Department for Environment, Food and Rural Affairs

Machinery Requirements for Paludiculture

15 December 2022

Summary

Current agricultural machinery is generally too heavy for use on wet peat soils and may not be appropriate for planting and harvesting certain paludiculture crops.

Figure 1 below summarises machinery and market readiness for key paludiculture crops and products. The priority areas for supporting machinery innovation for paludiculture are:

- Non-chemical weed control measures and technologies, that can operate safely in wetlands e.g., autonomous weed robots
- Innovative harvest and transport solutions that reduce ground pressure, e.g., lightweight, tracked harvesters or sledge-and-cable systems.
- Design of tracks to reduce ground pressure and shear forces while turning.
- Dedicated or adapted machinery for efficient planting and harvest of *Sphagnum*.
- Machinery for processing novel paludiculture products such as *Typha* seedheads.

Beyond these areas, suitable machinery exists in other sectors, but will need to be trialled and perhaps adapted further to operate efficiently on wet peat soils. Funding for paludiculture test and demonstration projects is therefore needed to test and adapt this existing machinery to a paludiculture setting.

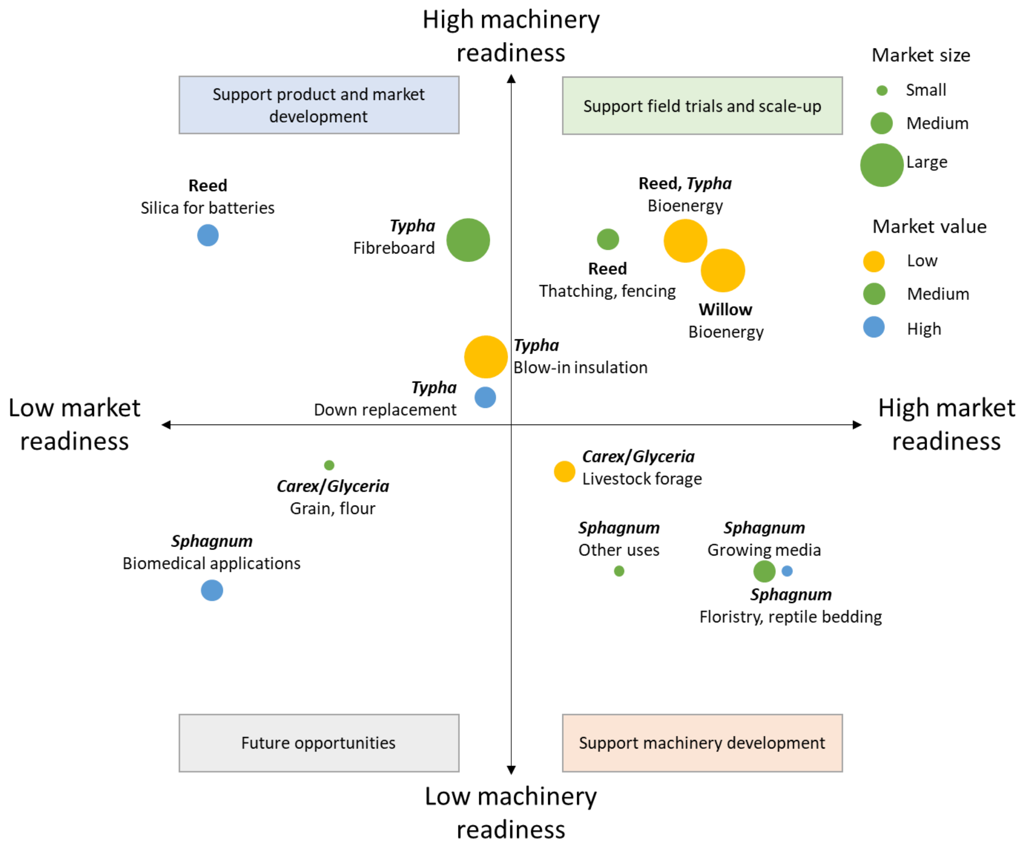

Figure 1: Machinery readiness, market readiness and market size and value for priority paludicultural crops and products.

Contents

Introduction

Purpose of the report

Paludiculture refers to productive farming of wetland crops on wet or rewetted peatlands. By maintaining a high water table and minimising disturbance of soils, adoption of paludiculture has the potential to reduce greenhouse gas emissions and soil degradation in peatlands that have been drained for agriculture. A recent Defra-funded review of the potential of paludiculture in England and Wales concluded that it could help meet climate change mitigation and adaptation targets, as well as reduce loss of productivity in farmed peat soils[1].

Current agricultural machinery is generally not suitable to be used in paludiculture. Wet peat soils have a low load-bearing capacity, and heavy machinery without appropriate tyres or tracks can easily become stuck or else damage the crop or soil by compaction or wheel slippage. This can lead to erosion, greenhouse gas emissions and loss of production. The specialised crops grown in paludiculture also have distinct requirements for planting, maintenance and harvest, which in some cases require dedicated machinery.

The Paludiculture Sub-Group of the Lowland Agricultural Peat Task Force convened by Defra has developed a Paludiculture Roadmap to support the development of a commercially viable paludiculture sector in England by 2033. One of the key themes covered by the Roadmap concerns the availability of suitable agricultural machinery for growing and harvesting paludicultural crops at scale in wetland environments (the Machinery Pathway).

This report fulfils three of the five objectives of Year 1 and Year 2 of the Machinery Pathway, namely:

1. Plan out whole-chain machinery requirements for priority crops, including off-site transport.
2. Review potential machinery solutions from other industries and countries for moving materials and working on wet soils.
3. Undertake a gap analysis of the whole-chain machinery requirements.

The Paludiculture Machinery Workshop

This report is in large part based on an expert workshop held virtually with members of the Paludiculture Subgroup and additional experts in paludicultural systems and machinery on 25th October 2022. The workshop participants are listed in Annex 1.

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[1] Mulholland et al. (2020). An assessment of the potential for paludiculture in England and Wales.

Priority Crops and Products for Paludiculture in England

Most crops grown in conventional agriculture are not adapted to the wet soils used in paludiculture. Instead, wetland-adapted plants today tend to be harvested at smaller scales from mostly natural environments such as reed beds.

While many useful plants are able to grow in wetland environments, a smaller number have been identified as having significant near-term potential as paludiculture crops in the UK. In part because of the need to avoid disturbance and oxidation of the soil, most paludicultural crops being considered today are perennials. Workshop participants have identified six priority crops, given in Table 1.

Table 1: Priority paludicultural crops and end uses considered in this report.

Crop	Common name	Main products	End uses
Phragmites australis	Common reed	Stem/leaves	Thatching Fencing Paper Lithium-ion batteries Bioenergy
Typha species	Bulrush, reedmace, cattail	Seedhead Stem/leaves	Down replacement in clothing Building insulation Fibreboard Construction materials Bioenergy
Carex species	Sedges	Seeds Foliage	Edible flour Livestock forage
Glyceria species	Sweetgrass, Mannagrass	Seeds Foliage	Edible flour Livestock forage
Salix species	Willow	Shoots	Fencing Weaving Bioenergy
Sphagnum species	Peat moss	Whole plant	Growing media Reptile bedding Floristry Medical / antimicrobial compounds Water filtration

Further details on these crops are given in Annex III.

Cross-Cutting Challenges for Paludiculture Machinery

Most agricultural harvesting machinery is designed for use on mineral soils with a low moisture content. Harvesting of peatland plants has typically been done on a small scale, often using handheld tools or small, custom-built machinery. Operating on wet peat soils poses several challenges to the use of large-scale machinery:

Minimising damage to the peat surface

The high water content of wet peat soils dramatically reduces the load-bearing capacity of the ground, and increase the risk of damage to the soil surface by tyres or tracks. Conventional agricultural machinery is usually too heavy for wetland soils, and conventional tyres concentrate the weight onto a small contact area, leading to high ground pressure where the tyres meet the soil. This can lead to machinery getting stuck in boggy soils, and to compression and damage to the crop and the peat surface. Over several trips, this can make areas of the peat soil impassable.

A common rule of thumb is that water-saturated peat soils require machinery with a ground pressure less than 100 g cm^{-2}. Conventional agricultural machinery, in contrast, typically has a ground pressure between 200 and 2,000 g cm^{-2}.

The challenge is even greater during harvest because of the need to transport the weight of the harvested biomass, and because multiple trips are usually needed into and out of the field to take the crop to a storage area. This can be exacerbated by the high water content of some wetland crops: a trailer loaded with wet *Sphagnum* moss has a much greater weight (and therefore ground pressure) than the empty trailer. Harvesting of biomass in paludiculture settings therefore typically requires machinery that has been specially designed or adapted to operate on wet soils.

Reducing ground pressure on the peat surface can be achieved in various ways[2]:

Use of small and lightweight machinery: reducing the overall vehicle weight, for example by using small tractors or pedestrian-operated machinery (e.g., a two-wheeled mower where the operator walks behind). While often used in conservation management or small-scale reed harvest, these machines are economical only for small areas[2].

Low ground pressure tyres: machinery can be fitted with special tyres to increase the contact area and reduce ground pressure. Lighter machinery can be fitted with twin tyres to distribute the weight. Heavier machinery may use dedicated low-

[2] Schröder et al. (2015), [Towards large-scale paludiculture: addressing the challenges of biomass harvesting in wet and rewetted peatlands.]

pressure tyres, such as balloon or flotation tyres. These are large rubber tyres filled to low air pressure, increasing the contact area with the soil surface and providing some buoyancy over wet soils. They are not as effective at reducing ground pressure as tracks, but wheeled vehicles can be driven on roads more easily.

