Towards large-scale paludiculture: addressing the challenges of biomass harvesting in wet and rewetted peatlands

C. Schröder[1,4]; T. Dahms[1,4]; J. Paulitz[2], W. Wichtmann[1,3,4] and S. Wichmann[1,4]

[1] Institute of Botany & Landscape Ecology, Greifswald University, Germany
[2] Ingenieurbüro Dr.-Ing. Jürgen Paulitz, Dresden, Germany
[3] Michael Succow Foundation, Greifswald, Germany
[4] Greifswald Mire Centre, Germany

SUMMARY

Peatland drainage causes peat degradation, which results in high greenhouse gas emissions and ongoing subsidence of the ground surface. To avoid further land degradation, the rewetting of peatlands is essential. The new land use concept of paludiculture - the use of wet and rewetted peatlands for agriculture and forestry - now offers possibilities for landowners and land managers to continue using these sites under wet conditions. But new challenges arise due to the limited bearing capacity of wet soils, which restricts accessibility for machinery. Whilst many site-specific technical solutions for harvesting on wet peatland are available, it remains unclear whether current machinery is suitable for use in the large-scale implementation of paludiculture. Repeated crossings of the same ground can easily disturb the upper peat layer and cause serious problems for the removal of biomass. In this article we present available machinery and approaches to biomass harvesting; and explore how the number of transport runs required for biomass removal varies with productivity of the site, cargo capacity and working width of the harvesting machinery. The results are used in a discussion of logistics and infrastructure requirements to facilitate the implementation of paludiculture. Whilst there is still considerable scope for improvement of harvesting technologies, our results show that a peat-conserving harvest from wet and rewetted peatlands is possible with adjustments to harvesting technique, logistics and site infrastructure.

KEY WORDS: biomass removal; infrastructure; logistics; rewetting; tracked vehicle

INTRODUCTION

Peatland drainage is responsible for almost 25 % of worldwide carbon dioxide (CO_2) emissions within the land use, land use change and forestry (LULUCF) sector (Joosten *et al.* 2012). Including emissions from peat fires, around 2 Gt of CO_2 is released to the atmosphere from drained peatlands annually (Joosten 2010, Joosten *et al.* in press). Peatland drainage is also responsible for ongoing subsidence of peat surfaces. The annual loss of peat soil is 1–2 cm in the temperate zone (Akker *et al.* 2008, Leifeld *et al.* 2011) and about 5 cm in the tropics (Hoojer *et al.* 2012). To prevent this land degradation, high water tables are required (Joosten *et al.* 2012). Thus, it is necessary to adapt land management to the required water levels in order to develop sustainable land uses for peatland.

Paludiculture is a new approach for agriculture and forestry on wet and rewetted peatland (Wichtmann & Joosten 2007). The main goal is to use the land in such a manner that peat degradation, greenhouse gas emissions and nutrient losses are significantly reduced or avoided (Wichtmann & Joosten 2007, Wichtmann *et al.* 2010a, Wichtmann *et al.* 2010b, Wichtmann & Wichmann 2011, Wichtmann *et al.* in press). Various useful plants which can grow under permanently wet conditions throughout the Holarctic (Abel *et al.* 2013) and in Indonesia (Giesen 2013) have already been identified.

The use of wetland biomass has a long history (Granéli 1984, Succow & Jeschke 1986, Haslam 2010). In Europe, animal fodder and bedding were once harvested extensively from undrained and slightly drained fen meadows (Succow & Jeschke 1986); but this traditional land use has now been largely abandoned and many peatlands were drained during the twentieth century. The only traditional use of wet peatlands that has survived is the harvesting of reed (*Phragmites* spp.) for thatched roofs (Haslam 2010, Wichmann & Köbbing 2015).

There are now various initiatives to re-establish 'wet' uses of fens worldwide, and these illustrate the variety of benefits attainable. Under new agri-environmental programmes in Poland, biomass harvesting for habitat management purposes has recently been reinstated on areas up to several hundreds of hectares each (Kotowski *et al.* 2013, Dubowski *et al.* 2014), with the result that about 10,000 ha of public land in Biebrza National Park and protected areas in Lublin region is currently leased to farmers for periodic harvesting (Tanneberger *et al.* in press). In other European countries, small-scale (<10–150 ha) biomass removal is carried out to create or maintain peatland habitat for endangered birds such as the Great Bittern (*Botaurus stellaris*) (Hawke & José 1996, White 2009), the Aquatic Warbler (*Acrocephalus paludicola*), and waders (Tanneberger *et al.* 2012). In the Baltic countries, biomass harvesting has been tested as a means of controlling reed encroachment and making the reed available as a renewable resource (Ital *et al.* 2012, Kask 2013). Several projects conducted in Germany, Austria and Finland have aimed to combine biomass production with the interests of environmental protection, nature conservation and peatland restoration (Wild *et al.* 2001, Schäfer & Joosten 2005, Komulainen *et al.* 2008, Wichmann & Wichtmann 2009, Wichtmann & Wichmann 2011, Kitzler *et al.* 2012, Gaudig *et al.* 2014). In the 1980s, prospects for harvesting reed and cattail (*Typha* sp.) biomass were considered in Sweden (Graneli 1984) and the United States (Dubbe *et al.* 1988). At Lake Winnipeg (Canada), the harvesting of cattail has recently been established for nutrient removal and the biomass is being used to promote new developments in the bio-economy (Cicek *et al.* 2006, Grosshans *et al.* 2011, Grosshans in press).

At present, biomass harvesting on wet and rewetted peatlands is usually restricted to small areas and pilot sites because financial resources for nature conservation and environmental protection are limited. However, new drivers for large-scale implementation include an increasing demand for biomass (Lotze-Campen *et al.* 2014) on the one hand, and national commitments to the reduction of greenhouse gas (GHG) emissions on the other. In the latter context, the reduction in GHG emissions (expressed as carbon dioxide equivalent, CO_2e) that can be achieved by rewetting drained peatlands in the temperate zone is around 26.4 t CO_2e ha^{-1} a^{-1} for former cropland, 18.2 t CO_2e ha^{-1} a^{-1} for nutrient-rich grassland and 20.6 t CO_2e ha^{-1} a^{-1} for nutrient-poor grassland (Joosten *et al.* in press).

One of the main reasons for peatland drainage is to enable the use of powerful but heavy agricultural machinery (Zeitz 1999). Nonetheless, even on drained peatland meadows, vehicle access is challenging. If the wheels or tracks of the vehicle sink into the soft ground by more than about seven centimetres, the sward (upper layer of topsoil held together by the roots of plants) fails (Prochnow & Zeitz 1999, Tölle *et al.* 2000). The bearing capacity of drained peatland meadow depends directly on the strength of the sward; and this, in turn, is influenced by vegetation composition, vegetation density and soil water content (Kraschinski *et al.* 1999, Prochnow & Zeitz 1999, Tölle *et al.* 2000). The degradation of peat soil may also influence bearing capacity (Schweikle 2011, Wiedow *et al.* in press a).

