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BUILDING THE POLICY ECOSYSTEM IN EUROPE FOR CULTIVATION AND USE OF PERENNIAL BIOMASS CROPS

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ABSTRACT: Perennial biomass crops (PBCs) can potentially contribute to all ten Common Agricultural Policy (2023-27) objectives and up to eleven of the seventeen UN Sustainable Development Goals. This paper discusses interlinked issues that must be considered in the expansion of PBC production: i) available land; ii) yield potential; iii) integration into farming systems; iv) research and development requirements; v) utilisation options; and vi) market systems and the socio-economic environment. The challenge to create development pathways that are acceptable for all actors, relies on measurement, reporting and verification of greenhouse gas emissions reduction in combination with other environmental, economic and social aspects. This paper makes the following policy recommendations to enable greater PBC deployment: 1) incentivise farmers and land managers through specific policy measures, including carbon pricing, to allocate their less productive and less profitable land for uses which deliver demonstrable greenhouse gas reductions; 2) enable greenhouse gas mitigation markets to develop and offer secure contracts for commercial developers of verifiable low carbon bioenergy and bio-products; 3) support innovation in biomass utilisation value chains; and 4) continue long-term, strategic research and development and education for positive environmental, economic and social sustainability impacts.
Keywords: perennial biomass crops, ecosystem services, upscaling feedstock for the bioeconomy, land use change, social acceptance, policy recommendations

1 BACKGROUND AND OBJECTIVES

Perennial biomass crops (PBCs) include grasses and tree species with rotation lengths up to 20 years grown on agricultural land (arable or rotational grassland). PBCs can match the productivity of high input annual crops in terms of dry tonnes of biomass per year with lower environmental impacts [1] whilst providing a wider range of ecosystem services [2, 3] (Figure 1A). However, as with all crops, PBCs require land, water, and nutrients and therefore fall within the land-water-food-energy nexus [4, 5]. Increasing PBC production in an already established landscape has both 'perceived' (because quantitative evidence is often lacking) benefits and potential dis-benefits (Figure 1). Some have strong quantitative evidence but, for many, our knowledge is limited by temporal and spatial factors that interact from crop production right through to product (and product end-of-life or recycling). PBC research programmes over the past three decades have been driven by the need to reduce the use of fossil fuels in energy and materials production and to maximise the environmental sustainability of growing raw materials for these purposes.

Up to the year 2021, total planted areas of PBCs had stagnated despite industrial partnerships embedded in public-private funded projects promoted by organisations such as the EU's Biomass-Based Industries Consortium (https://www.bbi.europa.eu/). This stagnation may be attributed to several uncertainties, both for potential growers and supply chain managers; some related to technical aspects of crop management [6], some to non-technical barriers such as indirect land use change and others due to insufficiently joined-up policy support from governments, needed to create a sufficiently profitable market for the biomass produced [7]. Multi-actor communication is still lacking and we, the scientists working on PBCs, are increasingly being encouraged to engage with the public and policymakers. This paper is a contribution to a large discussion at this, and many other, biomass conferences and is an abridged version of a recent opinion paper [8].

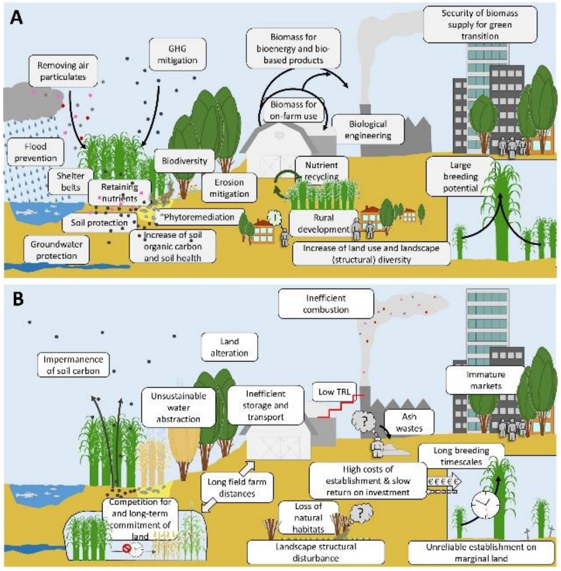

Figure 1: Perceived benefits (A) and potential dis-benefits (B) associated with perennial biomass crops (PBCs) drawn from project results, the literature, and practical experience depending on previous land use and social context. The term 'Biodiversity' refers to modifying landscapes providing habitats with lower disturbance than arable systems which have been shown to support birds, plants, and small mammals especially on the transition zones (edges) between PBCs and the surrounding land use. 'Security' refers to security of supply of biomass for the green transition and transformation of society (Figure adapted from [8]). GHG = greenhouse gas, TRL = technology readiness level