Tracks: increasing the ground contact area by replacing tyres with tracks. Available options include (in order of decreasing ground pressure):

1. "Bogie" tracks: plastic, metal or rubber track loops that can be fitted around conventional wheels on a tractor or harvester to reduce ground pressure by up to 20%.
2. "Delta" tracks: short, modular track units that can be fitted to tractors or other vehicles as wheel replacements.
3. Full tracks: vehicles designed or adapted to use full-length tracks instead of wheels.

The first two options are readily available and can be fitted to conventional vehicles. Fully tracked trailers and some harvesters are also available commercially, while some tracked vehicles designed for other sectors (e.g., snow groomers) have been widely adapted for use in wetland settings.

Even tracked vehicles with low overall ground pressure can still damage the crop or soil surface. If soils are particularly wet or waterlogged, or if multiple passes are made, vehicles can still churn up the soil and leave deep ruts in the soil surface. Damage can also occur during turning (since the tracks drag across the soil surface) or if the load is distributed unevenly (so that the weight is concentrated on the front or rear edge). The risk of damage can be reduced further by improving vehicle design, for example:

- Reducing the size and weight of vehicles, e.g., by using lightweight components;
- Ensuring even load distribution;
- Improving design of tracks and wheels to reduce drag on the soil surface, e.g., by using low-tread, rubber tracks;
- Use of in-built sensors to detect and reduce slippage.

Managing logistics to minimise ground damage: careful logistical planning is crucial to minimise the number of trips over peat soils and the ground pressure of individual vehicles. For example, depending on the setting, use of a trailer separate to the harvester can reduce soil damage by distributing the weight across multiple vehicles. Lightweight or low ground pressure machinery can also be used for cutting and transport to the field edge, where conventional vehicles can collect the crop for further transport.

Operating from causeways, canals or rails: the risk of soil damage can be avoided by constructing raised causeways, canals or other structures within the field where conventional machinery can be used to harvest and transport the crop. In some European trials of *Sphagnum* cultivation, excavators scoop up *Sphagnum* from causeways and deposit it in conventional trailers[3]. The advantage is that farmers can use standard machinery (which they may already possess), but it requires sacrificing a portion of the cropping area. For other crops, harvesting from a causeway would be more difficult, but a lightweight harvester could deposit biomass in trailers on causeways or barges on canals for onward transport.

Reducing the total weight of harvested biomass: the ground pressure of vehicles for transporting biomass from the field could also be reduced by reducing the weight of the crop, either by harvesting only the parts of the plant required (e.g., seeds) or by reducing water content (e.g., by cutting and allowing stems to dry before removal).

Harvesting specialised, small-volume crops

At first, paludicultural crops will be grown on a smaller scale than most conventional crops. This poses a challenge to the availability of harvest machinery adapted to wetland soils or to the needs of specific crops, since the sector cannot readily benefit from economies of scale that come with development of standardised, off-the-shelf machinery solutions or large-scale harvesters.

The challenges associated with particular crops, such as harvesting *Sphagnum* or separating the seedhead from *Typha*, are also likely to require crop-specific machinery, which will in most cases need to be custom-built or adapted from existing machinery. This increases the cost and barriers to scale-up of paludiculture.

Weed control

In conventional agriculture, weeds are usually dealt either by spraying with herbicide or by regular ploughing the soil. Neither of these are desirable for wet peat soils. Chemical herbicides could leach into groundwater or surface water and affect the crop or nearby watercourses. Ploughing can lead to loss of soil carbon and is in any case not possible once a perennial crop is established. Paludicultural systems must therefore rely on non-chemical measures or on precision application of herbicide to targeted plant species without contamination of surface or groundwater. Table 2

[3] Gaudig et al. (2017), Sphagnum farming from species selection to the production of growing media – a review.

shows a range of weed control measures that could be used in paludiculture contexts.

In addition, emerging non-chemical and precision technologies such as AI-driven laser targeting of weeds, weed electrocution and autonomous weeding robots have potential for use in paludiculture. Further details of crop-specific solutions are given in the Establishment and Maintenance section.

Table 2: Currently available weed control methods and machinery suitable for use in paludiculture.

Method	Description	Advantages	Limitations
Strimming, mowing	Mechanically cutting back weed species with a handheld strimmer or tractor-mounted mower.	Low cost, non-chemical	Labour intensive, only viable at small scales.
Mulch	Material laid over the soil surface to prevent weed emergence or growth.	Low cost, non-chemical	Not suitable where crop needs to spread across soil surface (e.g., *Sphagnum).*
Weed wipers	Tractor-mounted machines using a rotating brush or belt to apply herbicide to target weeds.	Avoids chemical spraying	Only targets weeds growing above the level of the crop.
Soil sterilisation	Soil steaming or other non-chemical sterilisation of soil seed bank before planting.	Non-chemical, reduces contamination of crop.	Expensive, only feasible before establishment.
Torsion or finger weeders	Mechanical tools towed behind tractors that grip and uproot fragile weed species between crop rows.	Non-chemical, can be done after crop is established.	Requires crop that is stronger or better anchored than weeds.
Water table management	Managing water levels to suppress weed growth (e.g., temporary standing water)	Non-chemical	Difficult in uneven soils; can increase methane emissions.

Establishment and Maintenance of Paludiculture Crops

Since most paludicultural crops are perennial species, a crop typically only needs to be established once to remain productive for years or decades. This means that preparation and planting in drained peatland can be done before rewetting of the soil, allowing conventional machinery to be used. The exception is *Sphagnum*; since mosses lack persistent roots or rhizomes, the whole plant is removed at harvest and a new crop must be established afterwards. Other crops may also need to be periodically cleared and re-established to manage encroachment of competing species or declining vigour of the original plants (e.g., willow).

Land preparation and hydrology

Unlike mineral soil agriculture, successful establishment of paludiculture crops requires careful management of the site's hydrology. Some crops (e.g., reed) thrive in moving water, requiring a continuous flow to be set up through the field; for others, maintaining water levels at or just above the soil surface can help to prevent weed encroachment. Young seedlings can be sensitive to the level of water, and especially to flooding.

Excavators or bulldozers may be needed to level the site, or to create topography favouring water flow, before planting. Levelling or removal of topsoil also helps remove competing vegetation. This can usually be done using conventional machinery before rewetting of the peat. However, the peat surface can subsequently undergo swelling or subsidence, leading to localised areas of shallow flooding where the water table is close to the surface. Top-down irrigation is an alternative solution to maintain moist conditions for crops vulnerable to flooding.

Sphagnum may benefit from further weed eradication before planting. Since *Sphagnum* species are slower-growing and low-lying, they are vulnerable to competition from other plants that may be present as seeds, roots or rhizome fragments in the soil. Soil steaming technology may be valuable for minimising weed contamination and competition before establishing a *Sphagnum* crop.

Planting or seeding

Planting of most priority paludiculture crops could be done with existing or adapted conventional machinery on drained soils before the peat is rewetted. Once the water table is raised (e.g., if a crop needs to be replanted), current machinery may be less effective. Less is known about the potential for planting equipment to operate in wet soils, but methods that minimise soil disturbance (e.g., broadcast seeding or spreading moss across the soil surface) or establish more mature plants (i.e., plug plants) are likely to be more successful. Conventional tractor-drawn planting machinery may also need to be adapted to reduce ground pressure on wet soils.

Reed

If a mature reedbed exists nearby, reed may naturally colonise exposed wet peat soils over 2-3 years via underground rhizomes. However, establishing larger reed plots will require dedicated planting.

It is reportedly difficult to grow reed reliably from seed[4], with the tiny seeds prone to periods of dormancy and vulnerable to both drying out and flooding. However, reed regrows well from rhizomes, and rhizomes are better able to tolerate waterlogging and drying. Pieces of reed rhizome can be planted directly using a modified potato planting machinery in peat soils. Another emerging approach is to encapsulate primed plant material in a growing medium to create a self-contained unit that can be planted like a seed, again using a potato planter or similar conventional machine (e.g., "CEEDS™" being developed by New Energy Farms).

A more expensive but faster approach is to use plug plants, employing small-scale transplanter technology as is widely used in vegetable farming or tree planting. Once established, reed will vigorously outcompete other wetland plants and will tend to form a dense reedbed without further management.

Typha

Typha shares many characteristics with reed. Like reed, growing *Typha* from seed is challenging[4], both because of the difficulty in handling or distributing the fluffy seeds evenly and their vulnerability to flooding or drying out. *Typha* also grows well from rhizomes and plug plants, and can be planted using the same machinery as for reed. Encapsulated cuttings may also be viable for *Typha*, although have not yet been developed as they have for reed.

Carex and *Glyceria*

Unlike reed and *Typha*, both sedge and sweetgrass species tend to grow well from seed provided flooding is avoided. Direct drill seeding systems (designed to minimise soil disturbance) could be adapted to sowing these species in paludiculture settings before soils are rewetted, but it is not known how well they would perform in wet peat soils.

[4] Geurts, J.J.M. and Fritz, C. (2018), Paludiculture pilots and experiments with focus on cattail and reed in the Netherlands.

Several species are also available to be planted as plug plants, using similar machinery as for reed and *Typha*. However, the relatively higher planting density needed means this will probably prove less cost-effective than seed.

Sphagnum

In most existing *Sphagnum* farming trials, wild-growing whole moss plants have been removed from natural donor sites and spread mechanically over the paludiculture plot. This has been done either manually or using a muck spreader. However, this requires large amounts of donor material, is labour-intensive and carries a high risk of contamination with weeds from donor sites.

