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Review

Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land?

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ABSTRACT

Eutrophication is a major water pollution issue and can lead to excessive growth of aquatic plant biomass (APB). However, the assimilation of nutrients into APB provides a significant target for their recovery and reuse, and harvesting problematic APB in impacted freshwater bodies offers a complementary approach to aquatic restoration, which could potentially deliver multiple wider ecosystem benefits. This critical review provides an assessment of opportunities and risks linked to nutrient recovery from agriculturally impacted water-bodies through the harvesting of APB for recycling and reuse as fertilisers and soil amendments. By evaluating the economic, social, environmental and health-related dimensions of this resource recovery from 'waste' process we propose a research agenda for closing the loop on nutrient transfer from land to water. We identify that environmental benefits are rarely, if ever, prioritised as essential criteria for the exploitation of resources from waste and yet this is key for addressing the current imbalance that sees environmental managers routinely undervaluing the wider environmental benefits that may accrue beyond resource recovery. The approach we advocate for the recycling of 'waste' APB nutrients is to couple the remediation of eutrophic waters with the sustainable production of feed and fertiliser, whilst providing multiple downstream benefits and minimising environmental trade-offs. This integrated 'ecosystem services approach' has the potential to holistically close the loop on agricultural nutrient loss, and thus sustainably recover finite resources such as phosphorus from waste.

1. Introduction

By 2050 there are predicted to be shortages in the global supply of essential minerals used in synthetic fertilisers, and consequently, fertiliser prices have progressively risen over the last 25 years (Ashley et al., 2011; Cordell et al., 2009). This is coupled with patterns of agricultural intensification whereby increased fertiliser use is driven in part by increased pressure from concerns over food security and a changing climate (Harris and Heathwaite, 2012). Excessive growth of aquatic plant biomass (APB) in eutrophic water bodies associated with nutrient-enriched agricultural land is widely reported around the world (Heathwaite, 2010; Smith and Schindler, 2009; Dodds et al., 2009; Csatho et al., 2007). With storm frequency predicted to increase as a result of climate change there is an elevated risk of nutrient mobilisation and transfer (and thus economic loss) from land to aquatic systems, which threatens further the sustainability of valuable ecosystem services provided by clean and safe water (Reichwaldt and Ghadouani, 2012). Currently, on-farm nutrient management and improvements in sewage treatment are the primary measures for controlling eutrophication of fresh water bodies; and although upstream catchment management reduces nutrient loading into waterbodies, it does not tackle the excessive nutrient concentrations that are already present in aquatic systems, e.g. within sediments. However, the assimilation of nutrients by primary producers provides a gateway to the recovery and re-use of these 'lost' nutrients. It is already common practice to harvest problematic APB in heavily impacted freshwater bodies to maintain land drainage, flood conveyance, water quality, visual appeal, navigation and recreational fisheries (Mattson et al., 2004; Wagner, 2004). Exploiting harvested

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material, e.g. for re-use on land or as livestock feed, offers a complementary approach to aquatic restoration, which could potentially deliver multiple wider ecosystem benefits such as enhanced recreational values.

Early measures to control eutrophication from non-point sources were directed at reducing external phosphorus (P) loadings but this approach has not always resulted in the predicted reductions in internal P loadings (Jarvie et al., 2013). This is in part because P accumulated throughout a catchment system in soils and lake sediments (legacy P) continues to be released gradually for many years (in some cases decades) after mitigation measures have been introduced and in turn provides a lag effect in water quality signals (Meals et al., 2010).

The challenge of reducing nutrient loss from agriculture is not only of economic relevance. While it may be convenient in the short term to view the loss of a few kg P ha^{-1} yr^{-1} from agricultural soils as being negligible in economic terms, the environmental costs of wider non-point source pollution can pose a significant cost to ecosystem health and human well-being (Johnson et al., 2010) and continue to thwart the effectiveness of costly point-source reduction (Harris and Heathwaite, 2012). In the USA, the annual costs of freshwater eutrophication, i.e. the loss in value combined with the cost of recovery projects, was estimated to be \$2.2 billion yr^{-1} (Dodds et al., 2009). In England and Wales, the combined figure has been estimated at \$182 – 237 million yr^{-1} (£130–169 million yr^{-1}) (Pretty et al., 2003). Consequently, action is now needed to identify the opportunities, and quantify the benefits, to the wider environment that may result from integrated research targeted at nutrient recovery from excessive APB growth in eutrophic waters. The objectives of this critical review are therefore to: (i) identify opportunities and the associated challenges (and trade-offs) linked to nutrient recovery from APB in agricultural systems that span the social, economic, environmental and health-related disciplines; and (ii) outline a strategic roadmap of research needs that couple the remediation of degraded aquatic environments with a strategy for efficient and novel resource recovery from waste. Through highlighting the knowledge gaps related to the collection and processing of APB and its potential reapplication to agricultural land, we propose a temporally-structured research agenda that is aimed at closing the loop on nutrient transfer from land to water.