2 BIOMASS SUPPLY (PUSH) AND UTILIZATION (PULL)

To provide a structure for this opinion paper, we use a 'pipeline model' (Figure 2) divided into production (push) and demand (pull).

These factors interact to determine the deployment opportunities for PBCs (production and utilisation chains) and identify broad areas for discussion on policy interventions. We use this structure to identify where barriers to upscaling exist, and their consequences from a production and utilisation perspective. Only if all actors in the pipeline can make a profit comparable to other potential activities with the same resources (i.e., benefits outweighing opportunity costs) will upscaling occur

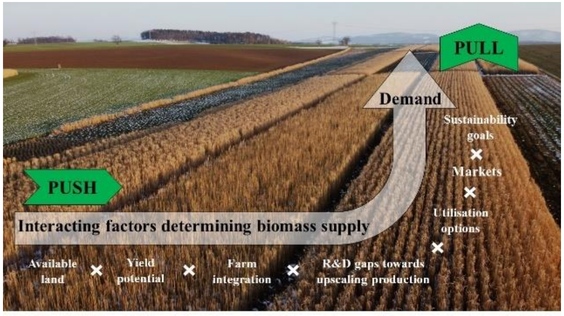

Figure 2: Factors involved in production (PUSH) and market demand (PULL) perennial biomass crop upscaling (discussed in sections below). (Photo: Uwe Kuehn. R&D=research and development).

2.1 Push factor 1: Available land

How much land could be used for PBCs without detrimentally affecting essential food production or ecosystem services? This is a complex question to answer, as there are many interacting factors including population demographics and distribution, diet, technological advances, and political shocks [9, 10]. One suggestion is the concept of land sparing associated with sustainable intensification [11, 12]. This was unintentionally tested by the EU Common Agricultural Policy (CAP) 'set-aside' policies of the early 1990s where it was found that leaving 10% of arable land fallow did not result in the reduction of overall food produced in the EU as predicted by Hodge [13]. This highlights the complexity of assessing land availability as individual land managers can alter practice in a myriad of ways to either maintain production or meet changing demands. In Brazil, the US, EU and UK, a large amount of land is used to produce high input annual crops (food crops and silage maize) for bioenergy purposes (i.e., 'first generation' bioenergy crops such as oil seed rape and soybean being used for bio-diesel production or maize for bioethanol and biogas). Subsequently, concerns about indirect land use change were triggered by policies supporting the use of first generation bioenergy crops, first in the US [14] and then in the EU by the Institute for European Environmental Policy [15] due to a failure to meet sustainability criteria. Focussing PBC planting on land less suitable for food production (often referred to as marginal land) has been proposed as an effective way to mitigate indirect land use change risks [16] and improve habitat for biodiversity. Marginal land categorisation is complex and comprises many factors [17]: soil texture [18], aspect ratio, drainage, climate, stoniness, altitude etc. (e.g. MAFF [19]), and must also consider sociological and economic contexts [20, 21]. Earlier estimates of the 'marginal' agricultural land in Europe that could potentially be used for PBCs range between 69 and 95 million ha [18, 22]. Recent programmes, including the EU MAGIC project (https://magic-h2020.eu/), have worked to improve these definitions and quantify potential land area to better evaluate the impact of land use change to PBC production [22-24]. At a European level, spatial analyses are beginning to use remote sensing to identify abandoned, degraded or contaminated lands that could move from annual to perennial crop production, i.e. available for PBCs, afforestation or rewilding [23, 25].

It has been argued that a reduction in consumption of livestock products is required to 'free up' land for biomass feedstock cultivation as well as for afforestation and restoration of other natural ecosystems [26].

