control, often at the landscape scale. The general land-use trend for these wet landscapes, however, has been to drain them in order to make them more amenable to exploitation (IPBES, 2018). When water is removed from the peat matrix as a result of drainage, the peat undergoes significant shrinkage through "primary consolidation" and "secondary compression", resulting in subsidence of the ground surface. Moreover, when air penetrates the normally waterlogged peat it initiates rapid decomposition and the release of long-term carbon into the atmosphere ("oxidative wastage"), giving rise to carbon emissions as well as further ground subsidence.

It is unfortunate, therefore, that the drainage of such systems is inadequately captured in the present global atmospheric model of carbon fluxes in terms of emissions due to land-use change in peatlands (Houghton *et al*., 2012). Such emissions could be significantly larger than shown in Figure 1 but in that case they must also be balanced by greater carbon capture than indicated, resulting in the same overall rise in atmospheric CO_2. Should this additional take-up of CO_2 by terrestrial ecosystems begin to fail as a result of climate change, however, emissions from land-use change could take on considerable added importance. The main alternative source of estimates for emissions due to land-use change are the data collated from the individual national greenhouse-gas accounting reports submitted under the Kyoto Protocol. The guidance provided to those assembling these national reports (Intergovernmental Panel on Climate Change, 2014) has widened to include procedures for estimating carbon emissions from peatland systems subject to, for example, drainage for agricultural purposes. Even the collation of this information provides only a partial picture, however, because some nations do not participate and all nations have difficulty in deciding the area over which the particular peat-related emission factors should be applied because the extent of peatlands is so poorly known.

The problem of subsidence

Peat subsidence itself gives rise to undesirable consequences beyond those of carbon loss. In the lowlands of the United Kingdom of Great Britain and Northern Ireland, the area of East Anglia known as the Fens once consisted of a peatland covering 1 500 km^2. Records from the seventeenth century indicate that this accumulated peat was a key factor in holding back the sea from this large drainage basin (Darby, 1956, p. 107). The wholesale drainage of the area in the eighteenth and nineteenth centuries by "adventurers" (whom today might be called financial speculators) to grow arable crops on the rich peat soil has since given rise to some of England's finest agricultural land. There has been a significant price to pay, however, beyond the loss of the area's formerly rich biodiversity. The peat soils subject to intensive agriculture release as much as 8 tonnes of carbon per ha annually through oxidative wastage (Evans *et al*., 2016), and the ground surface has subsided to such an extent that many areas are now as much as 3 m below sea level. Continued farming is only possible because of substantial and very expensive drainage infrastructure, and the cost is now so high, and the threat of rising sea levels and subsiding ground levels so serious, that the country's Environment Agency is discussing the need to move entire communities to safer ground in the foreseeable future (UK Environment Agency, 2019).

Similar issues are being discussed in coastal areas of Southeast Asia, where extensive peatlands have been converted to major rice projects and, more recently, to oil-palm and acacia plantations; this has led to widespread peatland fires, and peatland subsidence is in danger of causing huge areas of coastal flooding (Hooijer, 2012). These and other problems have arisen time and time again, either because there was a failure to recognize that an area was a peatland or because the consequences of exploiting the peatland were insufficiently understood. Both these reasons continue to represent major challenges worldwide, and even major deposits of deep peat have continued to be overlooked, misclassified or subsumed under some other habitat type (as explored below). On the other hand, growing recognition that such actions also have major implications for carbon emissions (Page *et al*., 2002) could now be stimulating greater interest in establishing precisely where the peatlands are and how best to manage them. In recent years, several substantial peatland systems have been reclassified as peatland, having previously been described as other habitat types.

REGIONAL STATUS OF PEATLAND MAPPING FOR CARBON, WATER AND BIODIVERSITY

Substantial progress has been made in peatland mapping and the development of policy processes in the last decade or so, as illustrated by the examples below. Nevertheless, there are likely many more areas of overlooked peatlands awaiting discovery, particularly in Africa but also areas of thin peat on every continent currently classed as something other than peatland.