2. Macronutrient cycling in aquatic and agroecosystems

There is a well-developed evidence base underpinning our understanding of catchment contributions to nutrient cycling and also the limiting factors for plant growth in freshwater systems (Elser et al., 2009). Non-point nutrient pollution from agriculture can be conceptualised using a source-mobilisation-delivery-impact model (Fig. 1A) termed the transfer continuum (Haygarth et al., 2005). Management options, or interventions, to reduce nutrient pollution of water can therefore take the form of source control, mobilisation control, pathway interception or end point/receptor protection (McGonigle et al., 2012).

Critically, the transfer continuum does not currently extend beyond impact (e.g. eutrophication) and makes no attempt to account for the recovery of nutrients and their return to land. However, we argue that the transfer continuum concept can be extended to consider a nutrient recovery and re-use phase (Fig. 1B). This includes the extra pathways appropriate for nitrogen (N) and P that could be exploited in order to convert this conceptual framework into a cycle, thereby partially closing the loop on the *in-out* flow of nutrients through agricultural systems.

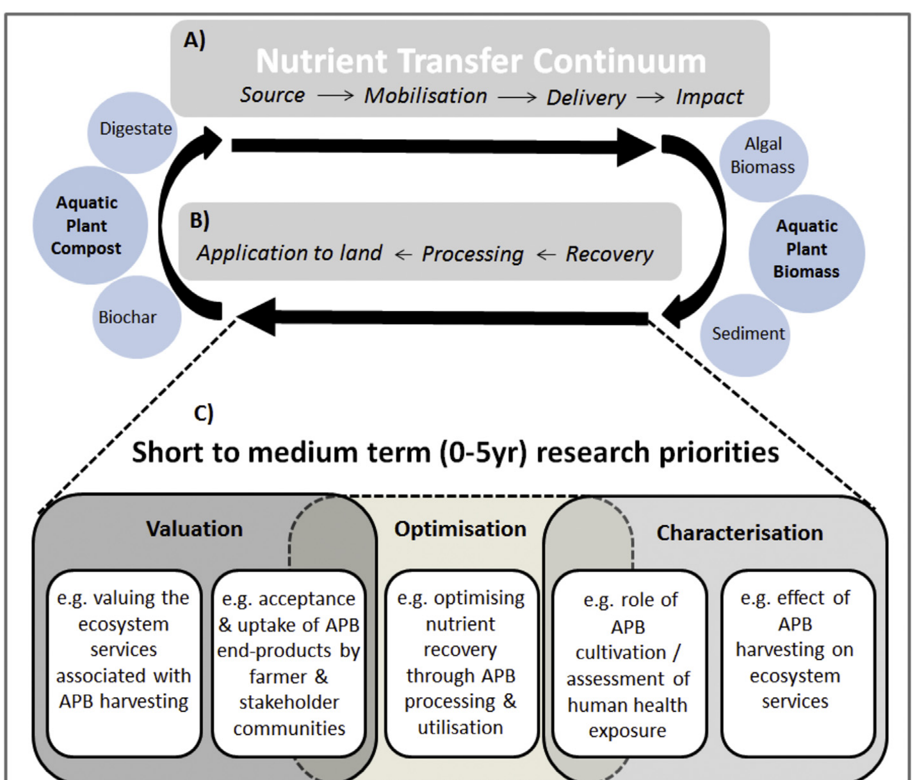

Fig. 1. Closing the nutrient loop; representing the transport of nutrients from agricultural land to receiving waters (A), the recovery and recycling of APB for the purpose of returning the nutrients back to land (B) and short to medium term (0–5 y) research priorities associated with APB harvesting, processing and reuse (C).