Conventional agricultural machinery is usually unable to operate on wet or rewetted peatland. Because the vehicle's weight is borne by a relatively small area of wheels or tracks, the machinery sinks deeply into the ground, exerting excessive stress on the sward. To reduce this stress it is essential to minimise the ground pressure applied (Komulainen *et al.* 2008, White 2009, Alsbury 2010, Wichmann *et al.* in press). For wet organic soils, the maximum ground pressure considered in literature is 100 g cm^{-2} (e.g. Chivu 1968, AmtsBl. M-V 2000, Schuster 1985). Additionally, repeated vehicle crossings of the same area (e.g. on access routes) increase the risk of sward disruption (Figure 1).

To support and facilitate change from current land-use practice on drained peatlands towards paludiculture, we undertook a study to address the following three questions:

1) What machinery is currently available for harvesting wet and rewetted peatlands, and how can it be improved?
2) What are the factors that must be considered when operating on wet and rewetted peatlands?
3) What are the implications for logistics and infrastructure at site level?

A general survey was carried out to gain an understanding of existing approaches and techniques. This survey focused on traditional land use practice in Europe, such as the harvesting of reed for thatch, as well as techniques used in nature conservation management. New approaches for harvesting biomass as a renewable resource were also considered. Information was gathered by reviewing published literature and project reports, as well as through contact with operators of adapted machinery. The advantages, disadvantages and potential for further adaptation of the options that were identified were discussed with practitioners, scientists, nature conservation managers and developers. Experience

Figure 1. Damage caused by harvesting machinery on wet peatland. Left: damaged sward on the transport route across a field after repeated crossings; right: access route with destroyed surface peat layer after 40–50 crossings by a tracked vehicle pulling a tracked trailer. Photos: Christian Schröder (2011), Murchiner Wiesen, Mecklenburg - Western Pomerania, Germany.

in dealing with the challenges of biomass removal was also shared at workshops and conferences. In order to gain deeper insights about harvesting options, problems and solutions, operators were visited during their work in the field if possible. We also gained personal experience of harvesting biomass from wet fens by testing a tracked machine on an area of approximately 100 hectares.

In this article we first evaluate and classify existing technologies and harvesting approaches in terms of their potential applications in wet agriculture, on the basis of all of the information gathered. We then clarify aspects of how agricultural vehicles function in wet fens. As tracked machines are widely used and a promising option for large-scale harvesting, we consider how the tracks exert force on the vegetation sward, and how the forces can be minimised through both good operating practice and optimisation of track design. We then identify the main factors influencing the effort required to remove the biomass from the field, and calculate (using Microsoft Excel 2007) the number of trips required to transport the harvest out of the wetland for four different harvesting approaches. The results are used in a discussion of requirements for site infrastructure and logistics of the harvesting operation. Finally, the insights gained from this study are applied in formulating recommendations for techniques, logistics and infrastructure that should be adopted to facilitate the implementation of paludiculture at larger scale.

EXISTING HARVESTING MACHINERY

The ground pressure of a vehicle can be lessened either by reducing its weight or by increasing the area over which it makes contact with the ground. In terms of these strategies, machinery that is currently used for harvesting wet peatlands can be divided into four groups (Wichmann *et al.* in press), namely: adapted conventional agricultural machinery; small-sized machinery; specialised machinery with wheels; and specialised machinery with tracks. Each group has advantages and disadvantages that make it suitable for a different range of applications (Tables 1 and 2).

Conventional agricultural machinery can be adapted by fitting twin tyres, low-pressure tyres, caterpillar bands pulled over the tyres (to convert a wheeled vehicle into a tracked one), or delta (short triangular) tracks; but a ground pressure below 200 g cm^{-2} is rarely achieved (Table 2). This makes the range of potential applications strongly dependent on water table depth and weather conditions (Wichmann *et al.* in press), and in many cases even winter harvesting on ice or frozen ground is not possible (Komulainen *et al.* 2008, Wichmann 2009). Thus, the use of adapted conventional machinery is largely confined to drier and transitional areas, or to dry periods with low water table.

Although small-sized machinery for harvesting wet sites is widely available, its usefulness is limited by low engine performance and small load capacity, which make harvesting time-consuming and

Table 1. Applications, advantages, disadvantages and limitations of the four different types of harvesting machinery that are currently used for harvesting wet peatland sites (after Wichmann *et al*. in press).

Type of machinery	Examples	Applications and advantages	Limitations and disadvantages
Adapted conventional agricultural machines	Tractor with low-pressure or twin tyres used with, e.g., a lightweight baler on a tandem axle, if necessary combined with bogie tracks (bands pulled over pairs of tyres); alternatively, equipped with delta tracks.	Used in transitional areas (moderately wet), during dry periods with lowered water table, and during periods of hard frost (frozen ground). High acreage performance (ha hr^{-1}) when mowing; biomass transport/removal is possible.	Range of applications is limited by water-level and/or weather conditions. Transport problems; in some cases it is necessary to move each bale separately to the edge of the field.
Small-sized	Single-axle tractor or small tractor with two axles equipped with cutter bar; twin tyres if necessary.	Used to maintain open habitat on wet meadows under nature conservation management for species protection and habitat development (small-scale). Usually mowing only; occasionally removal of biomass as small bales transported manually or on a sledge.	Suitability and cost-effectiveness for large-scale biomass harvesting is limited by low acreage performance/ high cost per hectare.
Specialised, with wheels	Mostly Seiga machines with two or three axles and balloon tyres.	Used in reed harvesting (e.g. in Europe and China). Low machinery weight and balloon tyres result in low ground pressure.	Seiga machines are no longer manufactured, so only old or replica machines are in use. Seigas have limited engine performance. Vehicle starts to float if water depth exceeds 40 cm; it then becomes difficult to operate and prone to wheel-slip, which may damage the soil.
Specialised, with tracks	Custom-made machinery and adapted snow groomers.	Conservation management and biomass harvesting (e.g. thatching reed). Other applications: peat industry, silage clamps, landfill remediation. Wide tracks result in low static ground pressure even for heavy machines.	Conversions are mostly individual solutions. Cannot be driven on roads, so must be transported on flat-bed trailers; wide tracks are an impediment for re-location (tracks must be removed, or transport permission required). Shear forces may damage the soil during turns.

expensive (Prochnow & Kraschinski 2001, Wichtmann & Tanneberger 2009). In comparison with adapted conventional agricultural machinery, ground pressure is slightly lower (Table 2) and, in the eventuality of getting stuck, a small machine can be more easily pulled out, for example by using a winch. Small-sized machines are most commonly used to maintain and develop small areas of protected habitat, and are less suitable for large-scale biomass harvesting (Wichmann *et al.* in press).