UK researchers are using micropropagation techniques to embed small plant fragments in a liquid, gel or beads that can be more easily applied to the soil. The liquid or gel can be applied evenly across the soil using a "dribble bar" system commonly used for slurry application in conventional agriculture, in which the liquid is distributed through a wide boom with closely spaced nozzles near to ground level. However, to establish a new *Sphagnum* crop after harvest, such machinery may need to be modified to travel on wet soils, e.g., by fitting with tracks or by drawing a boom across the field between two vehicles operating on causeways.

Willow

Willow coppice is typically established by planting short rods or billets (living willow shoots) directly into the soil. Specialised willow transplanters exist for doing this at large scales in non-wetland settings, and the same machinery could be used in a paludiculture setting. For smaller scales, use of handheld tree planters may be sufficient given the crop can last 15-20 years before replanting is necessary.

Weed control: crop-specific measures

Reed and *Typha*

Both reed and *Typha* grow quickly and naturally form dense stands, crowding out other species. Limited weed controls are therefore needed. Reed may begin to outcompete *Typha* over time if nutrient levels fall.

Carex and *Glyceria*

Ongoing weed control is likely to be needed, especially during establishment, to keep out reed, common rush and other species. Strimmers or weed wipers can be used to control these weeds in the early stages of crop establishment whilst they grow above the height of the crop.

More mature crops can be too tall for weed wipers to be effective, requiring other methods of non-chemical control. Soil steaming or sterilisation before planting may help to reduce competition issues, but can be costly.

Sphagnum

Since *Sphagnum* species are slower-growing and low-lying, they are vulnerable to competition from taller plants that may be present as seeds, roots or rhizome fragments in the soil. As above, soil steaming technology may be valuable for minimising weed contamination and competition before establishing a *Sphagnum* crop.

Once established, weeds can also be controlled with weed wipers or mowers that target plants growing above the moss layer.

Willow

Willow coppice can also be vulnerable to fast-growing weeds, especially in the first year, and control can be more difficult given the similar height of young willow shoots and competing weeds. Non-chemical weed controls for willow coppice are lacking[5]. Soil steaming before planting to sterilise the soil seed bank may help to control weeds during establishment. During early growth, mechanical tools such as torsion weeders (flexible metal tines pulled through the crop layer) or finger weeders (rotating wheels with rubber fingers that grip weed plants) have been used to uproot weeds without harming the crop. However, these tools may cause soil disturbance and can only be used if the willow is sufficiently established and well-anchored to resist the machinery.

Further development of non-chemical weed control methods for willow coppice may be needed to maximise the potential of willow as a wetland crop.

[5] Albertsson (2014), Impact and Control of Weeds in Biomass Willow Clones.

Table 3: Alternative planting or seeding technologies for paludiculture crops and their associated machinery needs.

Planting material	Suitable crops	Description	Machinery needs	Limitations and development needs
Seeds	*Carex* *Glyceria*		Direct drill seeder	Drill systems may need to be adapted to wetland/peat soils
Plug plants	Reed *Typha* *Sphagnum*	Small seedlings in "plugs" of potting soil	Agricultural transplanter Tree planting machinery (for larger spacings)	Widely available. *Sphagnum* or taller reed/*Typha* plants may cause issues.
Encapsulated propagules	Reed *Typha*	Capsules containing small plant propagules in growing medium.	Modified potato planter	Technology needs further development.
Rhizomes	Reed *Typha*		Modified potato planter	Available
Rods/billets	Willow	Cut willow shoots	Manual; Willow transplanter	Available
Whole plants	*Sphagnum*	Whole plants transplanted from natural donor sites	Muck spreader	Large volume of donor material required; difficult to get even spread.
Microprop gel/beads	*Sphagnum*	Micropropagated plant material embedded in liquid, gel or beads.	Modified dribble bar systems	Under development. Existing machinery adequate with modification, but may need to be adapted to wet soils for replanting after harvest.

Harvest, Removal and Processing

Crop-specific harvest requirements

In general, the need for low ground-pressure machinery means that harvesting equipment needs to be smaller and lighter than that commonly used in conventional agriculture. In most cases, the whole plant is cut and either chopped/processed by the harvesting vehicle or stored as whole stems or bundles for drying and later processing off-field.

For bioenergy uses and for *Sphagnum*, so-called “double chop” or “precision chop” harvesters can be used to chop biomass during harvest into smaller pieces for easier handling and transport. However, such finely chopped biomass is more difficult to dry and may require active drying to reduce moisture levels for storage or burning. For biogas, this is not an issue as high moisture contents are beneficial.

Reed

Reed is currently harvested widely in mainland Europe and some parts of the UK. Most reed today is cut in late winter using cutter-bundler systems, where reeds are cut close to the soil surface and tied into bundles that can be stacked in the field or a storage area to dry further before use in thatching or fencing. There are several machines available, ranging from small pedestrian-operated mowers to larger automated cutter-bundler systems that cut and tie bundles of reed for stacking on a trailer or storage platform. Smaller machines use multiple tyre setups or balloon tyres to reduce ground pressure; larger machines are typically tracked.

Some off-the-shelf smaller machines exist, but larger vehicles usually need to be made to order or custom-adapted from conventional tracked machinery (e.g., snow groomers) because of the relatively small scale of the reed industry.

Reed can also be harvested with a double-chop or precision-chop forage harvester and deposited straight into a trailer or bin if it is to be used for bioenergy, fibreboard or pulp and paper. This is faster than bundling, but makes drying more difficult for those end uses that require low moisture content.

Typha

Harvest of *Typha* has two possible products: the stem biomass and the seedhead. At present, no machinery currently exists that either harvests the seedhead alone, or that separates the seedhead from the stem and leaves during the harvest process.

The most viable current route for extracting the seedhead is a cut-and-bundle machine as is used for reed. Later separation of the seedhead is currently manual, and no machine yet exists that automates this process.

As with reed, a double- or precision-chop harvester may also be used to yield chopped biomass that can be easily handled and transported, subject to the same challenges of drying.

Carex* and *Glyceria

Carex and *Glyceria* harvest would most resemble grass, cereal or sesame harvest in conventional agriculture. The tiny seeds constitute the main crop, while the stem and leaves may also have value as hay, silage or as a bioenergy feedstock.

These crops would be harvested with a small combine harvester, able to cut the whole plant and thresh (separate the seed from straw) in a single pass. Most modern combine harvesters are designed for large-scale harvest of cereal crops and are relatively heavy, with even tracked versions having higher ground pressure than can be borne by wet peat soils. However, smaller tracked combines have been developed for rice harvest, and could be adapted to these crops.

Current (wild) varieties of these species also have characteristics that make efficient harvest difficult. For example, some species form wide clumps or hanging seedheads that are more difficult to uniformly harvest. Appropriate machinery for harvesting these crops will need to be determined along with further breeding to improve the yield characteristics and growth habit for harvest.

Sphagnum

Harvesting *Sphagnum* requires a different approach to the other crops discussed here for three reasons:

1. The whole moss layer should ideally be collected, meaning harvesters need to pick up material right down to the soil surface.
2. Live *Sphagnum* has a high water content, adding to the weight and therefore ground pressure of harvesting or transport vehicles.
3. It tends to form a continuous mat, which can be difficult to handle without chopping.

A single clear harvesting solution for *Sphagnum* has not yet emerged.

Many *Sphagnum* trials in Europe have used a combination of raised causeways and conventional tracked excavators fitted with mowing buckets. The excavator arm is used to scoop up the moss layer in strips and transfer it to a trailer. This has the advantages of requiring no dedicated machinery and minimising damage to the peat surface. However, the causeway reduces the total harvest area, and excavators lack the precision control to reliably harvest down to the soil surface. This approach is thus unlikely to be viable at scale.

An alternative is to use a dedicated tracked forage harvester that uses a "pickup reel", a rotating cylinder with protruding metal tines, to lift the moss as a layer and transfer it to a trailer or storage bin. Forage harvesters that include a chopping head can cut the moss layer into smaller pieces during harvest, making it easier to handle.

Collection and transport can be made easier by partly drying the moss before harvest. In Canada (where wild moss is harvested), a tractor is used to tow a light harrow through the soil to break up and turn the moss layer, which is then left to dry. The dried, broken-up moss can then be collected more easily using a forage harvester. The same result could be achieved by halting irrigation if the water table is maintained below the soil surface.

In the absence of in-field drying, another possible solution for reducing weight could be passing moss through rollers to squeeze out excess water. However, too much pressure from rollers could also damage the structure of the moss.

After harvest, *Sphagnum* in most cases would need to be further dried, chopped to fragments of appropriate sizes (from a few mm to 2-3 cm) and in some cases sterilised with steam to kill any microbes, pests or viable plant seeds within the crop. If weed species are present, they may also need to be separated before the *Sphagnum* can be used.

Further development and testing of mechanical harvesters capable of efficiently collecting *Sphagnum* in paludicultural settings is needed for this to become a mainstream crop.

Willow

Willow coppice is usually harvested in one of three ways[6]:

1. A whole-shoot harvester that cuts stems close to the base for collection into bundles or bales;
2. A billet harvester that cuts and chops shoots into "billets" (lengths of wood from 5-20 cm), often adapted from sugar cane harvest machinery;
3. A chip harvester (modified forage harvester) that chops biomass into small chips (2-3 cm) for use as fuel in a single pass.

Use of willow for fencing or weaving requires harvest as whole stems. This tends to be slower than harvesting as billets or chips and requires more labour to handle, but dries more efficiently. It is economical for small areas of coppice. Billet or chip harvesters

[6] Kofman (2012), Harvesting short rotation coppice willow.

tend to be heavier, but are more efficient at clearing larger areas of coppice. Chip harvesters are typically forage harvesters that have been modified to deal with the rigours of chopping tough, woody stems.