3. Nutrient acquisition and sequestration in APB

The use of aquatic plants for phytoremediation and the removal of nutrients from polluted water has a long history (Boyd, 1970), although most studies have failed to consider the utility of APB as a waste product, with the potential for recycling valuable resources back into agricultural systems. However, the relationship between the efficiency of nutrient removal from water and the production of APB remains unclear, and will depend upon a range of plant-based factors including: species-specific allometry, developmental stage, competition, predation and time of year (Willby et al., 2001). The growth strategy of aquatic macrophytes, i.e. floating, submerged or emergent, can also have important implications for their relative value for nutrient uptake and sequestration (Table 1), and an understanding of the allocation of nutrients between plant tissues will be crucial for maximising nutrient removal via harvesting (Reddy and Debusk, 1985). For example, there are limited concentrations of P in the leaves of emergent plants such as *Phragmites australis*, which store most P in their rhizome (Wersal et al., 2013); whilst many rooted aquatic plants translocate P from their above-ground parts to the rhizome in the latter part of the growing season. Therefore, targeting floating plants for nutrient recovery has the advantage of exploiting nutrient acquisition within the whole plant, without leaving a significant proportion of nutrients remaining in roots or rhizomes. Although a monoculture would probably be easier to harvest, a high diversity of macrophyte diversity can maximise the potential for nutrient acquisition in a eutrophic waterbody, particularly if there is a succession of species with different phenologies or if they occupy different spatial niches, possess contrasting nutrient acquisition mechanisms, or demonstrate complementary nutrient uptake and storage mechanisms (Sayer et al., 2010). In contrast to exploiting wild-growing plants, artificially seeding and cultivating aquatic macrophytes offers the prospect of harvesting much larger volumes of APB. For example, by selecting plant species that are already present, the potential for maximum nutrient resource recovery from eutrophic water could be optimised by developing site-specific cultivated AP 'aquaculture' systems.

4. Harvesting APB

The methods used for harvesting excessive aquatic plants from eutrophic water bodies range from simple removal by hand to large-scale cutting with mechanical weed harvesters (Table 2). The choice of harvesting method will be determined by the characteristics of the site (e.g. size, depth, flow) as well as access points, the density, species and growth form of the macrophytes being harvested and the presence of any potentially dangerous animals. There are also potential environmental costs and the removal of macrophytes from a waterbody will undoubtedly lead to varying levels of ecosystem disturbance, such as habitat destruction and a reduction in the amenity value of a lake or river (Bickel and Closs, 2009), particularly if it promotes the spread of invasive plant species or harvested material is left *in situ* (Dorahy et al., 2009). In addition, the re-suspension of sediment and the associated release of sediment-sequestered P, coupled with temporarily reduced uptake of nutrients by plants, might trigger the waterbody to a state of hyper-eutrophication as well as flushing other potential pollutants and microbial contaminants further downstream. The presence of aquatic macrophytes in eutrophic water often inhibits the growth of algae by reducing the availability of light and nutrients and potentially through the release of allelochemicals (Mulderij et al., 2009). Therefore, the removal of large stands of plants in a eutrophic waterbody could promote faster growing algae and shift the system towards phytoplankton dominance (Sayer et al., 2010). There is currently no agreement on the optimum coverage of a water body for maximising nutrient uptake and removal by macrophytes but values ranging between 5 and 20% have been suggested (Dai et al., 2012; Portielje and Van der Molen, 1999).

If judged on cost alone, APB harvesting is not a viable option for lake management and only addresses a symptom not the causes of eutrophication. However, valuation that recognises the provisioning of wider environmental benefits and services could provide the incentive needed to reuse and recycle this waste material and therein address some of the underlying causes of eutrophication. As herbicides become either ineffective or restricted due to their toxicological effects on non-target species, there is an urgent need for more environmentally sustainable strategies for managing excessive APB growth in eutrophic water.

5. Processing APB – biomass conversion

Adding APB directly to land after harvest without processing is possible (Fortuna et al., 2005), where there is deemed to be no environmental or human health risk, e.g. absence of invasive weeds and minimal risk of potentially toxic compounds entering the food chain. This strategy may also be appropriate for small isolated areas or linear features (e.g. drainage ditches) where post-harvest processing is not economically viable. In all cases the APB must be positioned sufficiently far away to prevent nutrient flow back into the watercourse. In most situations, however, some processing of the APB is likely as this will enhance its market value and reduce environmental risk.