Wheeled machinery with balloon tyres (large, low-pressure and usually treadless) such as the Danish Seiga vehicle, is proven technology for harvesting reed (Granéli 1984, Knoll 1986, White 2009, Wichmann 2009, Miljan 2013). Despite the low ground pressure of less than 100 g cm^{-2} (Granéli 1984, Table 2), the use of Seigas can be problematic under some circumstances because they tend to float in open water more than 40 cm deep. Floating increases the risk of wheel-spin, which can damage

Table 2. Technical characteristics of examples representing the four different types of harvesting machines (without attachments, trailer or load) that are used on wet or moderately drained peatlands. The calculations of ground pressure are based on the area in contact with the ground (contact area of wheels/tracks) when standing on a paved surface; the contact area on boggy ground may be different.

machinery type	adapted conventional[1]	small-sized[2]	specialised, with wheels[3]	specialised, with tracks[4]
name	Steyr CVT 6160	Kubota B2410	Seiga	PB 240D
adaptation	delta tracks	twin tyres	4 balloon tyres, 2 axles or 6 balloon tyres, 3 axles	modified snow groomer with rubber tracks
power (kW)	118	16	37	178
weight (kg)	9,000	975	1,500 or 2,000	7,000
contact area (cm^2)	42,000	5,490	22,000 or 33,000	86,400
ground pressure ($g\ cm^{-2}$)	214	178	61–68	81

[1]Fischer, pers. comm. (2015); [2]Tanneberger *et al*. (2012); [3]authors' calculation; [4]Wichmann & Schröder (in press).

the sward (Knoll 1986). Seiga technology has limited engine performance and is no longer commercially manufactured; but is, nonetheless, suitable if available (White 2009, Milijan 2013).

The use of tracked machinery effectively reduces ground pressure (Komulainen *et al*. 2008, Wichmann & Schröder in press, Table 2), and the area of contact with the ground can be further increased by lengthening or widening the tracks. Even though practical experience has shown that there is still a risk of disturbing the sward (Figures 1 and 2), tracked machines are a promising option for large-scale biomass harvesting on wet and rewetted peatlands because of their high performance (more power and cargo capacity). Various adaptations are available (cf. Wichmann *et al.* in press), and modified snow groomers (tracked vehicles manufactured for piste maintenance in ski resorts) are already used in the management of several thousand hectares of wet peatland for nature conservation in Poland (Kotowski *et al*. 2013, Dubowski *et al*. 2014, Tanneberger *et al*. in press).

Interaction between tracked machinery and sward

To identify the most suitable vehicles in the context of soil protection, it is not sufficient to consider only the relationship between weight and ground contact area (Saarilahti 2002). The forces acting on the vegetation sward or soil surface during machine operation are influenced by track characteristics (e.g. the shape, tread and tension of the tracks), the distribution of total weight (harvesting machinery, mounted equipment and cargo), and the rolling resistance of the vegetation. Another crucial factor in avoiding damage to the sward is the management of driving speed and the manner in which the machinery is driven and turned.

Where machine tracks come into contact with the sward, it is subjected to tension forces when the machine moves forward or sinks into soft ground. Due to the plasticity of a water-saturated peat body, harvesting machinery often sinks deeply when used on wet peatland. Thus, the bases of the tracks are below the ground surface in front of them and the machine has to drive steadily uphill, even on apparently flat ground. If the downward pull on the sward exceeds its resistance, the sward will tear. Damage is more likely to occur if there is too much weight at the front of the machine (Figure 2) or if the

Figure 2. An example of vehicle being off-balance due to harvesting equipment attached at the front. Photo: S. Wichmann (2011), Murchiner Wiesen, Mecklenburg - Western Pomerania, Germany.

vehicle starts to rock up and down. Therefore, each harvesting machine should be balanced individually, taking into account the changing weight of cargo during biomass uptake, so that the ground pressure is distributed evenly across the whole contact area.

Additional forces arise during a turn. The side of a straight track that faces outwards from the turn moves farther forward than its inward-facing side so the track must twist or swivel (‘wiper effect’), which involves lateral displacement of the track. If the track has sunk into the sward, it pushes against the ‘higher ground’ to the side, which increases the stress on the sward. The extra forces which are thus exerted on the sward are called shear forces. The analysis becomes more complicated when we consider both tracks together because, during a turn, the outside track must travel farther than the inside one (Figure 3).

To assess the pulling and pushing forces that occur when turning we have developed two indices which express the difference from driving straight ahead. The index for lateral displacement is the Lateral Pushing Index (*LPI*), calculated by dividing the total increase in trail width that occurs during a turn by the total width of the tracks:

$$LPI = \frac{(t_{wo}-t_w)+(t_{wi}-t_w)}{2t_w} \times 100 \qquad [1]$$

where t_w is the width of one track, t_{wo} is the trail width for the track on the outside of the turn, and t_{wi} is the trail width for the track on the inside of the turn. The Skew Pulling Index (*SPI*) is calculated from the difference in trail circumference for the inside and outside of each track, as:

$$SPI = \frac{\left[\frac{(t_oc_o-t_oc_i)}{t_oc_i}+\frac{(t_ic_o-t_ic_i)}{t_ic_i}\right]}{2} \times 100 \qquad [2]$$

where t_oc_o is the circumference of the curve travelled by the outside of the track on the outside of the turn, t_oc_i is the circumference for the inside of the outside track, t_ic_o is for the outside of the inside track, and t_ic_i is for the inside of the inside track. The *LPI* and *SPI* can be evaluated (e.g., in a spreadsheet such as Microsoft Excel 2007) and compared for different track designs and turning radii.

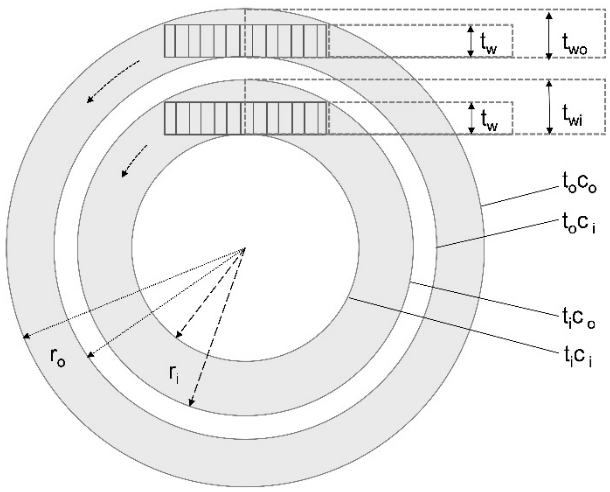

Figure 3. Schematic illustration of distances driven and areas crossed by tracks when turning a tracked machine. Lateral pushing forces, associated with the increased width of crossed area for the outside (t_{wo}) and inside (t_{wi}) tracks as compared to the width of the tracks (t_w), are represented by the *LPI* (Lateral Pushing Index) (Equation 1 in text). For the outside (t_o) and the inside (t_i) track considered separately, the difference in circumference between the outside (c_o) and inside (c_i) edge of crossed area results in differential (twisting or skew) pulling forces, expressed by the *SPI* (Skew Pulling Index) (Equation 2 in text). *LPI* and *SPI* increase as turning radius (r) becomes smaller, and differ between the two (outside and inside) tracks.