Bulk green willow chips are much harder to dry than bundles or billets. Such chips must either be burned immediately (e.g., in a large facility with high demand for chips) or subjected to active drying (e.g., an air blower system), increasing the cost. Whole stems or billets can also be chipped in a separate unit once dried and used as a fuel, or smaller billets can be used directly in large biomass boilers.

Both self-propelled and tractor-drawn machinery is available. Self-propelled machines tend to be heavier and may not be suitable for wet soils, but are more efficient for harvesting large areas.

Willow coppice is a relatively mature crop, both as a material and a bioenergy feedstock. This means there are several machinery options available for efficient harvest of willow, including smaller and tracked variants more suitable for use on wet peat soils.

Collection and transport off-field

One of the greatest challenges in paludiculture is how to collect and remove large volumes of biomass from the field without causing damage to the soil surface.

There is often a trade-off between the size of a trailer or other vehicle and the number of passes it needs to make across soft ground: smaller trailers may have lower ground pressure, but more trips across the field will be needed to harvest the crop. Generally, the choice of solution will be determined by logistical factors (e.g., the size of the field and distance to storage area) and by the characteristics of the crop and soil.

The most compact solution is an integrated bin or hopper mounted on a harvester vehicle, which can store a small amount of harvested biomass without the need for a separate trailer. This is suitable for sites where the harvester can deposit the crop to a dry landing area out of the field where it can be transferred to a conventional trailer. However, vehicles with an integrated bin can increase the weight and require more many trips to unload during harvest.

The most flexible solution is to use one or more dedicated low ground pressure trailers (either small and lightweight or fitted with tracks) to receive the crop from the harvester. This can reduce the number of trips needed. However, trailers fitted with tracks are more costly, and may not be suitable to transport crops on roads if the field is not close to the storage area.

The same is true of proposed sledge systems that aim to reduce ground pressure by doing away with wheels and tracks entirely, distributing the load over the full base area of the vehicle. Sledges would create higher friction and would not be suitable for road transport, but could be towed across and out of fields using long cables drawn by vehicles on the field boundary.

Since these solutions are not generally crop-specific, many are readily available and in use in conventional agricultural or forestry settings where wet or soft soils are a concern. These existing vehicles could be readily transferred to peatland settings.

However, further development of transport vehicles could be needed to operate on soils with the lowest load bearing capacities. If the ground is not able to support fully loaded tracked trailers, for example, then development of wetland-specific solutions such as sledge-and-cable systems may be beneficial.

Machinery readiness and innovation needs

The key machinery challenges for scaling up paludiculture are:

1. Traversing wet peat soils without damaging the sward or soil surface;
2. Managing weeds without extensive spraying of herbicide;
3. Developing and adapting machinery for novel crops.

Traversing wet peat soils without damaging the sward or soil surface

The challenges of movement on wet peat soils can in many cases be managed by using smaller vehicles, using tyres or tracks that minimise ground pressure, planning logistics to minimise repeated passes and harvesting material at low moisture content. Where these strategies are not sufficient (e.g., for very wet soils), use of raised causeways or canals for machinery access or transporting biomass can protect soils at the cost of reducing crop area.

Across all paludiculture crops, further machinery development should focus on:

- Reducing the size and weight of vehicles and harvesters (e.g., by using lightweight components);
- Improving the design of tracks and tracked vehicles to minimise soil and crop damage, e.g., by reducing dragging forces during turning;
- New low-ground-pressure solutions for transporting harvested biomass such as sledge-and-cable systems.

Managing weeds without spraying of herbicide

Weed control in paludiculture needs to be tailored to the crop and context, and non-chemical methods are lacking for some crops. At small scales, handheld strimmers or mowers are sufficient. Weeds that grow taller than the crop (e.g. for *Sphagnum* or *Carex*) can be managed with mowers or with “weed wipers” that apply herbicide to weeds above a certain height. For strong and well-anchored crops, torsion or finger weeders towed behind tractors can uproot more fragile weeds between crop rows.

Further development of non-chemical weed control methods would expand the tools available for paludiculture. Emerging technologies include automated weed control systems, such as machines that use image recognition to identify weed species and target them with a laser, electric current or precision application of herbicide.

Developing and adapting machinery for novel crops

Planting most of the priority crops could be done with machinery from conventional agriculture (or adapted versions) towed behind tractors adapted for wetland soils. For example, conventional crop transplanters or potato planters could be used to plant reed or *Typha* plug plants or rhizomes, respectively. However, the performance of some machinery (e.g., direct drill seeders) on wet peat soils is relatively unknown and some modifications may be needed. Depending on the site, the water table may in some cases need to be temporarily lowered before planting.

Machinery for harvesting willow and for reed (albeit at small scales) is already available, and reed machinery could also be readily adapted for harvesting *Typha*. *Carex* and *Glyceria* could be harvested with a lightweight combine harvester or grass harvester, but more crop development is needed before specific machinery can be identified.

Sphagnum least resembles conventional crops in terms of both planting and harvest. Most current trials rely on mechanical spreading of *Sphagnum* from wild sites, which suffers from weed contamination issues and is not scalable. Emerging technology to embed micropropagated plantlets in a liquid or gel for easier spreading will alleviate some of these challenges, but will require new or specially adapted machinery. Similarly, no single harvest solution for *Sphagnum* has yet emerged that resolves all the challenges. Dedicated or adapted machinery may be needed to efficiently chop and harvest *Sphagnum* while protecting soil and minimising crop water content.

Table 4 outlines the state of readiness and key innovation needs in machinery for the six priority crops considered here.

Table 4: Readiness of machinery for different management stages of priority paludicultural crops. Green indicates no specific machinery need or that conventional machinery is adequate. Yellow indicates machinery solutions exist but are currently at small-scale, custom-built or require significant adaptation of conventional machinery. Red indicates further investment and development are needed to identify effective solutions or make them commercially available to farmers.

Crop	Reed	*Typha*	*Carex & Glyceria*	*Sphagnum*	Willow
Land preparation	Conventional machinery (excavators, bulldozers)				
Planting & seeding	Standard crop planters or tree planters can be used for plug plants. Modified potato planters for rhizomes.		Adapted direct drill systems.	Existing solutions not scalable. Microprop gel needs further development.	Existing planters adequate.
Weed control	Minimal weed control needed.		Weed wipers when crop is short; more options needed for mature crop.	Weed wipers or mowers; steam sterilisation.	Torsion or finger weeders; more options needed.
Harvest	Reed harvesters and chopper systems exist at small scales.	Reed harvesters. No machinery exists for seedhead removal.	Small tracked combines available. Crop development needed.	Multiple proposed or bespoke solutions; no single solution has resolved all challenges.	Tracked harvesters available but weight may be a challenge.
Transport	Tracked, lightweight tractors and trailers exist. Further reductions in ground pressure may be needed.				
Processing	No special requirements.	No machinery for seedhead removal or processing.	Standard milling machinery.	Fine chopping remains a challenge.	Standard chipping machinery.

Priority crops for developing paludiculture machinery

For all crops, improvements in lightweight harvest and transport vehicles, low-ground-pressure tracks and non-chemical weeding would improve their viability as paludiculture products. However, certain crops and products are closer to “machinery readiness” than others. Figure 1 summarises the current machinery readiness for priority paludiculture crops and products in comparison to their market readiness, market size and potential value.

Of the priority crops, reed, willow and *Typha* could largely be planted, managed and harvested using either existing machinery or adapted versions. These crops can best be commercialised by support for field trials and demonstration projects, adaptation of existing machinery and development of higher-value products and markets such as silica for reed and down replacement for *Typha*. Commercialisation of *Typha* could be further supported by machinery for removing and processing the seedhead into insulation material.

In contrast, *Sphagnum* is the most challenging crop in machinery terms, but is one of few crops to have existing medium- to high-value markets. Development of machinery for effective planting, management and harvest of *Sphagnum* is therefore a priority.

Carex and *Glyceria* require significant further development before they will become commercially viable. Adaptation and refinement of existing machinery will be needed in tandem with crop breeding.