5.1. Compost

Adding APB derived compost to soil following dewatering and shredding improves soil quality and increases crop yields (Balasubramanian et al., 2013), although the success of the compost in this capacity depends on both the concentration of plant available nutrients (i.e. the C:N:P ratio) and the composition of species

Table 1
Phosphorus & nitrogen uptake potential for a selection of aquatic plants.

Plant	Growth form	P uptake	N uptake	Biomass (t ha^{-1})	Growth (t ha^{-1} yr^{-1})	Reference
Eichhornia crassipes	Floating	Up to 93% removal. 49–252 mg m^{-2} day^{-1}	Up to 3.3 g N m^{-2} day^{-1}	20–24	60–110	Reddy and Debrusk, 1985; Gumbricht, 1993a.
Salvinia spp.	Floating	70%		2–3	9–45	Gumbricht, 1993a; Maine, 1998.
Phragmities australis	Emergent	0.9 g kg^{-1} dry matter	9.4 g kg^{-1} dry matter	>6	10–60	Gumbricht, 1993a; Hansson and Fredriksson, 2004.
Ceratophyllum demersum	Submerged	50% cover: TP 73%, SRP 72%, PP 84%				Dai et al., 2012.
Elodea canadensis & Chladophera glomerata	Submerged	57-68% (20% in harvested biomass)	26-37%, (10% in harvested biomass)			Gumbricht, 1993b.

TP, total phosphorus; SRP, soluble reactive phosphorus; PP, particulate phosphorus.

Table 2
Comparison of harvesting methods for aquatic plants, adapted from Wagner (2004) and Mattson et al. (2004).

Technique	Description	Advantages	Disadvantages
Hand pulling/ cutting	Carried out by a diver or snorkeler over a surveyed area. Removing unwanted plants individually.	Highly selective, can be used to remove undesirable but non-dominant species, low impact on other aquatic communities.	Labour intensive, time consuming, unsuitable for large areas. With cutting, regrowth is possible and may be rapid. With pulling small scale sediment disturbance is likely.
Mechanical cutting with collection	Plants removed using a variety of mechanical equipment often based on purpose built boats.Harvested plants can be placed on shore for composting.Harvesting more than once a year is usually needed.	Clears target area of plant biomass to selected depth. Allows rapid plant removal on greater scale.	Expensive equipment. Possible impacts on aquatic fauna. Non-selective removal of plants and animals in treated area. Possible spread of undesirable species by fragmentation. Possible generation of turbidity. Rapid regrowth.
Rototilling	Rotating mechanical blades disturb plants, roots and sediment. Collection carried out separately.	Enables whole plant removal.	May spread plants that reproduce by fragmentation can damage fauna not selective creates turbidity. More expensive than harvesting. Needs separate collection equipment.
Hydro-raking	Floating backhoe plus a rake similar in appearance to machinery for tilling soil. Movement through the sediment, rips out roots.	Effective for removing submerged stumps, water lily root masses, or floating islands.	May spread plants that reproduce by fragmentation can damage fauna not selective creates turbidity.

used in the composting process. It is most likely that APB would be composted outdoors in open windrows with frequent turning; however, mobile in-vessel composting plants could be used to ensure complete sanitisation, particularly if invasive weeds or animal pathogens, e.g. liver fluke, are suspected to be present. A significant concern of applying compost made from APB to agricultural land is the potential for facilitating the propagation and spread of weeds and invasive species. For example, alligator weed (*Alternanthera philoxeroides*) can grow vigorously on land and may colonise areas where it is composted or has not been destroyed completely (Dorahy et al., 2009). Compost maturity usually infers that the thermophilic phase of the composting operation has sanitised the compost by destroying both pathogens and weed propagules, however many countries also enforce strict certification guidelines that composts must comply with if they are to be used as growing media. Composting requires controlled conditions and can take up to 18 months for stabilisation, however, the transportation of relatively small but water laden quantities of APB biomass to centralised composting facilities is both expensive and unsustainable.