Although the indices do not directly quantify the forces acting on the sward, we set a goal for least possible damage that they should be approximately equal to one another. Figure 4 shows how the relationship between *LPI* and *SPI* is affected by changing the shape (width:length ratio) of the tracks. In each case considered, the same weight is distributed over two tracks with a total contact area of 10 m^2. *LPI* and *SPI* are approximately balanced when the width:length ratio of the tracks is between 1:4 and 1:5.

Shear forces could be reduced by spreading the contact area over more tracks or wheels. However, Figure 4 shows that the values of both *LPI* and *SPI* are highly sensitive to the radius of the turning curve, increasing sharply as the turns become tighter. Therefore, the index values can be substantially reduced by making wider turns; and if the radius of the turning curve is always greater than 10 m, increasing the number of tracks will have little effect (Figure 5). Therefore, the use of several track elements as suggested by Dubowski *et al.* (2014) may be unnecessary from this point of view; it could even be contrary if the track elements on each side of the vehicle travelled along the same trail, because a single journey would then involve multiple crossings of the same area. The most appropriate way to minimise shear force is to avoid tight turns.

The forces arising during turns can be further reduced by making adjustments to the tracks themselves. Skew pulling forces can be reduced

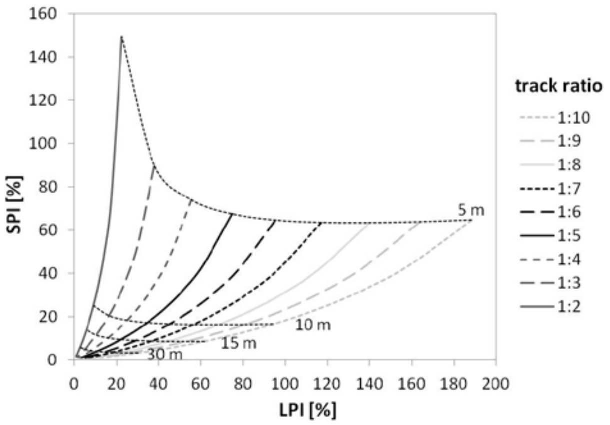

Figure 4. The relationship between *LPI* (Lateral Pushing Index) and *SPI* (Skew Pulling Index) for a machine with two tracks and a total sward contact area of 10 m^2 executing turns of radius 5, 10, 15 and 30 m (fine dashed black lines), calculated for tracks with width:length ratios ranging from 1:2 to 1:10.

by fitting tracks with almost no tread and reduced tension (to reduce grip and pull on the sward), whilst lateral pushing forces can be alleviated by rounding the edges of the tracks. A review of currently-used tracks can be found in Wichmann *et al*. (in press).

Impact of machinery use on wet fens

The long-term impact of machine harvesting on peatland sites is still unknown. The removal of biomass can induce vegetation change by altering the competitive relationships between plant species, and the use of tracked machinery can flatten the ground surface (Kotowski *et al.* 2013). The loss of surface structure (microrelief) can also affect species composition and may contravene nature conservation objectives for protected habitats, especially those with varied topography such as a mosaic of hummocks and hollows. Therefore, any decision to use tracked harvesting technology in a nature conservation area should not be taken lightly (Kotowski *et al.* 2013).

We were not able to find any studies on the effects of machinery passes on the upper peat layer. If machinery use causes irreversible compaction of the peat, the rate of peat formation may increase due to reduced aeration arising from reduced porosity and consolidation, as described for grazed transition mires on the southern coast of the Baltic Sea by Jeschke (1987). On the other hand, reducing porosity also reduces water storage capacity (*per* unit volume) and permeability, which may increase the amplitude of water table fluctuation and thus the peat decomposition rate (Joosten 1993, Joosten & Clarke 2002). Which of these feedback mechanisms is triggered may be influenced by the existing degree of peat degradation and the hydrogenetic mire type.

A discussion of possible effects on peat formation and decomposition rates may seem too academic for practitioners. However, it is important to minimise the impact of present harvesting operations on the land in order to safeguard the availability of future harvests. Future research should investigate whether any physical effects of biomass harvesting in wet and rewetted fens can be detected; for example, by measuring the shear strength and penetration resistance of the soil before and after machinery use (Wiedow *et al.* in press b).

Improvement of harvesting technology

Although suitable machinery for harvesting wet and rewetted fens is available, there is still room (and need) for improvements. At present, no site-adapted harvesting machines are produced commercially, and this is an impediment to scaling-up of paludiculture. Many individual and bespoke technical solutions exist, but the maintenance of custom-made machinery requires specialised technical knowledge. Also, the use and adaptation of machinery that was originally designed for other applications (such as the snow groomer) is innovative but can be sub-optimal for the site (Dubowski *et al.* 2014). The development of new harvesting technology that specifically meets the requirements for wet peatlands (Dubowski *et al.* 2014, Kranemann in press) is necessary. Features to be encouraged in future designs include: reduced machinery weight; increased ground contact area; and intelligent systems to minimise shear and tension forces on the sward. Our recommendations for technical improvements (see also Wichmann *et al.* in

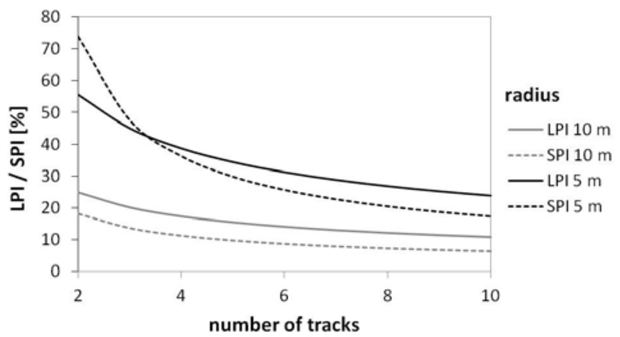

Figure 5. *LPI* (Lateral Pushing Index) and *SPI* (Skew Pulling Index) if the machine weight is allocated to a different number of tracks with a total contact area of 10 m^2 when making turns of radius 5 m or 10 m. For the calculations, a fixed width:length ratio of 1:4 was chosen for the tracks.

press) are:

- use lightweight components to reduce overall machinery weight;
- increase the contact area with the soil to reduce ground pressure;
- steer tracks, wheels or delta tracks individually to minimise shear and tension forces;
- use built-in sensors to avoid slipping;
- raise an alarm if the radius of a turn is too small; and
- improve the weight distribution of harvesting vehicle, attached equipment and cargo so that the machinery is always evenly balanced during operation.