A recent analysis found that 75% of agricultural land use in Germany is used for livestock production (mainly grain fed pigs) (Scheffler et al., 2021), with the figures for the UK being 85% [27], while globally around 40% of all arable crops grown are used to feed livestock for meat, egg and dairy production [28]. There is general agreement that meat consumption in the global north needs to decrease, and that this will free up significant areas of land for non-food uses. For example in the UK, the Climate Change Committee indicates a 35% reduction in meat and dairy consumption by 2050, thus allowing expansion of the planted area of PBCs. Changes in food consumption and production are more likely to be gradual than rapid. If landowners are to be persuaded to convert some land from livestock feed production to PBCs, the income to producers from growing PBCs needs to be at least as economically attractive as other alternative land use options. For such a transition comprehensive policy support (whole farming system) will be necessary to allow farmers and supply chains the confidence to adopt these new low-carbon enterprises [29, 30].

In addition to the challenges of identifying potentially available land, there are also important considerations of how PBCs can be spatially integrated into the landscape to maximise co-benefits for the ecosystem while minimising negative environmental impacts [3, 31, 32]. PBC strip/alley plantings into 'readily harvestable-hedgerows' could provide shelter, erosion control and landscape connectivity supporting wildlife and biodiversity [33-36]. Implementation details would depend on the specific site attributes, such as soil texture, rainfall, current land use, and landscape type [31]. To implement these would likely require a 'farm level' environmental impact assessment and a system for Monitoring, Reporting and Verification (MRV) certification with payments for ecosystem services using multi-dimensional metrics [37, 38].

The developers of new land use policies are grappling with this due to a scarcity of robust long-term quantitative evidence about land use transition to PBCs from alternative land use. As scientists, we would hope that data at the whole European level, from trials combined with crop modelling and remote sensing in Geographic Information Systems (GIS), would be used in planning and supporting spatially explicit land use, including PBC plantings.

In conclusion, these debates on land availability are nuanced, but extensive integrated assessment modelling, both within-country and EU-wide, does support the expansion of PBCs [39]. Based on these modelling outcomes, and our combined experience, we conclude that, with appropriate development of MRV schemes, a simple EU-wide target of 10% of total existing agricultural land (arable and rotational grassland) for PBCs is large enough to deliver sufficient feedstock to develop the sustainable biomass-based industries required, but small enough to provide protection for current food production capacity, water resources, biodiversity and the environment. We recommend therefore that agricultural and related policy support PBC production to 10% of the agricultural area and for this to be included within the following CAP period from 2028 to 2032. Clearly, however, pursuit of such a target must also consider the local context and conditions, such as changing climatic ranges for crop suitability, outbreaks of pests, diseases and political events (such as the Russian invasion of Ukraine [40-44]).

2.2 Push factor 2: Yield and carbon capture potential

To optimise the economic return from PBCs and the carbon savings or greenhouse gas (GHG) removals delivered by these crops, we need to maximise above-ground yield and below-ground soil carbon sequestration while minimising field-based GHG emissions. The yields of PBCs and short rotation forests vary depending on the harvest cycle/rotation length and time since planting, with the fastest growth rates in the early years in perennial grasses and woody crops (see Figure 3).

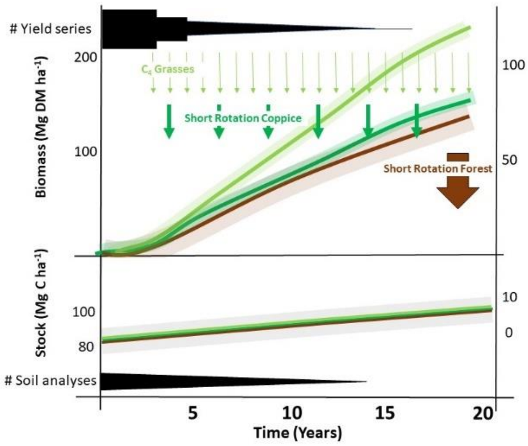

Figure 3: Top panel: Aboveground accumulated harvest yields for three different PBC systems with different harvest cycles: annually (C_4 grasses e.g. miscanthus/switchgrass), every 2–4 years (short rotation coppice, e.g. willow), every 5–15 years (short rotation forestry, e.g. poplar) indicated by the coloured coded arrows. Bottom panel: accumulative carbon stocks for topsoil (0–30 cm soil depths) as informed by Dondini *et al*. [45]. 'Sankey style' black line thicknesses schematically indicate how the numbers (#) of measured yields and soil carbon experiments diminish well before the expected crop lifespans are reached. (redrawn from [46])