5.2. Biochar

Biochar is produced from the pyrolysis of organic material, and when incorporated into soil can act as a long term soil carbon store, i.e. remaining >100 years, and contribute to offsetting C emissions associated with the burning of fossil fuels (Atkinson et al., 2010). In addition, biochar provides a slow release of nutrients and can increase crop yields and reduce the leaching of nutrients from soil (Jeffery et al., 2011). Recently, freshwater and marine species of macroalgae have been used as the feedstock to produce biochar as a by-product of their conversion into bioenergy (Bird et al., 2012). Therefore, there is the potential for producing biochar from harvested APB, which if applied to soil could recycle both macro- and micro-nutrients and sequester the C captured during photosynthesis (Bird et al., 2012; Masto et al., 2013). By its nature, pyrolysis of APB (which typically takes place at 400–700 °C) would produce a sterile product in which any potential algal toxins or pathogens would be destroyed making it a low risk additive for incorporation into soil. The nutrient availability of biochar depends upon pyrolysis conditions and the APB from which it was produced (Li et al., 2015); consequently, biochar is not a replacement for fertiliser, but instead could be used as a catalyst for a range of complementary benefits to total soil fertility and functioning. Effective dewatering and drying processes would be necessary for biochar production from ABP feedstock; however, the energy required to support this could be supplied using the syngas produced in the pyrolysis process (Muradov et al., 2010). In addition to producing biochar and biogas, pyrolysis of APB could also lead to the production of liquid petrochemicals, which could be used as diesel fuel supplements or as glycerine-free components of biodiesel (Miranda et al., 2014).

5.3. Anaerobic digestion

While the economically attractive aspect of anaerobic digestion (AD) is from the generation of biofuel or biogas, there is growing interest in optimising the sustainable use of nutrients within the digestate when applied to land. During the AD process, which is theoretically nutrient retentive (i.e. N and P are not lost from the system), some of the organic nitrogen content is mineralised, with the digestate containing a greater proportion of the total N content as plant available, ammonium-N; whilst there is no reported consistent effect of AD on P availability to plants (Moeller and Mueller, 2012). It seems timely therefore to explore whether there is potential to integrate APB into the AD process for existing businesses especially where there is active on-site harvesting of APB. It is also possible to produce biochar from the digestate, which could enhance the economic viability of biochar if it was made as part of biofuel production.

6. Application of APB to land & potential as animal feed

Applying APB to land is the final stage in closing the nutrient loop (Fig. 1B). In addition to sourcing markets for the end product(s), issues relating to product safety have to be addressed. These will influence the likelihood of APB products being accepted by a wide range of different stakeholder groups.

1. Health concerns

The concentration of cyanobacteria in waterbodies often correlates with increases in concentration of P, and thus the toxicity is likely to be much higher in the high biomass systems that would be targeted for APB harvesting. Investigations would need to determine whether epiphytic cyanobacteria were in any way associated with harvested APB. It is unclear exactly how algal toxins are affected by composting and AD, and comprehensive assessments would need to be carried out before APB products were returned to land. Similarly, there is potential for introducing human and animal pathogens (Johnson et al., 2010), and anti-microbial resistant genes (Wellington et al., 2013), to agricultural systems if APB material is not carefully treated before its application.

The nuisance filamentous green alga *Cladophora* which grows in eutrophic regions of the Great Lakes in the US is often associated with significant levels of *Shigella*, *Salmonella*, *Campylobacter*, and *Escherichia coli* O157, with evidence for enhanced survival of *Salmonella* and *Shigella* in association with *Cladophora* in freshwater microcosms (Ishii et al., 2006; Byappanahalli et al., 2009). However, there are strict standards governing the feedstocks that can be used as soil amendments in agriculture, together with regulations on the concentrations of pathogens and harmful substances, and in particular their bioavailability and their leaching potential in the end product (see section 6.2). Aquatic macrophytes are able to sequester significant concentrations of heavy metals (Bird et al., 2012; Xing et al., 2013) and although bioavailability in processed APB products will be dependent on other physiochemical properties such as pH, humic acid content and organic matter decomposition, the safety risks associated with agricultural re-use of plants from waterbodies polluted with even low levels of heavy metals may be significant.

2. Legal and regulatory implications

Recycling APB will be subject to regulatory and legal frameworks in the areas of waste management and habitat protection. At the broadest scale the key considerations needed are: (i) the protected status of the water body; (ii) species composition of the biomass and presence of invasive species; (iii) whether the APB is classified as waste; (iv) whether storing and processing the biomass are regulated activities; and (v) the composition of the end products and whether they have ceased to be classified as waste. Within the EU the key piece of legislation in this area is the Waste Framework Directive (Directive 2008/98/EC), although each member state has its own legislation to transpose the Directive.