The optimisation of harvesting technologies is essential, but the skill and experience of the driver are also crucial (Knoll 1986). As mentioned above, driving style is an extremely important factor in avoiding damage to the sward. This goes beyond the manner in which the machine is turned; the operator also needs to be capable of recognising sensitive areas like lawns with e.g. *Agrostis stolonifera*, and deciding during approach whether to reduce speed or circumnavigate (Wichmann & Schröder in press).

LOGISTICS OF BIOMASS HARVESTING IN WET PEATLANDS

Depending on the equipment carried by the machinery (mower, mulcher, baler, *etc*.), harvesting may be implemented in one, two or three working steps and the biomass may be chopped or processed into bales or bundles (Figure 6, Table 3, Wichmann *et al.* in press). The appropriate approach will be influenced by the time of harvest, site conditions, and how the biomass will be processed afterwards. For example, one-step harvesting systems are needed when high water table precludes temporary storage of the biomass on the ground. On the other hand, if the water table is below or close to ground level during mowing, the biomass may be laid on the ground and collected in a second or third working step, for example after drying on the field (Schröder *et al.* in press).

Biomass removal

Often, a site-adapted machine can be driven across a wet fen area once to mow the biomass without problems; but later removal of the biomass from the site proves to be challenging. Repeated crossings for biomass transport can seriously damage the sward and make further harvesting impossible (Figure 1). Therefore, it is necessary to consider the logistics of biomass removal. The treatment presented here focuses solely on the effort required to take up the biomass and transport it off the field; other harvesting operations such as tedding and swathing (different ways of arranging the cut harvest on the ground to dry) are not included.

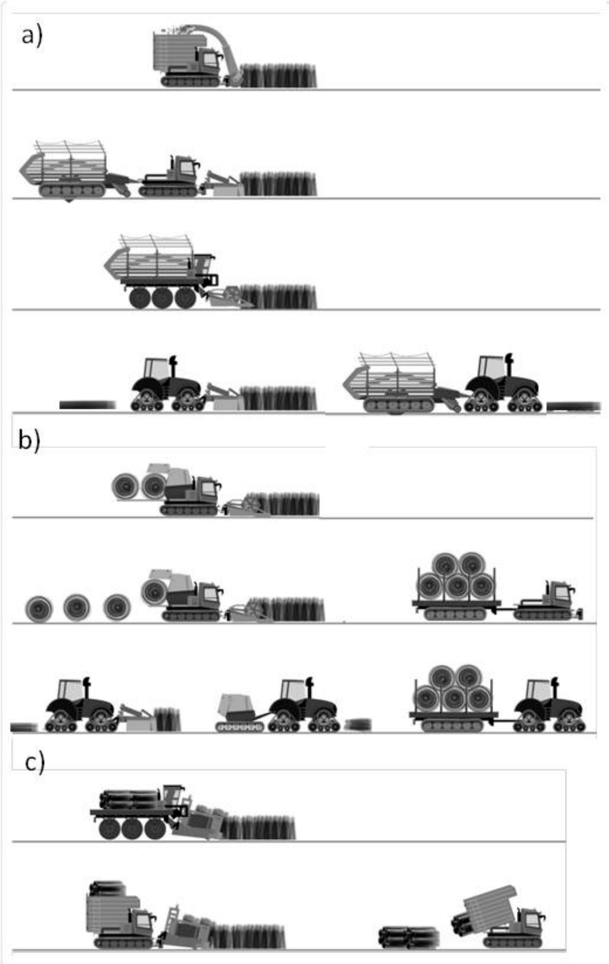

Figure 6. Examples of different approaches to biomass harvesting in wet peatlands. The biomass is: a) chopped or cut; b) baled; or c) bundled. Depending of the position of the water table, it is harvested in one, two or three working steps. If the biomass is dried on the ground, further steps such as tedding and swathing (i.e. arranging and re-working the cut harvest so as to promote drying) may be added.

Following Schröder *et al*. (in press), the number of transport trips is determined by the following factors:

- productivity of the site;
- volume and weight of the mown biomass;
- working width and transport capacity;
- frequency of harvesting; and
- harvesting approach.

Table 3. Harvesting approaches for herbaceous biomass at wet peatland sites (after Wichmann *et al.* in press; see also de Jong *et al.* 2003, Komulainen *et al.* 2008, White 2009, Alsbury 2010, Mucha 2011, Tanneberger *et al.* 2012, Kotowski *et al.* 2013, Miljan 2013 and Dubowski *et al.* 2014).

Harvesting approach	Harvested product	Description of approach	Examples in (countries)**	Harvest time	Condition of biomass
Harvest in one working step	chopped biomass	Harvest and transport of biomass in mounted container or in attached trailer on tracks.	BY, DE, GB, LT, NL, PL	summer/ autumn	fresh
				winter	dry
	bales	Harvester with cutter bar and mounted baler for round bales; bale transport on the harvester or a trailer.	AT, CH, (FIN*)	winter	dry
	bundles	For reed or cattail: whole culms harvested and tied into bundles for thatching or use as building material; transport on the harvester.	AT, DE, DK,HU, NL, PL, RO *etc*.	winter	dry
Harvest in two working steps	chopped biomass	1st step: mowing and deposition in swathes; 2nd step: collection, chopping and transfer to container or trailer for removal.	DE, NL, PL	summer/ autumn	pre-wilted/ dry
				winter	dry
	chopped biomass or long culms	1st step: mowing and deposition in swathes; 2nd step: collection and removal by self-loading wagon.	DE, NL	summer/ autumn	pre-wilted/ dry
				winter	dry
Harvest in three working steps	bales	1st step: mowing and deposition in swathes; 2nd step: collection and baling using attached baler with twin tyres or on tracks, bales left on field; 3rd step: removal of bales individually or by a tracked trailer that is equipped with a loading crane.	DE, PL	summer/ autumn	pre-wilted/ dry
				winter	dry

* in construction, according to Komulainen *et al.* (2008); no information on implementation or harvesting experience available.

** abbreviations: AT - Austria; BY - Belarus; CH - Switzerland; DE - Germany; DK - Denmark; FIN - Finland; GB - Great Britain; HU - Hungary; LT - Lithuania; NL - Netherlands; PL - Poland; RO - Romania.