The Congo's vast peatlands

Deep in the Congo Basin, in an area that is enormously difficult to access, a peat-bog system was brought to light only recently by scientific collaboration among several teams of researchers. This peatland complex is now recognized as the largest known continuous peat-bog system in the tropics, at almost 145 000 km^2, two-thirds of which is in the Democratic Republic of the Congo and the remaining one-third in the eastern part of the Congo (Dargie *et al*., 2017). The area is so enormous that it encompasses two very large Ramsar sites, Lac Télé in the Congo and Ngiri-Tumba-Maindombe in the Democratic Republic of the Congo, the latter being the world's second-largest Ramsar site. The known extent of the newly identified peatland area amounts to almost 4 percent of the Congo Basin (the world's second-largest river basin). With measured peat depths of 0.3–5.9 m, the recorded peatland area is estimated to contain 30 Gt of carbon; thus, this peatland system contains nearly 5 percent of the carbon contained in the world's known peatlands. This peatland plays an essential role in the regional climate of the Congo Basin and makes a significant and active contribution to the catchment dynamics of the Congo River, which is second only to the Amazon in the volume of its discharge. The peatland complex constitutes a huge reservoir of freshwater and, because it so large that it often covers entire interfluves, it is a key water source for various tributary systems (e.g. the Oubangui and Sangha) that flow through this vast ecological zone.

Driven by concerns about the potential impacts of climate change in the region, researchers in the CongoPeat project are seeking to understand how the peatlands originally developed and what has maintained them as waterlogged, peat-forming systems for the past 10 000 years or so, thereby enabling the establishment of the area's exceptional biodiversity. In addition to preparing preliminary maps of the peatlands to enable improved land-use planning, the CongoPeat team is attempting to understand the water balance of these systems because the majority appear to be water-shedding, meaning they rely solely on direct precipitation inputs for their water supply (i.e. they are ombrotrophic bogs). In such systems, losses from evaporation and drainage by gravity flow must be balanced by precipitation inputs, and there may be significant consequences if these inputs and outputs are altered by a regional decline of rainfall or longer-term climate change.

Given that the Congo peatlands rely on the basin's overall rainfall pattern, it is significant that recent recorded data and publications on rainfall in the (Republic of the) Congo have shown a marked decline in rain inputs. This is probably partly due to deforestation but mainly to recent negative trends in atmospheric and oceanic parameters: that is, the Atlantic Multi-Decadal Oscillation, the North Atlantic Oscillation and the Southern Oscillation Index (Ibiassi Mahoungou *et al*., 2017; Ibiassi Mahoungou, 2018). Particularly in light of these trends, important questions need to be answered: How much rainfall is required to maintain saturated conditions? And how much water is lost through evaporation, evapotranspiration and lateral drainage?

In addition to studies aimed at determining the water balance, field surveys have

© L. COLE

Local people receive training on the use of a mobile-phone-based application for collecting information on* Mauritia flexuosa *productivity in a palm swamp (regionally known as an* aguajal*) in the PMFB, western Amazonia

revealed the exceptional biodiversity of these peatlands, including iconic species such as the forest elephant and hippopotamus. The three large African primates – gorillas, chimpanzees and bonobos – all have significant populations there (Fay *et al*., 1989; Fay and Agnagna, 1992; Blake *et al*., 1995), and the region supports more than 350 bird species, including a number of endemic species (Evans and Fishpool, 2001). This highlights the fact that, because peatlands are so often overlooked, the remarkable and often highly distinctive biodiversity they support also remains hidden or is assumed to be dependent on other habitat types whereas peatlands may actually constitute the core habitat areas for certain key species (e.g. Singleton and van Schaik, 2001; Baker *et al*., 2010). Resources spent on maintaining habitats assumed to be vital for this biodiversity may be wasted if the true core habitat features are lost in the meantime through misplaced actions.

Peatlands in the Amazon

A similar story of discovery has unfolded in the world's largest river basin, the Amazon, in the last few decades. Some of the first published studies on the peatlands of the Pastaza-Marañón Foreland Basin (PMFB) in western Amazonia in the northern Peruvian lowlands described a peat-rich area of approximately 100 000 km^2 containing 2–20 Gt of carbon (Lähteenoja *et al*., 2009). Since then, research has been carried out to refine these estimates and to understand more about the area's developmental processes (Roucoux *et al*., 2013; Kelly *et al*., 2017) and ecosystem characteristics (Draper *et al*., 2014, 2018). Understanding the interannual flood variability, associated environmental disturbances and river-channel dynamics of the Amazon Basin is key to understanding the development of its peatlands (Gumbricht *et al*., 2017). Such factors have created a complex arrangement of environments that are waterlogged throughout the year and thus ideal for the development of peatlands (e.g. Householder *et al*., 2012).