3. Socio-economic considerations

Partly in response to concerns over the production implications of terrestrial biofuels (Fargione et al., 2008), there is current interest in the potential for cultivating aquatic plants as biofuel feedstock (Kuhlman et al., 2013). Previous research has suggested that the social acceptability of land spreading of organic waste, particularly to food crops, is generally not supported in industrialised nations (e.g. biosolids; Robinson et al., 2012). In contrast, there is greater public acceptability for the use of organic wastes in the restoration of post-industrial or contaminated land; however, transport distances between the origin of the organic material and the site where it is to be used often makes this economically unviable (Jones et al., 2009). However, compared with the perception of biosolids, using APB as a soil amendment may attract greater public support, and if marketed as contributing to the maintenance of a number of important ecosystem services could gain more widespread acceptance than biosolids.

4. Animal feed

Where legislation permits, untreated APB could be fed directly to livestock, although mechanisms need to be in place to ensure that cyanotoxins are either absent or in very low concentrations (Puschner et al., 1998). Compared to marine and freshwater algae, the potential for harvested APB to be used as an animal feed is an underexplored area (Christaki et al., 2010; Holman and Malau-Aduli, 2013). However, assuming that the feed source is free of pathogens and toxic cyanobacteria, it is clear from the literature that there are few negative effects of algal consumption by domesticated animals.

5. Existing markets and future opportunities

If valuation of products from APB recycling is based solely on the market price of compost and inorganic N and P, it is unlikely to compete with traditional and established fertilisers. Part of the problem is the low market value of the products of recycling, and although agriculture represents up to 97% of the potential market for waste-derived digestate and composts, it has one of the lowest derived demands (WRAP, 2009). Once the cost of transport and land spreading is taken into account the value applied to the material itself may be close to zero. The perceived low value of digestates is partly due to a lack of knowledge of how these materials can benefit soil structure and plant nutrition, but is mainly due to the connotations associated with 'waste' products (WRAP, 2009). However, agricultural demand for digestates will only increase as the products become better quantified and understood; and as the perceived value rises, the financial value of these materials will also increase.

The sustainable recovery of nutrients from APB clearly requires a systems-based approach that capitalises on opportunities arising from multiple benefits. Central to this is considering the P and N in APB as both a 'pollutant' and a commodity, and thus integrating ecological improvement with product delivery. Harvesting of APB could become more cost-effective if wider benefits such as habitat improvement and reductions in greenhouse gas emissions were included in assessments (Evans and Wilkie, 2010; Kaenel and Uehlinger, 1999). Although there are many life cycle assessments for the production of biofuels using land based feedstocks, there are far fewer examples that consider APB as a feedstock (Resurreccion et al., 2012).

7. Recycling aquatic biomass to agricultural land: an emerging research agenda

New global challenges and opportunities are emerging as research communities seek to develop an evidence-base to underpin efficient and cost-effective resource recovery from a variety of different waste streams (Shurin et al., 2013). This is driven, in part, by evolving policy and regulatory imperatives designed to ensure the long-term protection of ecosystems and to protect the health and wellbeing of society (Heathwaite, 2010). In turn, the future prospects of recovery and reuse of APB for safe recycling to land offer an exciting portfolio of cross-disciplinary research needs for closing the loop on nutrient transfers from land to water. By framing these needs within a wider ecosystem services approach, a research agenda linked to APB harvesting emerges that is both viable and essential for the delivery of sustainable solutions to nutrient recycling in catchments. Environmental benefits are rarely, if ever, prioritised as essential criteria for the exploitation of resources from waste and yet this is key for addressing the current imbalance that sees environmental managers routinely undervaluing the wider environmental benefits that may accrue beyond resource recovery. In response, a suite of research priorities have been identified that, when taken together, build towards a paradigm shift in this current thinking. Fig. 1C provides a summary of short-to-medium term [0–5 yr] research priorities associated with characterising, optimising or valuing APB.

1. Short term research needs (0–2 years)

In order to understand the full potential of APB harvesting there is a need to characterise not only the scale of the opportunity available to the research and policy community, but also the quality of the various end-products that may emerge – whether in the form of soil amendments for recycling to land, biofuels or as livestock feeds.