The productivity of the site directly affects the number of transport trips that will be required to gather up the biomass. Whilst low-productivity sites are often targeted for nature conservation management, nutrient-rich sites with high productivity are of interest for biomass production as well. The dry mass productivity of wet fen vegetation may be 20 t ha^{-1} a^{-1} or more (Schulz *et al.* 2011). Thus, the number of transport trips required can vary considerably between sites (Figure 7). For example, if the dry mass productivity is 20 t ha^{-1} a^{-1} and the transport capacity is one tonne of dry weight (dw), 20 trips will be needed to remove the biomass from one hectare of land; whereas, if the dry mass productivity of the site is 3 t ha^{-1} a^{-1}, only three transport trips will be required.

The volume and weight of the harvested biomass depend on its dry bulk density and water content. Harvesting wet biomass can substantially increase the transport effort required. The water content of reed biomass depends on the time of harvest; e.g. 56–69 % for summer harvesting *versus* 10–25 % for winter harvesting (Granéli 1984, Kitzler *et al.* 2012, Kask & Kask 2013). Our own measurements of bulk

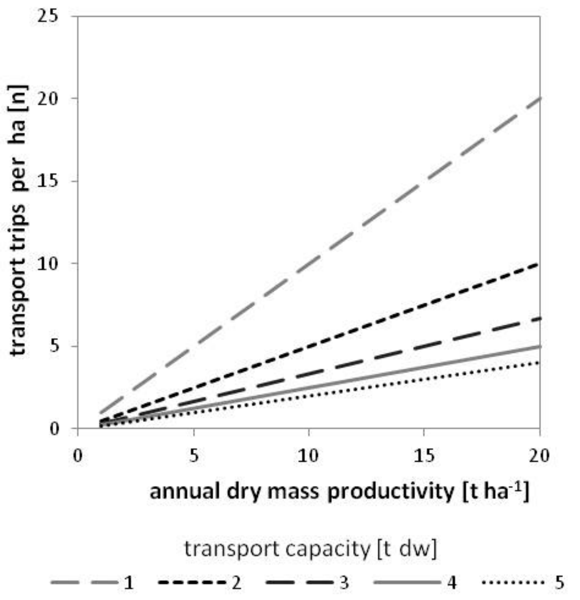

Figure 7. Relationships between number of transport trips required for biomass removal (*per* ha) and productivity, for different transport capacities (range 1–5 t dw).

density yielded values of 50 kg m^{-3} for fresh sedge biomass harvested in summer at water content 70 % (particle size 10–20 cm) and 100 kg m^{-3} for chopped reed harvested in winter at water content 30 % (particle size 2 cm). Thus, the maximum volumetric load capacity of the transport vehicle can vary widely. If the ground pressure of a tracked trailer with a contact area of 10 m^2 and an empty weight of 5 t should not exceed 100 g cm^{-2}, its maximum cargo load will be 5 t. When harvesting fresh biomass with water content 70 % and bulk density 50 kg m^{-3}, only 1.5 t of dry mass can be transported. In this case, the transport capacity is weight-limited and the transported volume should not exceed 30 m^3. In contrast, for dry or field-dried biomass (reed bundles, chaff or hay) with a water content of 20 %, a trailer of capacity 80 m^3 could be used to carry 4 t dw of biomass per trip. Because of the low bulk density, a transport capacity of more than 4 t dw can hardly be achieved in practice. Thus, in most cases, the transport of dry biomass is constrained by the volumetric capacity of the vehicle, whereas that of fresh biomass is restricted by the maximum cargo weight (Figure 8).

Working width and transport capacity strongly influence the efficiency of harvesting. With a larger working width, a reduced area is affected by wheels or tracks during each operation. For example, a machine with tracks or wheels 1 m wide and a working width of 3 m applies ground pressure to 66 % of the harvested area (2 × 1 m wide trails across a harvested strip 3 m wide). If the same machine is equipped with a 3 m front mower and two 4 m side mowers, just 18 % of the area covered is affected by the tracks or wheels (2 × 1 m wide trails across a harvested strip 11 m wide). Especially at low-productivity sites, it is possible to minimise the area affected by tracks or wheels by increasing the working width (Figure 9). However, only the maximum operating distance required to reach load capacity is changed, and there is no effect on the number of transport trips needed (*per* ha) for biomass removal. On high-productivity sites, large working width just makes sense if a dense network of strengthened field tracks is available. Otherwise, the transport distance driven with full load increases (see section on infrastructure).

The frequency of harvesting influences both the quantity and the quality of the biomass. In this context, ‘frequency’ refers to the full harvesting cycle for a specific field, and can vary from several times *per* year to only once in several years. As frequency increases, the amount of biomass that is harvested *per* cycle declines, reducing the number of trips required to remove it (*per* harvesting cycle). However, the total number of crossings *per* year may still increase overall, and the interval between successive harvests may become too short to allow regeneration of the sward (Schröder *et al.* in press).

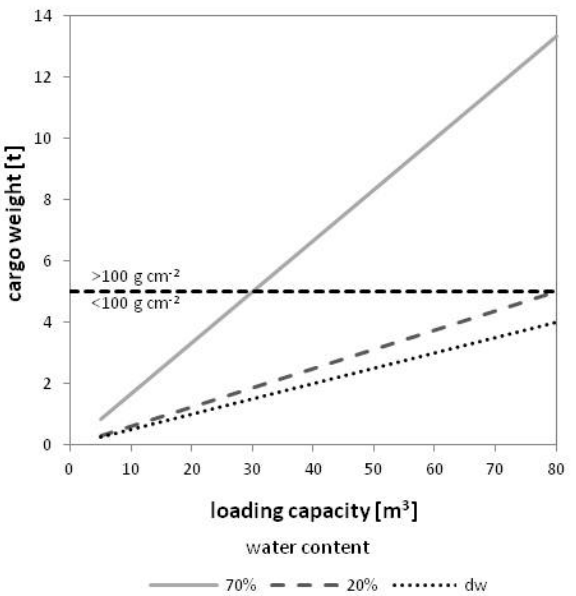

Figure 8. Relationships between calculated cargo weight and loading capacity for a vehicle with ground contact area 10 m^2 and empty weight 5 t, harvesting biomass of dry bulk density 50 kg m^{-3} at different water contents (70 % and 20 %). The vehicle can carry a maximum load of 5 t without ground pressure exceeding 100 g cm^{-2} (horizontal dashed line).