We estimate over 200 field trials have been planted with PBCs across Europe since the early 1990s to study the establishment and production potential. Of these perhaps ~20 were/are maintained beyond the initial project funding (of between 3 and 5 years). Even at the 'long-term sites' staff and equipment changes leads to protocol inconsistencies reducing the data quality. This makes it challenging to track the long-term trends with interannual variation in weather. Rainfall patterns are likely to be the most important determinants of yield variations, especially on lower grade marginal land, but the long-term data remain scarce.

To project above-ground harvestable yields, studies have used traditional crop models with parameters adapted to PBCs using field trial data (MiscanFor [47], Salix/PopFor [48]), Switchgrass [49, 50]). Yield potentials estimated by these crop production models are then used to determine potential soil carbon changes and GHG emissions from these crops [51, 52].

Output maps of potential yield are dependent on the spatial resolution of input climate, land use, and soil property maps, which are often at 1 km resolution. Whilst this is good enough for planning large-scale use of biomass, this is not spatially and temporally explicit enough to predict yields at field levels [53]. Differences between modelled yield potentials and farmer measurements can be explained by variation in crop establishment rate [54], effectiveness of crop management, and by missing fractions in commercial harvesting (e.g., stubble residue heights) [55].

Maximising aboveground yield is a significant factor in the carbon savings delivered from PBCs. However, changes in soil carbon stocks and GHGs which need to be accounted for in overall carbon budgets, or equivalent (see McCalmont, et al. [56]), as land use change to, and reversion from PBCs can result in net positive or negative emissions [57, 58]. There are very few trials where soil carbon is measured properly with adjustment for changes in bulk density over time, sampling before planting, or with an appropriate paired site, appropriate depth of sampling (min. of 30 cm), and with sampling conducted after a sufficient length of time to detect statistically meaningful stock changes [59, 60]. The eddy covariance technique (Fig. 4) measures carbon fluxes from land use in near real-time and these can be accumulated into daily, monthly, annual, and multi-annual budgets to identify sources and sinks of emissions well before changes can be detected in the soil. The delta ^{13}C shifts associated with converting to PBCs with C_4 photosynthesis can help with detection of new carbon such as in Dondini *et al.* [45]. Recently, GHG flux measurements in paired sites representing land use change and original land use are only just starting to be undertaken, one example being the PBC4GGR project in the UK (https:// pbc4ggr.org.uk), where verification and reporting of soil carbon change will be carried out by combining on-site eddy covariance monitoring with modelling [61, 62].

Figure 4: Developing measurement, reporting and verification of greenhouse gas emissions: Measurement of net ecosystem exchanges of carbon and water fluxes by eddy covariance over a 6-hectare field of *M. x giganteus* in Aberystwyth that began in 2011 before land use change from rotational grassland. (Photo: Jon McCalmont)

At the end of the crop lifespan the root and rhizome biomass of the PBCs is incorporated into the soil by maceration and is decomposed relatively quickly [63]. It should be noted that reversion to previous land use will likely result in a return over time to soil carbon levels commensurate with that land use and therefore should not be used for carbon credits at field scale. However, at landscape level, if new PBC plantings replace those that are reverted, then the overall net soil organic carbon should still increase at country level (and globally) relevant to carbon accounting systems aimed at mitigating emissions causing climate change.

We recommend policymakers put in place steps to ensure crop longevity and the performance of PBCs is monitored by measuring yields on farms over the crop lifespan (~15 years) to create a best practice knowledge base. This could be a requirement for receiving any financial incentive related to cropping PBCs.