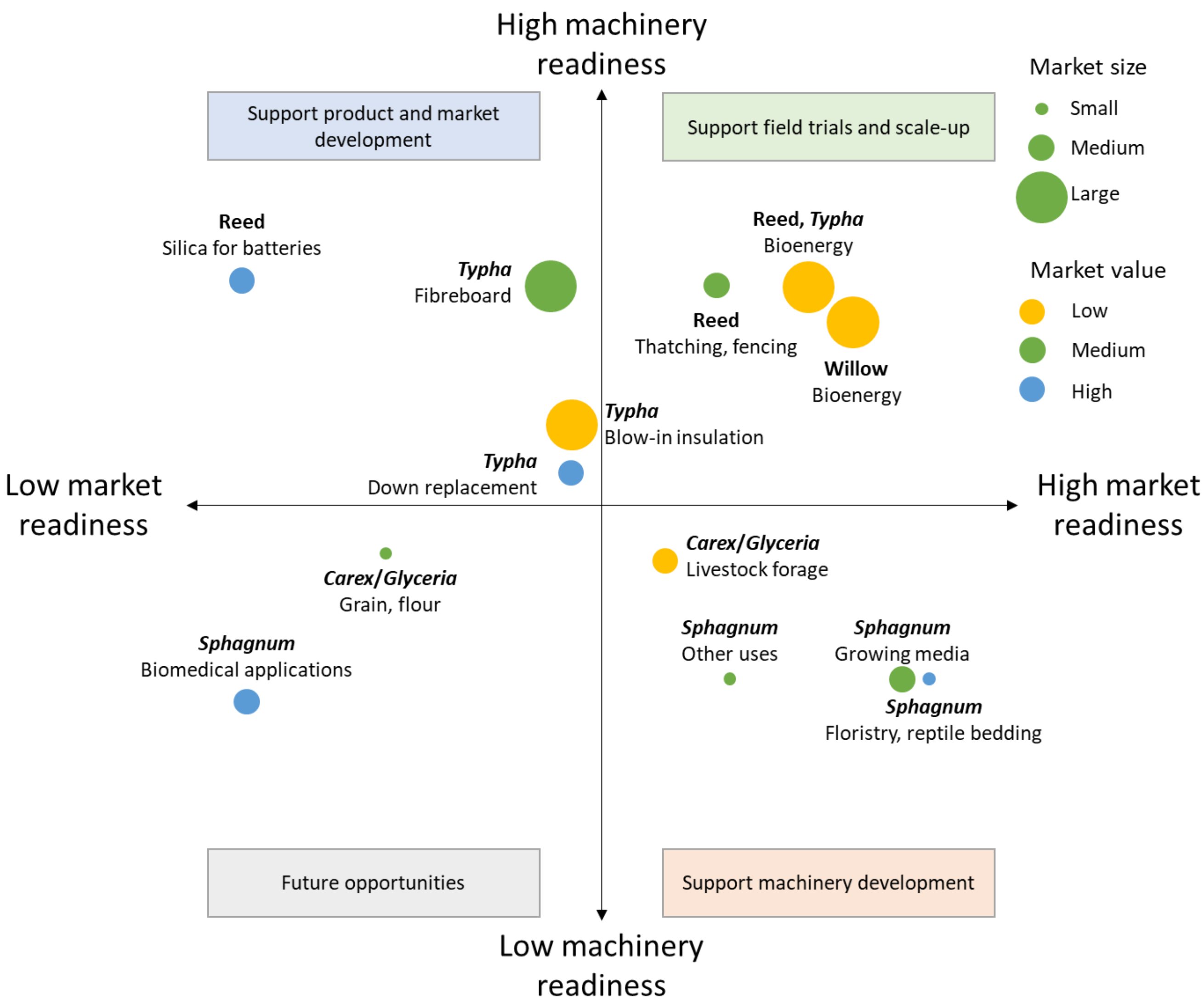

Figure 1: Machinery readiness, market readiness and market size and value for priority paludicultural crops and products.

Annex I: Workshop Participants and Acknowledgements

Much of the information reported here came out of a virtual expert workshop held on 25th October 2022 by Judith Stuart and Guy Lomax. We thank the following attendees for their participation and valuable contributions:

Name	Affiliation
Amber Barton	Agri-Epicentre
Jack Clough	University of East London
Finlay Duncan	saltyco
Marcus Frankpitt	Loglogic
Andrea Kelly	Norfolk Broads Authority
Richard Lindsay	University of East London
Paul Trevor	Wildlife Trust for Beds, Cambs and Northants
David White	Harper Adams University
Neal Wright	Micropropagation Services (EM) Ltd

Annex II: Agricultural and Paludicultural Machinery

Conventional machinery

Name	Description	Image/link
Baler	A machine that collects and packs grass, cereals or other crops into discrete bales for storage, transport or drying.	 Credit: Kevin Casper
Billet harvester	A modified sugar-cane harvester used to cut willow coppice into "billets" of 15-20 cm in length.	Video of willow coppice being cut with a modified billet harvester.
Combine harvester	A machine for harvesting grain or seed crops that cuts, collects and threshes the crop (separating seeds from the stem and leaves) in a single pass.	
Crop transplanter	A tractor-drawn machine for placing rows of evenly spaced plug plants in the soil. Plug plants are crop seedlings or cuttings grown and sold in a small "plug" of potting soil to preserve root structure.	Example of a fully automated transplanter from Standen Engineering Ltd.

Direct drill seeder	A machine that places crop seeds directly into the soil while minimising soil disturbance (i.e., without extensive tillage).	 Credit: merilijoost
Dribble bar	An implement consisting of a horizontal boom with multiple closely spaced vertical nozzles, designed for distributing liquid slurry precisely and evenly onto a field.	 Credit: "SuSanA"
Excavator	A machine (usually tracked) with a rotating cabin and controllable arm with a bucket. Typically used to move or displace soil, they have also been adapted to cut or collect paludicultural crops from raised causeways to avoid the need to drive on the peat surface.	
Forage harvester, forage wagon	A machine for chopping and harvesting forage crops (e.g., grass or cereals) to make into silage. They consist of a "head" to gather and chop the crop, which is then lifted or blown into a hopper or trailer. Harvester heads can be "single chop" (cutting biomass to 150-300 mm), "double chop" (40-60 mm pieces) or "precision chop" (4-30 mm).	 Credit: Robert Scarth

Muck spreader	A machine consisting of a trailer and a set of spinning “beaters” that chop and spread manure over a broad area across a field.	 Credit: Natural England/Peter Roworth
Pickup reel / header	A rotating implement with metal tines at the front of a forage harvester, designed to pick up already-cut crops from the field and feed them into a baler, chopper or storage bin.	 Credit: BulldozerD11
Potato planter	An implement designed to plant seed potatoes in the field and cover them with soil.	 Credit: Julian Paren
Tree planter / willow planter	An equivalent of a crop transplanter used for planting tree seedlings (typically larger than crop plug plants).	Example of disc tree planter from Damcon.
Weed wiper	An implement that uses a rotating brush or belt to apply herbicide directly to plants above a set height, as an alternative to spraying.	Example of weed wiper from Chapman Machinery Ltd.
Whole-shoot harvester	A harvester that cuts willow coppice and stores it as whole stems.	Video of a tractor-mounted whole stem harvester cutting willow.

Paludiculture machinery

Name	Description	Image/link
Balloon tyres, flotation tyres	Large, wide tyres designed to operate with low air pressure to increase contact area. Balloon tyres tend to have less tread than flotation tyres.	Examples of flotation tyres by Firestone.
“Bogie” tracks	Rubber, plastic or metal tracks that can be fitted across conventional wheels to reduce ground pressure.	An example of bogie tracks by Olofsfors.
Cutter-bundler	A machine commonly used for reed harvest that cuts reed stems and automatically ties them into bundles that can be placed in a trailer or left in the field for later pickup.	Example of a cutter-bundler harvester attachment by Loglogic.
“Delta” tracks	Modular, wheel-replacement track units that can be fitted to tractors or trailers.	 Credit: Dan
Pedestrian-operated mower	A small cutter or mower, typically two-wheeled, operated by a user walking behind the machine in the field.	Image of a pedestrian-operated mower being used to harvest reed.
Snow groomer	Tracked vehicles designed for maintaining ski slopes, commonly adapted for use in wetland settings.	Video of an adapted snow groomer being used to harvest reeds.

Annex III: Information on Priority Crops

Reed

The common reed (*Phragmites australis*) is a perennial grass that is among the most widespread of natural wetland plants. Reed naturally forms dense reedbeds in shallow flowing water and wet ground. The dense networks of roots and stems formed by reedbeds can be beneficial for improving water quality by removing nutrients and suspended sediment.

Natural reedbeds have been harvested by reed cutters for centuries in the UK and Europe to provide stems used primarily for thatching and fencing. Typically, reeds are harvested in late winter (January to March) when most of the leaves have dropped and the moisture content of the stem is low. Once widespread, about 5,000 hectares of reedbeds remain in the UK and are actively managed or harvested[7]. A large-scale reed industry also exists in China, where large quantities of reed are harvested each year to produce paper, sometimes mixed with a smaller quantity of tree fibre[8].

Figure 2: Common reed. Credit: Jonathan Wilkins

Without fertiliser additions, reed in climates typical of the UK tends to yield around 3.7-12.6 tonnes of dry biomass per hectare per year (t ha^{-1} yr^{-1})[9]. These high growth rates have meant that reed has recently attracted interest as a promising feedstock for bioenergy.

[7] Phillips et al. (2017), The use of conservation biomass feedstocks as potential bioenergy resources in the United Kingdom.
[8] Brix et al. (2014), Large-scale management of common reed, *Phragmites australis*, for paper production: A case study from the Liaohe Delta, China.
[9] Mulholland et al. (2020), An assessment of the potential for paludiculture in England and Wales.

Green reeds harvested in the summer are suitable for anaerobic digestion and conversion to biogas, while winter-harvested reeds can be burned directly as chaff or compressed into bales or pellets for combustion. Research has also suggested another potential future use for reed leaves: the silicon microstructures formed naturally in the leaves have been successfully extracted and used to improve the capacity of lithium-ion batteries (LINK).

After establishment, new reed plots can be harvested after 3-4 years, and from then on can be harvested every 1-2 years. Once established, reeds tend to form dense stands that crowd out competing vegetation, so new reedbeds could remain productive with little management for many years or decades.

***Typha* (bulrush or reedmace)**

The *Typha* genus contains several common species that hold promise as paludiculture crops. *Typha latifolia* (bulrush or reedmace), *Typha angustifolia* (lesser bulrush or narrow-leaved cattail) or the hybrid *Typha x glauca* all hold potential to be grown in paludiculture settings. Like reed, *Typha* has been planted to improve water quality and reduce nutrient pollution.

Typha species are tall, grass-like herbaceous wetland plants that produce a characteristic brown flower spike known as a “piston” at the top of the stem in summer. When pollinated, this spike transforms into a large seedhead filled with fluffy seeds that would naturally be carried by wind to new germination sites. The seedhead can be harvested in late summer to extract the downy fibre as an insulation material for construction or as a down replacement in clothing.