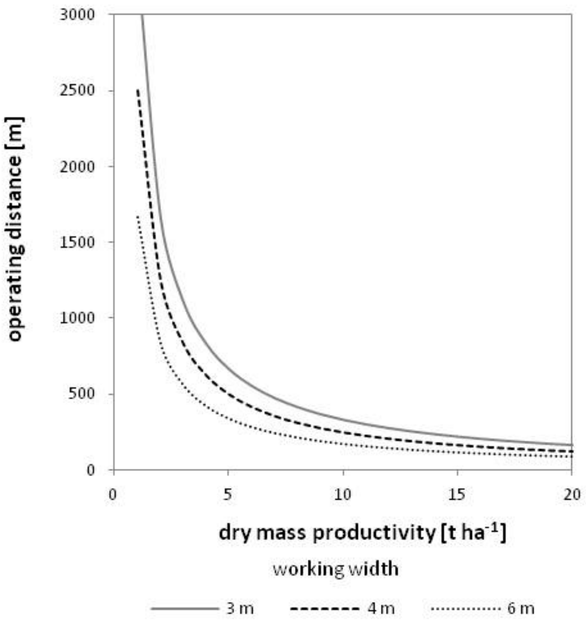

Figure 9. Relationships between maximum operating distance to fill a load capacity of 1 t dw and productivity, for working widths of 3 m, 4 m and 6 m.

Transport effort

The effort required to transport the biomass off the field depends on the harvesting approach. For example, to harvest one hectare with a dry mass yield of 5 t ha^{-1} a^{-1}, which is typical for wet meadows in Mecklenburg-West Pomerania (Dahms *et al*. 2015), a harvester with a mounted container of 9 m^3 capacity must make 11.1 trips; a harvester with mounted baler and capacity for 4 bales must make 6.4 trips; and a trailer with 25 m^3 capacity for chopped biomass must make 4.0 transport trips (Table 4). If the water level permits temporary storage of biomass bales on the field, only 1.8 transport trips *per* hectare will be required if 14 bales are transported together on a trailer (cf. Schröder *et al.* in press). To reduce the number of transport trips, the most viable option is to dry and compress the biomass on the field, then remove the bales using a separate trailer.

However, this method also has limitations; for example, if there is only one access point for a 10 ha field with a dry mass productivity of 5 t ha^{-1} a^{-1}, a machine with a separate trailer and a maximum load capacity of 14 bales must make 18 transport trips to remove the biomass. This amounts to 72 crossings (in and out, machine plus trailer) of the access point (Figure 10). Figure 1 shows the totally destroyed sward resulting from a well-adapted tracked harvesting machine pulling a separate tracked trailer, both with ground pressure less than 100 g cm^{-2}, crossing the same area 40–50 times. Even with improved machinery it will probably be impossible to avoid damaging the sward in making this number of trips. To further conceptualise the effect of 72 crossings, imagine being one of 72 people walking in single file across a wet peatland; it is easy to understand that the least favourable position in the line would be at the back!

Table 4. Calculated effort to transport biomass off wet peatland sites using different values for biomass yield, working width and transport capacity (cf. Schröder *et al.* in press). RD = Reload Distance (m); n = number of trips ha^{-1}; dw = dry weight.

Dry mass yield (t ha^{-1})	Working width (m)	Chopped biomass*				Bales**			
		Container 9 m³ (~450 kg dw)		Trailer 25 m³ (~1250 kg dw)		Combined harvester 4 bales (~777 kg dw)		Trailer 14 bales (~2720 kg dw)	
		RD	n	RD	n	RD	n	RD	n
3	3 5	500 300	6.7	1,389 833	2.4	864 518	3.9	3,023 1,814	1.1
5	3 5	300 180	11.1	833 500	4.0	518 311	6.4	1,814 1,088	1.8
10	3 5	150 90	22.2	417 250	8.0	259 155	12.9	907 544	3.7
15	3 5	100 60	33.3	278 167	12.0	173 104	19.3	605 363	5.5
20	3 5	75 45	44.4	208 125	16.0	130 78	25.7	453 272	7.4

* Dry bulk density: 50 kg m^{-3}, own measurement, higher if chopped very short.

** Dry bulk density: 122 kg m^{-3} (Wulf 2009); bale: 194 kg total dry mass (diameter: 1.30 m, width: 1.20 m).

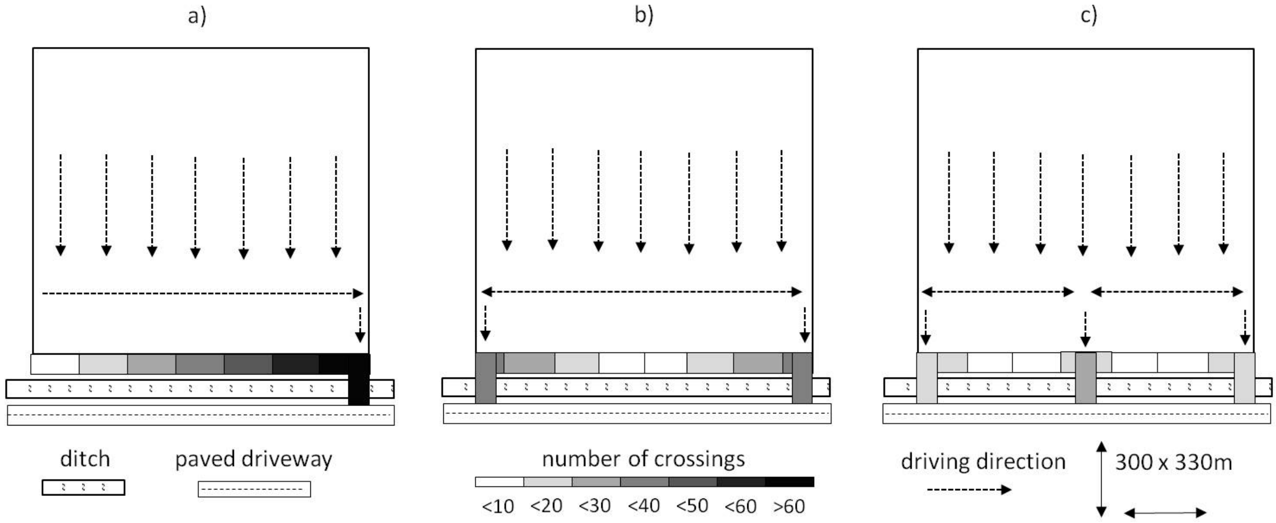

Figure 10. Visual representation of the number of access-point crossings required to remove mown biomass from a 10 ha field with a) one; b) two; and c) three access points, using a machine with a separate trailer and a maximum loading capacity of 14 bales (2,720 kg dw). The biomass is transported along the edge of the field to the closest access point. The calculation assumes a dry mass productivity of 5 t ha^{-1} a^{-1}.

Improvement of logistics

A well-designed logistical concept for biomass harvesting on wet peatland would avoid repeated crossings of the same ground. How often it is possible to drive over the same area before the sward is destroyed is only part of the question, however. The formation of a new resilient sward takes more than one year and there is a high risk of machinery getting stuck in destroyed areas over many years. Ideally, all transport trips which are not directly linked to biomass uptake must be avoided, as each additional crossing of the same area could be the critical one that finally destroys the sward. As the load capacity of the harvester is reached, it should be arriving at a reinforced track or unloading point and, after unloading, it should find itself located so that it can return immediately to collecting biomass (Schröder & Dettmann in press). An appropriate harvesting approach, with pre-arrangement of routes, is essential. Planning must take into account site characteristics and established infrastructure. If access is restricted, as often occurs in protected areas, it may be preferable to harvest only part of the area, as biomass harvesting in alternate years may be sufficient to prevent scrub encroachment. In such cases, biomass removal may be counter-productive in terms of the aims set out in site management plans.