Currently, there is little appreciation of the potential of APB as a global 'resource', and insufficient understanding of the data available to begin to quantify this nutrient reserve (Reddy and Debusk, 1985). Expanding capacity in next generation Earth Observation offers considerable potential for helping to understand the global stock of APB and should be exploited fully to assist in mapping the nutrient recovery potential from aquatic biomass from plant to planet (Hunter et al., 2010). A clear priority at the regional to national level is to identify those waterbodies and surrounding landscapes that contribute to optimum conditions for APB proliferation and harvesting. Crucially, this must recognise the importance of both environmental drivers and existing social and economic infrastructure. Such characterisation needs to be coupled with a systematic and comprehensive audit of published nutrient concentrations in APB material if we are to fully appreciate the spatial and temporal fluctuations in resource recovery opportunities. It is generally accepted that the spatial and temporal distribution of nutrients differs between species (Willby et al., 2001) but there are significant gaps in our knowledge of the potential for the sequestration of other contaminants, e.g. heavy metals, radionuclides, toxins and human pathogens. Early characterisation of APB communities is thus essential for the development of characterisation-specific libraries of when, where and how to harvest at a site, and how to effectively manage the seasonality constraints of biomass production and associated nutrient recovery.

The environmental and health hazards presented by algal and cyanobacterial mass populations are relatively well recognised in terms of the production and impacts of their toxins (Codd et al., 2005). Consequently, robust systems for the early examination of harvested macrophytes will need to be put in place for determining whether they bear a (significant) burden of attached cyanobacteria (epiphytic cyanobacteria). If so, appropriate health and safety measures will be needed to reduce the risk of worker exposure to potent cyanotoxins in eutrophic waterbodies, whether on a brief seasonal basis, or for extended periods. Persistence of these cyanotoxins after application to agricultural land requires urgent attention from the research community, and data on the fate of cyanotoxins in processed APB would be crucial to underpin future decision-making on post-harvest storage conditions.

An improved knowledge of how to process APB in order to guarantee consistency in quality is of less immediate concern than site characterisation and APB assessment for nutrient content yet is equally critical for ensuring a pathway to acceptance for APB reuse. In particular, fundamental method development for short term intensive composting is required and while some progress has been made to find the optimal conditions for rapid composting, there is scope for further research to find innovative methods for mobile harvesting and recycling units. While there is evidence for the rapid biodegradation of toxins under aerobic conditions we lack knowledge on the role of AD for toxin breakdown. Thus a wealth of science opportunities exist linked to the optimisation of nutrient and energy recovery through processing and the role of AD, composting and pyrolysis need to be evaluated robustly across multiple spatial and temporal scales and for a range of contrasting conditions.

Recycling aquatic biomass to agricultural land, or converting it to livestock feed ultimately offers an opportunity for stakeholders to 'capitalise' on eutrophication. Such a turn of phrase may sit uncomfortably with some government departments and regulatory organisations because of connotations of benefitting from environmental degradation. However, resource recovery from waste, or by-products of waste (in this case APB in eutrophic waters), represents an opportunity of not only facilitating a more rapid remediation of nutrient impacted waterbodies, but also of delivering multiple downstream benefits and wider ecosystem services. Raising stakeholder awareness about the full spectrum of remediation options available is still needed to highlight the toolbox of catchment management approaches available to help deliver more immediate environmental improvements. We are not suggesting that awareness-raising represents a research priority but bringing environmental benefits to the forefront of resource recovery from waste to 'capitalise' on an existing environmental impact does require a shift in mind-set and the possibility of a range of unintended outcomes linked to farmer and landowner behavioural responses to APB recycling do need considering. In response, well-designed investigations linking across social science and behavioural economics are needed. Such approaches offer potential for capturing the attitudes of farmers and landowners to different regulatory, environmental and economic scenarios and will provide a fundamental building-block in our understanding of wider socio-economic impacts of the APB recycling and reuse agenda.

2. Medium term research needs (2–5 years)

The risk of ecological damage to other aquatic flora and fauna from harvesting APB needs to be explored in combination with other management activities. Acknowledging that different impacts may materialise over varied timescales and that ecological indicators and water quality signals may exhibit complex patterns in their response to harvesting is critical. Fundamental questions concerning the magnitude of effect (and rate of response) of harvesting APB on standard water quality parameters such as nutrients, dissolved carbon, pH, EC, chlorophyll *a*, turbidity, BOD, heavy metals, and potential pathogens need answering at field-relevant scales and across a continuum from agricultural waterbodies such as ponds and wetlands through to larger receiving waters such as lakes.