Figure 3: *Typha latifolia* showing flower spikes. Credit: Amadej Trnkoczy

The stem and leaves are also fibrous and can be harvested in late winter for use in construction materials such as fibreboard or magnesite board. Like reed, the dry stem and leaves can be harvested in winter and used directly as bioenergy fuel, or the green biomass can be harvested in summer as feedstock to produce biogas.

Typha is highly productive and spreads rapidly via underground rhizomes to cover a site after planting. Crops are ready to harvest 2 years after establishment, with subsequent harvests possible annually.

***Carex* (sedges) and *Glyceria* (sweetgrass)**

Carex is a large plant genus related to grasses, known as the "true sedges". *Carex* species thrive in wet soils or shallow water. *Glyceria*, also known as sweetgrass or mannagrass, is a genus of grasses adapted to living in wetland environments.

Some wetland species in both *Carex* and *Glyceria* produce seeds during late summer that have traditionally been used to make porridge or ground to make an edible flour. The leaves of both groups of plants have also been used historically as forage for livestock, and may also be used as a bioenergy or biochar feedstock in common with other wetland crops. Recent trials have begun exploring whether some of these traditional species could be grown in modern paludiculture systems as a low-volume, high-value grain crop (LINK).

All *Carex* and *Glyceria* species are perennial, and none has yet been the focus of domestication or breeding efforts to improve their suitability for use as a crop. As such, they currently have relatively small seeds and low productivity. However, future development could make them a more promising option for wetland farming.

Figure 4: Glyceria fluitans. Credit: Elena Smyrnova

Sphagnum (peat moss)

Sphagnum is a large genus of peat-forming mosses that occur globally in peatlands. *Sphagnum* forms mats on the peat surface, protecting peat from erosion and maintaining moisture levels.

The cells of *Sphagnum* mosses are able to hold many times their weight in water, and as such are increasingly looked to as renewable substitutes for peat in growing media for gardening and commercial plant growing. Historically, *Sphagnum* has been used to dress wounds owing to the antimicrobial effects of compounds produced by the moss, raising the prospect of biomedical uses. However, further research is needed to establish whether these compounds have strong enough antimicrobial properties to find use in the modern biomedical sector.

Sphagnum is slower growing than the other crops considered here. Experimental *Sphagnum* plots have yielded 2-6 t ha^{1-} yr^{-1} of dry matter[10], and would typically be harvested every 3-5 years.

Figure 5: Close-up image of Sphagnum moss. Credit: Christian Fischer

Willow

Several tree species are also able to grow well in wet soils. Among these, willow species (*Salix* genus) are among the most productive and widely planted for biomass production. Traditionally, willow has been managed with regular coppicing (cutting growing stems close to the ground) or pollarding (cutting the upper branches and shoots only, allowing a trunk to form) in order to harvest the fast-growing young shoots for use in weaving, fencing or as a livestock forage (“tree hay”). More recently, the high productivity of willow coppice

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[10] Mulholland et al. (2020), An assessment of the potential for paludiculture in England and Wales.

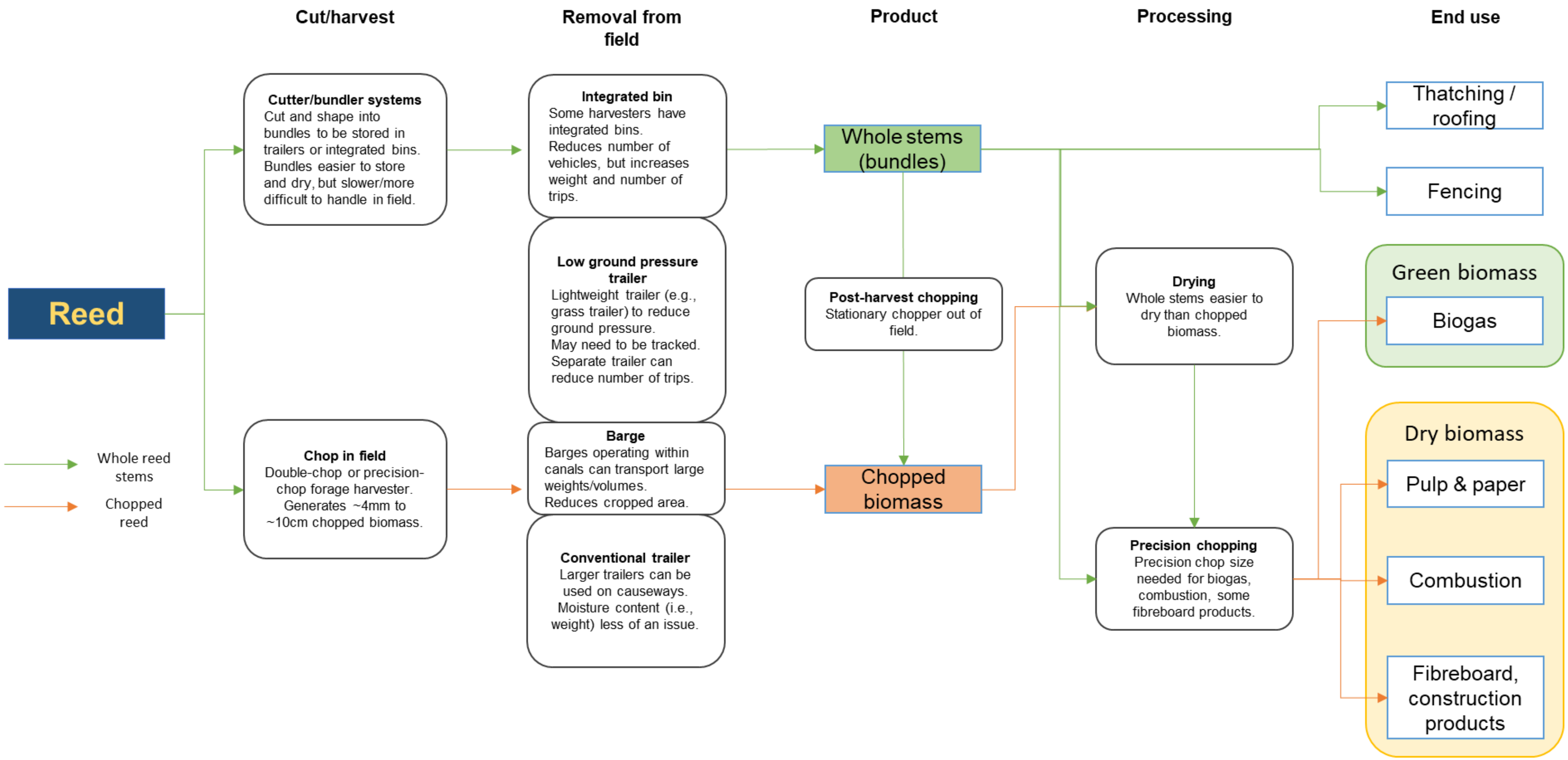
has seen it become a priority crop for production of woody biomass for combustion as a low-carbon energy source.

Willow can be easily planted and established in wetlands by inserting rods or billets (small lengths of living willow branch) into the soil. These will quickly form roots and grow into new trees, becoming ready for harvest in 2-3 years. Green shoots used for weaving, fencing or as livestock fodder may then be harvested annually, while for biomass chips the optimum harvest cycle is 2-5 years (LINK).

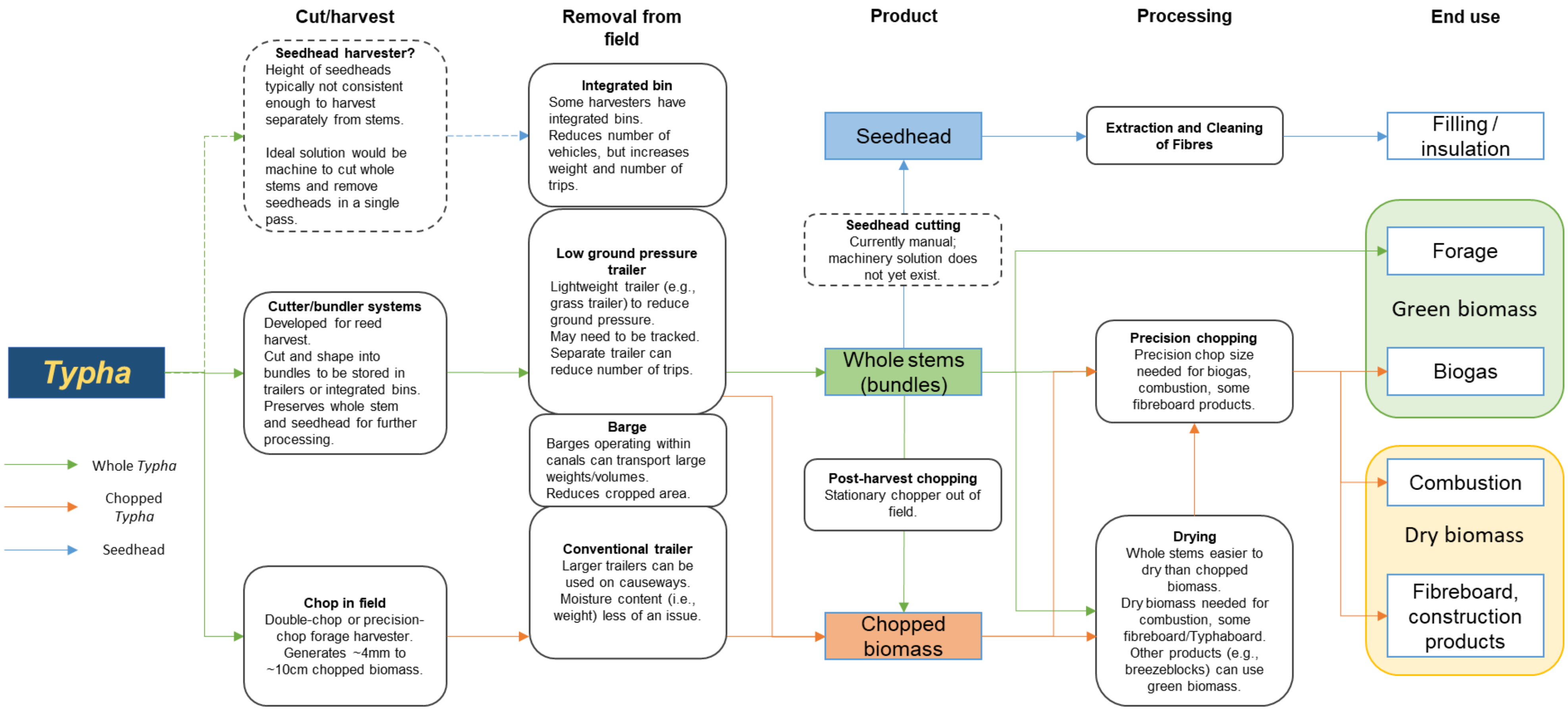
Figure 6: Willow coppice in Southern England. Credit: Kate Jewell