© L. COLE

A palm swamp (aguajal) dominated by* Mauritia flexuosa *in the PMFB, western Amazonia

Unlike in Southeast Asia, where coastal domes are the dominant form in which peat is found (Dommain, Couwenberg and

© R. LINDSAY

The carnivorous sundew* Drosera binnata *on the margin of a peat pool formed within a patterned fen peatland near Moon Point, Fraser Island, Australia

Joosten, 2011), many of the PMFB's peatlands are small, discrete and transient over geological timescales. To date, depths of up to 7.5 m have been found (Lähteenoja *et al*., 2009), covered by vegetation communities varying from open grass and sedge-rich ecosystems to pole forests and palm swamps, where one particular palm of economic value, *Mauritia flexuosa*, commonly dominates (Lähteenoja *et al*., 2009). People living in and around the peatlands of the PMFB classify and use these ecosystems in various ways (Schulz *et al*., 2019), although they tend to avoid them when alternative landscape types are available (L. Cole, personal communication, 2019). Locally, peatlands are often referred to as "sucking" environments (*chupaderas* in Spanish), illustrating the lived experience of traversing them.

Although large and significant, the PMFB is just one of the basins in the Amazon that contains peat. Others have been classified in the eastern Amazon in Peru (Householder *et al*., 2012) and in the Brazilian Amazon (Lähteenoja, Flores and Nelson, 2013), and there are probably many more, currently "invisible" areas that need to be formally identified and classified and which are subject to various threats. Compared with the situation in Southeast Asia (Page and Hooijer, 2016), many of the Amazon's peatlands are relatively intact and under limited immediate threat of drainage or conversion. The interannual flooding variability of the basin's rivers, with waters rising in some places by up to 10 m, means that draining the peatlands would be near-impossible. The lack of a coherent road network also prevents the overland transportation of machinery and human resources to support industrial-scale drainage. Plans to greatly extend the regional infrastructure and enhance extractive capabilities in the future, however, would increase the vulnerability of the peatlands of the PMFB and beyond (Roucoux *et al*., 2017). The challenge for the scientific community is to evaluate the contributions that Amazonian peatlands make to carbon and water cycling, thought to be of huge significance on a local to global scale

(Gumbricht *et al*., 2017), before such contributions are compromised.

Fraser Island's newly discovered peatland

On Fraser Island off the coast of the Australian state of Queensland, areas formerly classified as relatively uninteresting "wet heath" have now been acknowledged as highly distinctive peatland systems that support a significant number of endangered species (Fairfax and Lindsay, forthcoming). Having previously been excluded from the Fraser Island World Heritage Site, these peatlands may now be incorporated in it as important ecosystem components. With sympathetic management, the peatlands also have the potential to be valuable carbon sinks and key hinterland providers of iron-rich waters to support the role of coastal mangroves as nursery grounds for local fish populations.

Peatlands in Europe

Tanneberger *et al*. (2017) estimated the area of peatland in Europe at 593 727 km^2. Mires, which by definition are dominated by living and peat-forming plants, were found to cover more than 320 000 km^2 (around 54 percent of the total peatland area). If shallow peatlands (< 30 cm peat) in the European part of the Russian Federation are included, the total peatland area in Europe is more than 1 million km^2 – almost 10 percent of the total land area. Peatlands are distributed widely among the European Union countries, with concentrations in northern, central and eastern Europe (Germany, Ireland, the Netherlands, Poland, the United Kingdom of Great Britain and Northern Ireland, and the Nordic and Baltic countries). Official policy research efforts, political appraisals and firm legislative provisions exist that recognize the need to protect peatlands and the inherent vulnerability of their soils. In practice, however, the degradation of these ecosystems is continuing across the European Union, due mainly to drainage for agriculture and forestry and peat extraction for fuel and horticulture.

Despite the continued efforts of the European Union member states and policymakers to reverse the trend and protect and restore peatlands and other wetlands and avoid their continued drainage and degradation, little research exists on the direct effectiveness or cross-sectoral impacts of the numerous interventions. The European Union's environmental laws and incentive schemes, particularly those linked to the Natura 2000 framework, have established a strong protection regime for peatlands, but other legislative frameworks, including the Common Agricultural Policy and the renewable-energy policy, have arguably yielded opposite effects by providing perverse incentives. The specific effects of the European Union's climate policy frameworks on peatlands have not yet been fully addressed (Peters and von Unger, 2017). A new effort may be initiated, however, in response to a recent resolution by the United Nations Environment Assembly (2019), which calls for more emphasis on the conservation, sustainable management and restoration of peatlands worldwide, as also recommended in a recent assessment by the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES, 2018).