The relative merits of wild harvesting versus deliberate cultivation of APB in eutrophic waters also require careful evaluation. Trials of APB cultivation and harvesting in natural environments and scaling up methodologies from existing laboratory studies would provide insight into the practical, ecological and economic viability of commercial enterprises, although the caveats associated with such extrapolation would have to be acknowledged (Shurin et al., 2013). Whilst nested experiments are essential to up-scale laboratory observations to the landscape level, the impact of uncertainty from climatic drivers, contamination and unreliable biomass production on nutrient recovery efficiencies will need to be quantified (Gret-Regamey et al., 2013). One of the major concerns with harvesting APB in natural environments is the potential for further dissemination of propagules, which in the case of invasive species would have potentially negative effects. This underscores the need for further investigations to determine whether it is possible to grow safely contained APB biomass.

The value to ecosystem services of, for example, removing invasive APB through harvesting is unlikely to be represented in conventional commercial financial analyses. The effect of nutrient removal on the value of changes in ecosystems services such as, carbon sequestration potential, nutrient cycling and effects on biodiversity measures must be incorporated into social cost-benefit assessments. Thus, further weight is given to adopting an ecosystems approach because of the potential to capture and account for wider environmental benefits (and trade-offs), which can be conveyed to decision-makers via a framework that is increasingly understood and utilised (Jones et al., 2013). Improvements in the generalisation and availability of robust cost-benefit analyses will emerge when research can measure the broader benefits that accrue through a catchment system beyond *in-situ* improvements at the point of immediate management activity. This is extremely relevant given the long-term goal for ecological sustainability and a growing remit to protect not just the quality of freshwater environments and the livelihoods of those who depend on it, but also the problems of resource scarcity (Corominas et al., 2013). Any thorough economic modelling of freshwater restoration must recognise that some changes to lake ecology will be more immediate following an intervention whereas a range of alternative catchment management approaches may bring about a long time lag before an effect on lake quality is observed. Finally, there is significant scope to explore the role of governance structures and the facilitation of payments for ecosystem services in line with current environmental stewardship schemes to promote APB recycling and reuse. Identifying how to deliver appropriate financial incentives is highly relevant as the idea of Payment for Ecosystem Services (PES) schemes becomes more widespread and accepted globally (Engel et al., 2008).

3. Longer term 5–10 years

Longer term questions must be framed around maximising the potential economic, social, environmental and ecological rewards linked to the resource recovery from wastes. For the recycling and reuse of APB, considerations of genetic modification, breeding to improve phenotype and advances in molecular and transgenic technologies could offer significant improvements in the quality of harvestable biomass. Such approaches offer significant opportunities in terms of screening for nutrient accumulators and enhancing resource capture and recovery processes. These approaches to bio-engineering could help to secure economic viability, although the science needed to progress this particular aspect of the APB research agenda is still in its infancy.

Over time, and with a growing evidence-base, integrated modelling approaches designed to identify resource recovery opportunities, and predict spatial and temporal windows for resource exploitation with minimal catchment-wide environmental impact, will begin to emerge. However, this cannot happen until sufficient high quality underpinning data are available and the emerging research agenda outlined above suggests that there is some distance to go in terms of fundamental information needs. In line with the earlier recommendations it is apparent that such a modelling framework would necessitate the coupling of economic, social, ecological and environmental understanding to enable a more holistic approach to future decision-making and this in itself represents a long-term challenge.

8. Conclusion

The approach we advocate for the recycling of 'waste' APB nutrients is to couple the remediation of eutrophic water bodies with the sustainable production of feed and fertiliser, whilst providing multiple downstream benefits and minimising environmental trade-offs. This integrated 'ecosystem services approach' has the potential to holistically close the loop on agricultural nutrient loss, and thus sustainably recover finite resources such as P from waste. The challenges in realising this ambition are complex, and while the environmental benefits of remediating eutrophic waterbodies are clear, the social and economic viability of APB recycling and reuse must first be demonstrated and wider market benefits accounted for.

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