Annex IV: Flow charts for crop harvest and processing

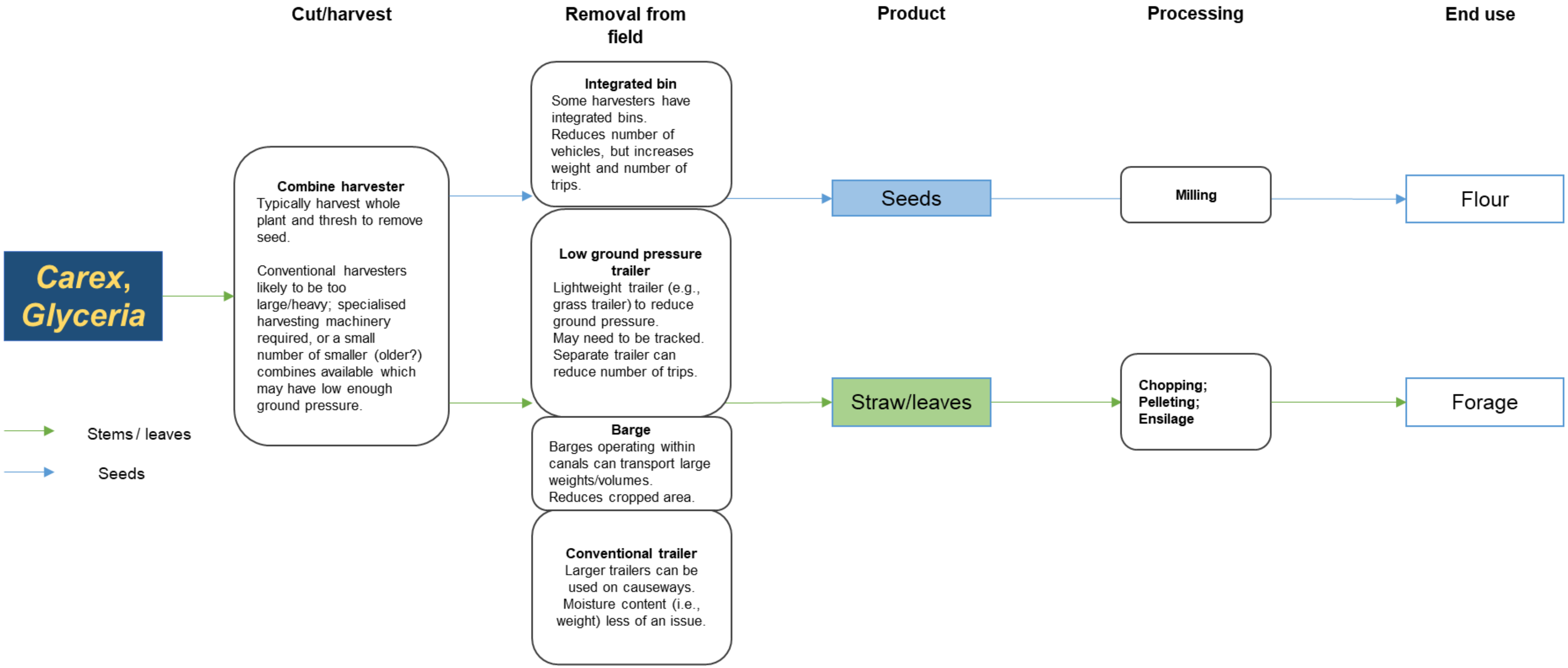
This section presents the flow charts of crop harvest, transport and processing stages for different paludiculture crops and products as developed during the expert workshop. Dotted lines and boxes indicate machinery that doesn't currently exist.