REQUIRED INFRASTRUCTURE

Existing infrastructure in formerly-drained peatlands is often extensive, yet insufficient to support sward-sensitive removal of biomass. The arrangement of field tracks, access points and crossing points to neighbouring fields was mostly planned and established during ‘amelioration’ campaigns and, therefore, tailored to the requirements of fodder production using large harvesting machinery on drained soils. The standard of infrastructure required for paludiculture is substantially different, which means that infrastructure must be adjusted in advance of the implementation of paludiculture.

Problems relating to infrastructure

Bottlenecks at access points to or between fields make repeated crossings unavoidable. In many cases, not only drainage ditches, but also woodland, water and other barriers at the edges of peatlands can restrict access. Long distances from the edge of the peatland to the harvesting sites also lead to concentration of traffic. In formerly-drained peatlands, tracks have often already been strengthened, but because they were designed for lowered water tables, they may become unstable after rewetting. Furthermore, if present, paved areas for storage and transfer of biomass are usually too few or too infrequent to adequately support biomass removal after rewetting.

Upscaling the biomass harvest

Both upscaling of field size and enhanced yields increase the challenges of biomass removal. Therefore, it is essential that the infrastructure and the harvesting approach should complement one another. As the calculation of transport effort (Table 4) has shown, the operating distances required to reach load capacity vary remarkably amongst the different harvesting approaches considered. The required spacing of strengthened unloading points also varies with the cargo capacity of the harvesting machinery. For example, for a site whose dry mass productivity is 5 t ha^{-1} being harvested with a working width of 3 m, a machine with cargo capacity for 9 m^3 of chopped biomass must reach the next unloading point or strengthened track after 300 m of operation to avoid driving any distance empty or with a full load. If a trailer with cargo volume 25 m^3 was used, it would be full after 833 m; whereas a harvester with storage capacity for four bales would require unloading facilities after 518 m; and a trailer with capacity for 14 bales could travel 1,814 m before unloading was necessary (Table 4, cf. Schröder *et al.* in press). Because it is hardly possible to adjust the productivity of the site, the operating distances to reach cargo capacity can be adjusted only by changing the working width of the harvester (Figure 9). However, it would be nonsensical to reduce the working width to less than 3 m, i.e. to less than the physical width of the machine, because it would then have to make more than one pass along the same track. The most viable option is to adjust the network of agricultural paths and the number of unloading points.

Improvement of infrastructure

In order to prevent damage to the sward, it is necessary to reinforce tracks and existing access points. In Biebrza National Park in north-east Poland, fascines (bundles of long wooden sticks) are used to protect the ground along transport routes (Wichtmann & Tanneberger 2009, Wichtmann & Schröder in press). The use of fascines is labour-intensive and they have limited lifespan, but mobile plastic boards can be used as an alternative (Wichtmann & Schröder in press). These options are valuable in protected areas where biomass production is not the priority, but are not suitable for larger production sites which are harvested more frequently.

In formerly-drained peatlands the existing track network is sufficiently extensive to support biomass removal (Schröder & Dettmann in press), although strengthening of tracks and removal of bottlenecks is usually required (Wichtmann & Schröder in press). Drainage ditches that impede required access routes must be filled or, if the ditches are essential for water level regulation, a dense system of crossing points must be established (Figure 10). Alternatively, the harvesting machine can be adapted to cross small ditches or to unload its cargo onto a transport vehicle on the other side of a ditch.

These improvements to infrastructure are essential to enable paludiculture, for which the amount of preparation required will often be considerably greater than for conventional rewetting programmes. As peatland drainage was originally financed by public money, the cost of its reversal should be funded in the same way (Wichtmann & Wichmann 2011, Wichtmann & Schröder in press). The use of public money for such 're-amelioration' can be justified in terms of the recovery and improvement of ecosystem services delivered by rewetted peatlands, which include carbon storage, nutrient and flood retention, climate regulation and the preservation of biodiversity (Schäfer 2004).

CONCLUSIONS AND RECOMMENDATIONS

Many technical solutions and harvesting approaches are available for wet and rewetted peatlands. Nevertheless, there is still enormous scope for further improvements in design, innovation and adaptation of machinery. Particular attention must be paid to the technological and logistical challenges presented by the prospect of biomass removal being carried out at larger field size. In many cases the harvesting of wet and rewetted peatlands will be impossible without complementary adjustment of the harvesting machinery, logistics, and infrastructure of the target areas.

The harvesting machinery and appropriate use of machinery can be improved through the following technical and educational approaches:

- reduce machine weight;
- increase the contact area to reduce ground pressure;
- balance the weight of machinery, harvesting attachments and load;
- develop technical solutions to avoid shear forces;
- separate harvesting and transport vehicles;
- if using a tracked machine, ensure that its tracks have width:length ratio between 1:4 and 1:5;
- train operators on the peculiar features of specialised machinery and wet sites.

The harvesting logistics must reflect the specifics of the site. When upscaling biomass harvesting in wet and rewetted fens, the following recommendations should be followed:

- avoid repeated crossings of the same area;
- especially when using tracked machines, make wide turns rather than sharp ones;
- plan the driving routes for harvesters and transport vehicles beforehand;

- adjust the cargo capacity to the bearing capacity of the sward;
- compact the biomass on the fields prior to removal whenever possible;
- balance the logistics with the infrastructure.

The importance of infrastructure is frequently neglected. In preparing wet and rewetted peatlands for biomass harvesting, the following requirements should be fulfilled:

- eliminate access bottlenecks;
- reinforce existing biomass removal routes;
- construct new paved field paths;
- establish biomass unloading points;
- adjust the infrastructure to fit the requirements set by logistics.

Engineers, land users and scientists must work together closely in order to enable harvesting of biomass from wet and rewetted peatlands in conjunction with soil conservation. Furthermore, research on the bearing capacity and effects of machinery use on soil and vegetation is needed. Demonstration projects are essential to improve harvesting technique, logistics and infrastructure. Future work towards improving our expertise in managing wet and rewetted peatlands should place emphasis on linking these three factors.

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Author for correspondence:
Christian Schröder, Ernst Moritz-Arndt University Greifswald, Institute of Botany and Landscape Ecology, Partner in the Greifswald Mire Centre (GMC), Soldmannstrasse 15, 17487 Greifswald, Germany.
Tel.: +49 (0) 3834-864027; Fax: +49-(0) 3834-86-4114; E-mail: christian.schroeder@uni-greifswald.de