CONCLUSIONS

Here, we make some simple recommendations for improving understanding of the true extent of peatlands on the planet – the first step in their protection, for all the benefits this will bring.

Recommendations for action – finding the peat

Two simple steps can be used to determine whether you are standing on peat:

1. Peat is a relatively soft soil, so it should be possible to push a rod or stick with a diameter of 6–8 mm at least 30 cm into the soil using only hand pressure. We use a length of 6-mm-diameter threaded steel rod – widely available around the world. This may not work so easily in some tropical peats that consist largely of wood but, even so, it should be possible to find at least some places where the rod or stick can be made to penetrate to a depth of at least 30 cm with relative ease.
2. Take a sample from a depth of 20–30 cm, air-dry the sample and see if it will burn. The high organic matter content of peat means that, once dry, it should ignite readily.[1]

Perhaps the greatest challenge in determining the true extent of peatlands identified through surveys is the resolution used. If a small pocket of peat measuring 100 m × 100 m (i.e. 1 ha) × 30 cm deep can contain as much carbon as the same area of primary tropical rainforest, there is evident benefit in ensuring that the mapping resolution is sufficiently fine to identify areas of this size. Ideally, therefore, mapping would be undertaken at a scale of 1:10 000, but for large areas a scale of 1:20 000 may be the highest resolution achievable with current technology and available resources.

Recommendations for policymakers

Policymakers should:

- Verify whether it is likely that more peatlands would be found in the country.
- Prioritize the mapping of peatlands at a scale of at least 1:20 000 but ideally 1:10 000.
- Map past, ongoing and planned management ("activity data", under the United Nations Framework Convention on Climate Change), including existing drainage infrastructure and other livelihood activities in the area (e.g. fishing and peat extraction).
- Include peatland maps in planning processes from the local to the regional scale, not only for climate and biodiversity benefits but also for water security and disaster risk reduction.
- Protect undrained peatlands to avoid activities that might cause important

---

[1] Note that soils containing agrochemical residues can release noxious or toxic fumes when heated. Please take suitable precautions.

changes to their hydrology and associated ecosystem services.

- Budget for the restoration of drained peatlands and for documenting and developing drainage-free livelihood options.
- If peatland drainage continues, invest in the development of systems for fire risk assessment, fire reduction and fire management.
- Harmonize incentives, laws and law enforcement to support these goals.
- Communicate to all decision-makers, stakeholders and the public the importance of peatlands for water, biodiversity and climate change.
- Monitor the status of peatlands to detect potential signs of emerging drainage-based land uses and land-use impacts.
- Report on the status of peatlands against the Sustainable Development Goals and under international conventions.

Final thoughts

Spaceship Earth is not a new concept, but, around the globe, young people's active responses to the climate protest of schoolgirl Greta Thunberg suggest that the youth of today perhaps grasp the reality of this concept rather more urgently than have preceding generations. Young people are looking to those in power to make the same kinds of bold and imaginative decisions as the highly focused team who brought the Apollo 13 crew safely back to Earth. Identifying the true extent of the world's peatlands and working to return them to sinks rather than sources of carbon is undoubtedly a difficult challenge. But, in the words of the late John F. Kennedy (the 35th president of the United States of America and a leading proponent of the United States of America's Space Program in the 1960s), we choose to do these things "not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept".

The next generation looks to us to address the challenge of climate change so that they, and Spaceship Earth, can survive. Because, for them, there is no LM, there is no lifeboat, there is no alternative. ◆

References

Baker, J.R., Whelan, R.J., Evans, L., Moore, S. & Norton, M. 2010. Managing the ground parrot in its fiery habitat in south-eastern Australia. *Emu: Austral Ornithology*, 110(4): 279–284.

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science,* 47: 151–163.

Blais, A.M., Lorrain, S., Plourde, Y. & Varfalvy, L. 2005 Organic carbon densities of soils and vegetation of tropical, temperate and boreal forests. *In*: A. Tremblay, L. Varfalvy, C. Roehm & M. Garneau, eds. *Greenhouse gas emissions — fluxes and processes*, pp. 155–185. Environmental Science. Berlin, Germany, Springer.