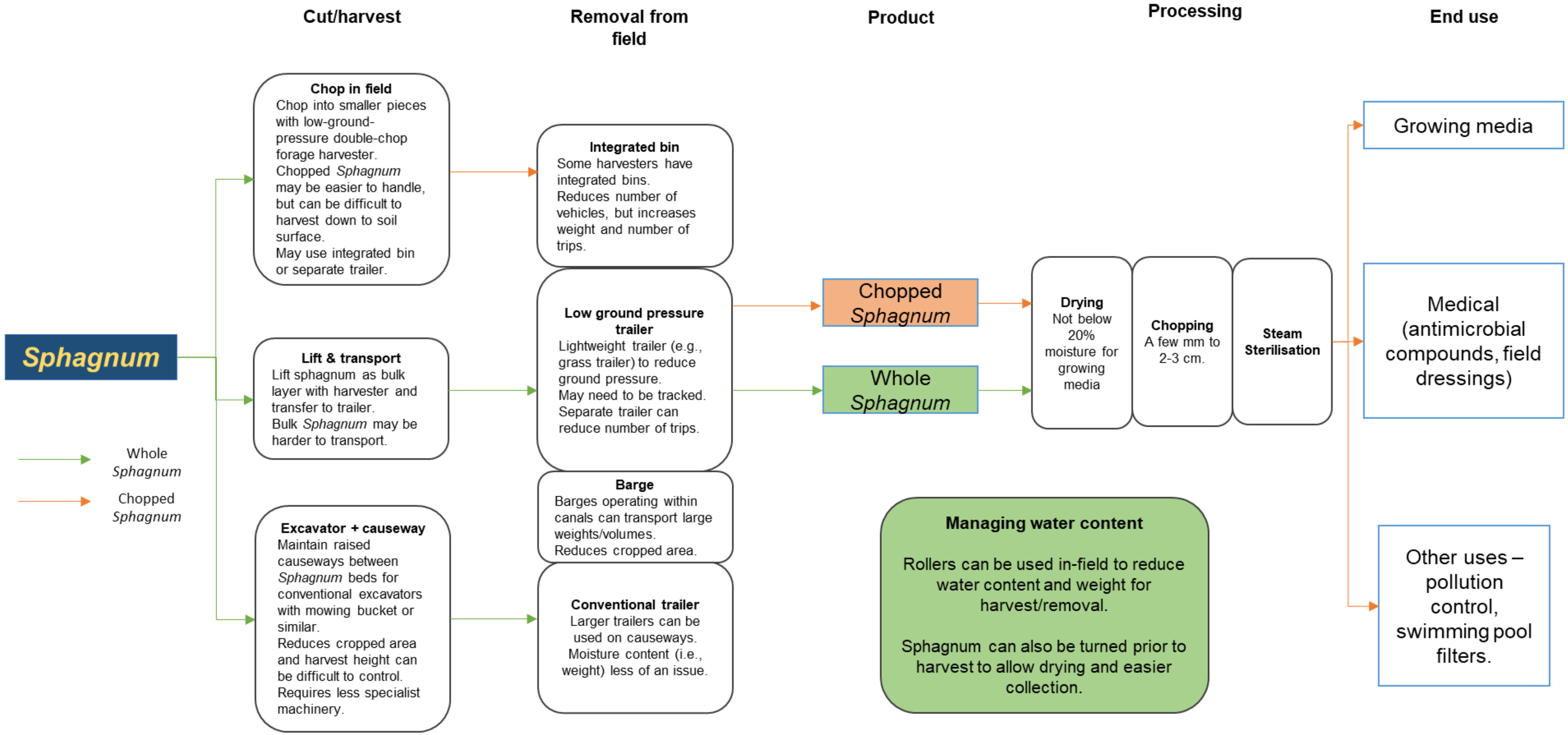


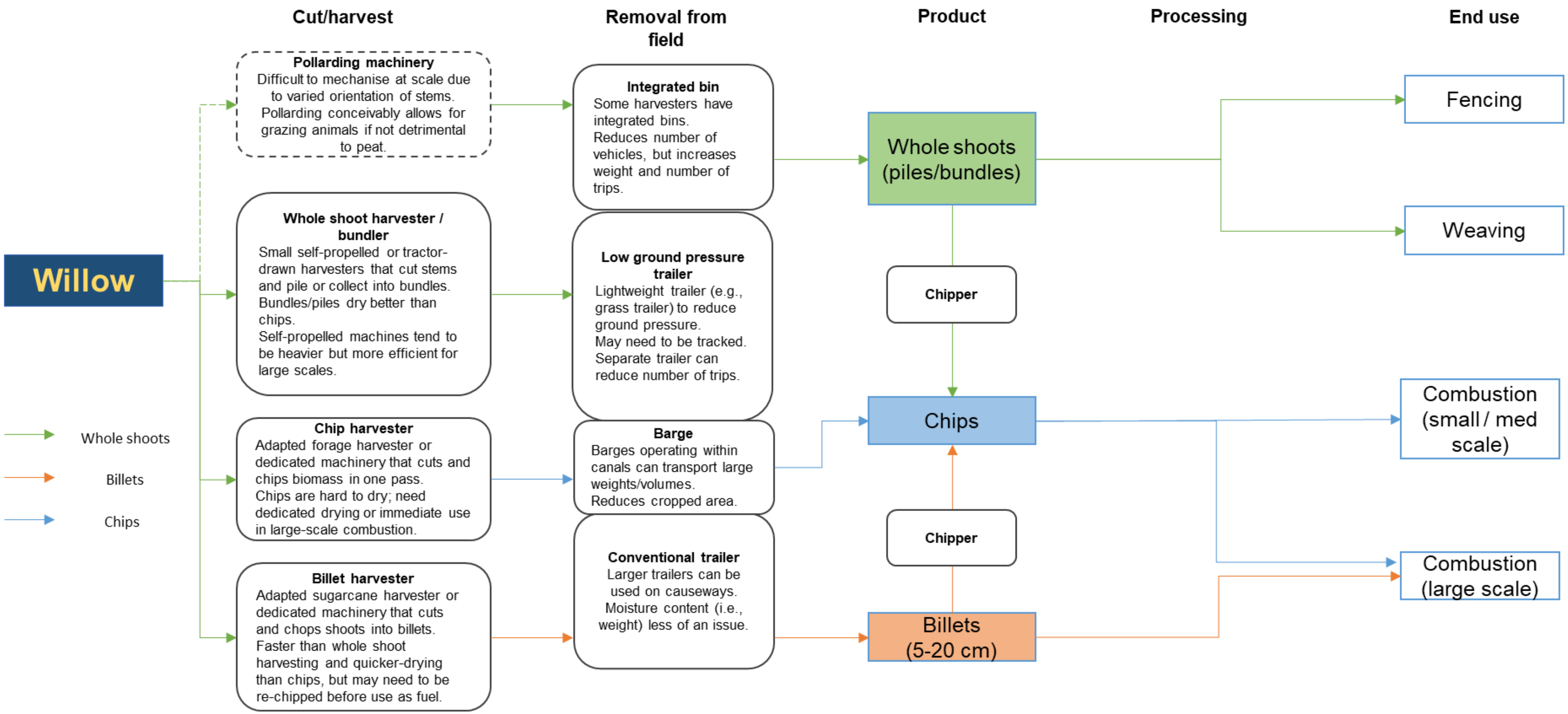
Cut/harvest
Removal from field
Product
Processing
End use
Reed
Cutter/bundler systems
Cut and shape into bundles to be stored in trailers or integrated bins. Bundles easier to store and dry, but slower/more difficult to handle in field.
Chop in field
Double-chop or precision-chop forage harvester. Generates ~4mm to ~10cm chopped biomass.
Integrated bin
Some harvesters have integrated bins. Reduces number of vehicles, but increases weight and number of trips.
Low ground pressure trailer
Lightweight trailer (e.g., grass trailer) to reduce ground pressure. May need to be tracked. Separate trailer can reduce number of trips.
Barge
Barges operating within canals can transport large weights/volumes. Reduces cropped area.
Conventional trailer
Larger trailers can be used on causeways. Moisture content (i.e., weight) less of an issue.
Whole stems (bundles)
Post-harvest chopping
Stationary chopper out of field.
Chopped biomass
Drying
Whole stems easier to dry than chopped biomass.
Precision chopping
Precision chop size needed for biogas, combustion, some fibreboard products.
Thatching / roofing
Fencing
Green biomass
Biogas
Dry biomass
Pulp & paper
Combustion
Fibreboard, construction products
Whole reed stems
Chopped reed



Cut/harvest
Removal from field
Product
Processing
End use
Seedhead harvester?
Height of seedheads typically not consistent enough to harvest separately from stems.
Ideal solution would be machine to cut whole stems and remove seedheads in a single pass.
Integrated bin
Some harvesters have integrated bins.
Reduces number of vehicles, but increases weight and number of trips.
Seedhead
Extraction and Cleaning of Fibres
Filling / insulation
Seedhead cutting
Currently manual; machinery solution does not yet exist.
Forage
Green biomass
Biogas
Low ground pressure trailer
Lightweight trailer (e.g., grass trailer) to reduce ground pressure.
May need to be tracked.
Separate trailer can reduce number of trips.
Typha
Cutter/bundler systems
Developed for reed harvest.
Cut and shape into bundles to be stored in trailers or integrated bins.
Preserves whole stem and seedhead for further processing.
Whole stems (bundles)
Precision chopping
Precision chop size needed for biogas, combustion, some fibreboard products.
Barge
Barges operating within canals can transport large weights/volumes.
Reduces cropped area.
Post-harvest chopping
Stationary chopper out of field.
Combustion
Dry biomass
Whole Typha
Chopped Typha
Seedhead
Conventional trailer
Larger trailers can be used on causeways.
Moisture content (i.e., weight) less of an issue.
Drying
Whole stems easier to dry than chopped biomass.
Dry biomass needed for combustion, some fibreboard/Typhaboard.
Other products (e.g., breezeblocks) can use green biomass.
Chop in field
Double-chop or precision-chop forage harvester.
Generates ~4mm to ~10cm chopped biomass.
Chopped biomass
Fibreboard, construction products


Cut/harvest
Removal from field
Product
Processing
End use
Carex, Glyceria
Combine harvester
Typically harvest whole plant and thresh to remove seed.
Conventional harvesters likely to be too large/heavy; specialised harvesting machinery required, or a small number of smaller (older?) combines available which may have low enough ground pressure.
Integrated bin
Some harvesters have integrated bins.
Reduces number of vehicles, but increases weight and number of trips.
Low ground pressure trailer
Lightweight trailer (e.g., grass trailer) to reduce ground pressure.
May need to be tracked.
Separate trailer can reduce number of trips.
Barge
Barges operating within canals can transport large weights/volumes.
Reduces cropped area.
Conventional trailer
Larger trailers can be used on causeways.
Moisture content (i.e., weight) less of an issue.
Seeds
Straw/leaves
Milling
Chopping;
Pelleting;
Ensilage
Flour
Forage
Stems / leaves
Seeds


Cut/harvest
Removal from field
Product
Processing
End use
Sphagnum
Chop in field
Chop into smaller pieces with low-ground-pressure double-chop forage harvester.
Chopped Sphagnum may be easier to handle, but can be difficult to harvest down to soil surface.
May use integrated bin or separate trailer.
Lift & transport
Lift sphagnum as bulk layer with harvester and transfer to trailer.
Bulk Sphagnum may be harder to transport.
Excavator + causeway
Maintain raised causeways between Sphagnum beds for conventional excavators with mowing bucket or similar.
Reduces cropped area and harvest height can be difficult to control.
Requires less specialist machinery.
Whole Sphagnum
Chopped Sphagnum
Integrated bin
Some harvesters have integrated bins.
Reduces number of vehicles, but increases weight and number of trips.
Low ground pressure trailer
Lightweight trailer (e.g., grass trailer) to reduce ground pressure.
May need to be tracked.
Separate trailer can reduce number of trips.
Barge
Barges operating within canals can transport large weights/volumes.
Reduces cropped area.
Conventional trailer
Larger trailers can be used on causeways.
Moisture content (i.e., weight) less of an issue.
Chopped Sphagnum
Whole Sphagnum
Drying
Not below 20% moisture for growing media
Chopping
A few mm to 2-3 cm.
Steam Sterilisation
Growing media
Medical (antimicrobial compounds, field dressings)
Other uses – pollution control, swimming pool filters.
Managing water content
Rollers can be used in-field to reduce water content and weight for harvest/removal.
Sphagnum can also be turned prior to harvest to allow drying and easier collection.


Cut/harvest
Removal from field
Product
Processing
End use
Willow
Pollarding machinery
Difficult to mechanise at scale due to varied orientation of stems. Pollarding conceivably allows for grazing animals if not detrimental to peat.
Whole shoot harvester / bundler
Small self-propelled or tractor-drawn harvesters that cut stems and pile or collect into bundles. Bundles/piles dry better than chips. Self-propelled machines tend to be heavier but more efficient for large scales.
Chip harvester
Adapted forage harvester or dedicated machinery that cuts and chips biomass in one pass. Chips are hard to dry; need dedicated drying or immediate use in large-scale combustion.
Billet harvester
Adapted sugarcane harvester or dedicated machinery that cuts and chops shoots into billets. Faster than whole shoot harvesting and quicker-drying than chips, but may need to be re-chipped before use as fuel.
Integrated bin
Some harvesters have integrated bins. Reduces number of vehicles, but increases weight and number of trips.
Low ground pressure trailer
Lightweight trailer (e.g., grass trailer) to reduce ground pressure. May need to be tracked. Separate trailer can reduce number of trips.
Barge
Barges operating within canals can transport large weights/volumes. Reduces cropped area.
Conventional trailer
Larger trailers can be used on causeways. Moisture content (i.e., weight) less of an issue.
Whole shoots (piles/bundles)
Chipper
Chips
Chipper
Billets (5-20 cm)
Fencing
Weaving
Combustion (small / med scale)
Combustion (large scale)
Whole shoots
Billets
Chips