Blake, S., Rogers, E., Fay, J.M., Ngangoué, M. & Ebeke, G. 1995. Swamp gorillas in northern Congo. *African Journal of Ecology*, 33, 285–290.

Crump, J., ed. 2017. *Smoke on water – countering global threats from peatland loss and degradation. A UNEP rapid response assessment.* Nairobi, Kenya, United Nations Environment Programme (UNEP), and Arendal, Norway, GRID-Arendal. www.grida.no

Darby, H.C. 1956. *The draining of the Fens.* Second edition. Cambridge, Cambridge University Press.

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: 86–90. DOI: 10.1038/nature21048

Dommain, R., Couwenberg, J. & Joosten, H. 2011. Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. *Quaternary Science Reviews*, 30(7–8): 999–1010.

Draper, F.C., Honorio Coronado, E.N., Roucoux, K.H., Lawson, I.T., Pitman, N.C.A., Fine, P.V.A., Phillips, O.L., Torres Montenegro, L.A., Valderrama Sandoval, E., Mesones, I., García-Villacorta, R., Ramirez Arévalo, F.R. & Baker, T.R. 2018. Peatland forests are the least diverse tree communities documented in Amazonia, but contribute to high regional beta-diversity. *Ecography,* 41, 1256–1269.

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).

Evans, C., Morrison, R., Burden, A., Williamson, J., Baird, A., Brown, E., Callaghan, N. *et al.* 2016. *Lowland peatland systems in England and Wales – evaluating greenhouse gas fluxes and carbon balances.* Final report to DEFRA on Project SP1210. Bangor, UK, Centre for Ecology and Hydrology.

Evans, M.I. & Fishpool, L.D.C. 2001. *Important bird areas in Africa and associated islands: priority sites for conservation.* Cambridge, UK, Birdlife International & Pisces Publications.

Fairfax, R. & Lindsay, R. Forthcoming. An overview of the patterned fens of Great Sandy Region, far eastern Australia. *Mires and Peat.*

FAO/IIASA/ISRIC/ISS-CAS/JRC. 2009. *Harmonized World Soil Database (version 1.1).* Rome, FAO and Laxenbrug, Austria, International Institute for Applied Systems Analysis (IIASA).

Fay, J.M. & Agnagna, M. 1992. Census of gorillas in northern Republic of Congo. *American Journal of Primatology*, 27, 275–284.

Fay, J.M., Agnagna, M., Moore , J. & Oko, R. 1989. Gorillas (*Gorilla g. gorilla*) in the Likouala swamp forests of North Central

Congo: preliminary data on populations and ecology. *International Journal of Primatology*, 10, 477–486.

Gumbricht, T., Roman-Cuesta, R.M., Verchot, L.V., Herold, M., Wittmann, F.K., 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.

Hansis, E., Davis, S.J. & Pongratz, J. 2015. Relevance of methodological choices for accounting of land use change carbon fluxes. *Global Biogeochemical Cycles*, 29: 1230–1246.

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: 1053–1071.

Houghton, R.A. 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus*, 51B: 298–313.

Houghton, R.A. 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus*, 55B: 378–390.

Houghton, R.A., House, J.I., Pongratz, J., van der Werf, G.R., DeFries, R.S., Hansen, M.C., Le Quéré, C. & Ramankutty, N. 2012. Carbon emissions from land use and land-cover change. *Biogeosciences,* 9: 5125–5142.

Householder, J.E., Janovec, J.P., Tobler, M.W., Page, S. & Lahteenoja, O. 2012. Peatlands of the Madre de Dios River of Peru: distribution, geomorphology, and habitat diversity. *Wetlands*, 15: 2311–2320.

Ibiassi Mahoungou, G. 2018. *Variabilité pluviométrique en République du Congo: dynamique océanique et atmosphérique*. Editions Universitaires Européennes.

Ibiassi Mahoungou, G., Pandi, A. & Ayissou L. 2017. Extrêmes hydrologiques et variabilité décennale des précipitations saisonnières dans le bassin versant du fleuve Congo à Brazzaville (République du Congo). *In*: B.M. Mengho, ed. *Géographie du Congo*, pp. 207–223. Paris, L'Harmattan.

IPBES. 2018. *The IPBES assessment report on land degradation and restoration*. L. Montanarella, R. Scholes & A. Brainich, eds. Bonn, Germany, Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). https://doi.org/10.5281/zenodo.3237392

Intergovernmental Panel on Climate Change (IPCC). 2014. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda & T.G. Troxler, eds. Switzerland, Intergovernmental Panel on Climate Change (IPCC).

IUSS Working Group WRB. 2015. *World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps*. World Soil Resources Reports No. 106. Rome, FAO.

Joosten, H., Tanneberger, F. & Moen, A., eds. 2017. *Mires and peatlands of Europe – status, distribution and conservation*. Stuttgart, Germany, Schweitzerbart Science Publishers.

Kelly, T., Lawson, I.T., Roucoux, K.H., Baker, T.R., Jones, T.D. & Sanderson, N.K. 2017. The vegetation history of an Amazonian domed peatland. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 468: 129–141.

Lähteenoja, O., Flores, B.M. & Nelson, B.W. 2013. Tropical peat accumulation in Central Amazonia. *Wetlands*, 33*:* 495–503.

Lähteenoja, O., Ruokolainen, K., Schulman, L. & Oinonen, M. 2009. Amazonian peatlands: an ignored C sink and potential source. *Global Change Biology,* 15(9): 2311–2320.

Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P.A., Korsbakken, J.I., ***et al.*** 2018. Global carbon budget 2018. *Earth System Science Data*, 10: 2141–2194.

Lindsay, R.A. 1993. Peatland conservation – from cinders to Cinderella. *Biodiversity and Conservation*, 2: 528–540.

Lindsay, R.A. & Clough, J. 2017. United Kingdom. *In:* H. Joosten, F. Tanneberger & A. Moen, eds. *Mires and peatlands of Europe – Status, distribution and conservation*. Stuttgart, Germany, Schweitzerbart Science Publishers.

Page, S.E. & Hooijer, A. 2016. In the line of fire: the peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 371.

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: 61–65.

Peters, J. & von Unger, M. 2017. *Peatlands in the EU regulatory environment*. BfN-Skripten 454. DOI 10.19217/skr454, Bonn, Germany.

Roucoux, K.H., Lawson, I.T., Baker, T.R., Del Castillo Torres, D., Draper, F.C., Lähteenoja, O., ***et al.*** 2017. Threats to intact tropical peatlands and opportunities for their conservation. *Conservation Biology*, 31(6): 1283–1292.

Roucoux, K.H., Lawson, I.T., Jones, T.D., Baker, T.R., Honorio Coronado, E.D., Gosling, W.D. & Lähteenoja, O. 2013. Vegetation development in an Amazonian peatland. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 374: 242–255.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R. & Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management*, 5(1): 81–91.

Schulz, C., Martín Brañas, M., Núñez Pérez, C., Del Aguila Villacorta, M., Laurie, N., Lawson, I.T. & Roucoux, K.H. 2019. Peatland and wetland ecosystems in Peruvian Amazonia: indigenous classifications and perspectives. *Ecology and Society*, 24(2): 12.

Singleton, I. & van Schaik, C.P. 2001. Orangutan home range size and its determinants in a Sumatran swamp forest. *International Journal of Primatology,* 22(6): 877–911.

Tanneberger, F., Tegetmeyer, C., Busse, S., Barthelmes, A., Shumka, S., Moles Mariné, A., ***et al.*** 2017. The peatland map of Europe. *Mires and Peat,* 19(22): 1–17 (available at www.mires-and-peat.net/pages/volumes/map19/map1922.php).

UK Environment Agency. 2019. Draft National Flood and Coastal Erosion Risk Management Strategy for England. Rotherham, UK (available at https://consult.environment-agency.gov.uk/fcrm/national-strategy-public/user_uploads/fcrm-strategy-draft-final-1-may-v0.13-as-accessible-as-possible.pdf).

United Nations Environment Assembly. 2019. Conservation and sustainable management of peatlands. UNEP/EA.4/L.19, Nairobi, 11–15 March 2019.

Warren, M.W., Kauffman, J.B., Murdiyarso, D., Anshari, G., Hergoualc'h, K., Kurnianto, S., *et al.* 2012. A cost-efficient method to assess carbon stocks in tropical peat soil. *Biogeosciences*, 9: 4477–4485.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W. & Hunt, S.J. 2010. Global peatland dynamics since the last glacial maximum. *Geophysical Research Letters*, 37: L13402. ◆