2.3 Push factor 3: Integration into farm businesses

As with any new cropping system, innovation or policy instrument, many factors interact and affect land managers' decisions on whether to grow PBCs. There is a growing body of work in the UK that identifies social, economic, technical, and political barriers to integrating PBCs into farming systems as well as identifying 'enablers' to facilitate change. There has been resistance to adoption due to attitude and perceived risk of loss [64]. Decision factors include upfront investment, long-term commitment of land, potential crop failure, yield variability that is not protected by crop insurance, competition with alternative land use (including other non-food options), immature markets, limited number of end-users, and lack of long-term market certainty. The capacity to absorb these risks varies according to farming system characteristics (e.g., size, tenure, level of investment in other enterprises and a positive grower attitude towards innovation of new products and markets).

In Europe, capacity for uptake of PBCs is greater at large arable farms (farms >100 ha account for 50% of the utilised agricultural area [65]) with appropriate infrastructure and machinery. Farmers have also been found to prefer the flexibility of annual crops which allow them to respond to changing commodity prices. Uncertainties associated with future policy instruments such as emerging carbon markets, as well as the food and energy security debates and volatile cereal and oil crop prices associated with the war in Ukraine, are all disincentives to commit to PBCs [66].

On a more positive note, evidence for the ecosystem service benefits of PBCs is building, for example, using PBC strips (which could include agroforestry) in open arable landscapes to promote biodiversity [36] (Figures 5, 6). These aspects of PBCs are viewed positively by farmers and large-scale land managers (such as the UK's Royal Society for Protection of Birds, the National Trust, the military, Crown Estates, golf course owners etc.) and could support PBC integration into future land management payments in the EU and UK focused on environmental and public goods, but this will require the development of novel measurement, reporting and verification methods.

Figure 5: A *Miscanthus* strip strategically planted in an open arable landscape. Fam. Schmitt, Limburg, Hessen (Germany). (Photo: John Clifton-Brown)

Within farming systems, supply chain intermediaries or innovation brokers can be influential in increasing uptake [67]. The importance of supply chain companies in building confidence in the farming community and developing market and industrial capacity and lobbying government is clear. Contracts are being specifically developed to overcome the effects of inadequate markets [68-70]. For both growers and supply chain companies to expand production of PBCs, they need stronger, longer, and more integrated policy support and the confidence that this support will remain consistent over time scales that are relevant to the economic performance of perennial crops. Small adjustments such as the relatively recent inclusion of PBCs in CAP 'greening payments' [71] have helped but are insufficient. Adams and Lindegaard [69] identified similar obstacles in a policy review for the period 1990-2015.

Figure 6: Silvoarable agroforestry on the farm 'Gladbacherhof'. (Photo: Dr. Suzanne Jacobs)

More recently, in a study in 2020 using a Delphi approach [72], UK PBC stakeholders (from farmers, industry and academia) identified the top 5, out of 13, biomass policies according to categories for 'desirability', 'feasibility' and 'effectiveness' (Ford *et al.*, pers comm). The panel recognised the need for long-term commitment and strongly recommended policy intervention at the end of the PBC supply chain to provide users with the financial security needed to offer attractive contracts to farmers, which would then in turn stimulate development of the full supply chain. But, as mentioned earlier, incentivising large scale end-users may not pull through small-scale supply chains. These comments are also reflected in other stakeholder workshops concerning feedstocks for negative emission technologies [73]. This view was also reflected in a survey of 20 existing *Miscanthus* growers who identified the largest barrier to extending their *Miscanthus* crop areas was the establishment cost. MRV could play a crucial role in ensuring/incentive the placement of PBCs in location where the greatest gains in ES can be achieved. For forestry planting an Environmental Assessment framework already exist in the UK. These frameworks manage the potential for negative impacts of sensitive species such as farmland land waders, which also apply to PBC's. Applying such practices to all PBC would be effective in overcoming risk and maximising benefits [74]. In a recent Delphi study [8], stakeholders identified that further investment in breeding-agronomy research to improve establishment speed and the promotion of advisory support for growing PBCs were desirable. However, the balance of public and private investment was debated; some panellists supported including PBCs in the English Environmental Land Management Schemes designed to deliver public goods, while others felt that the benefit of PBCs were not as great as other uses of land, such as woodland creation, and political opposition to inclusion could be expected. Several studies emphasised the need for policy integration across government departments, government continuity and communicating strategic priorities which would help build market confidence. They also identified the need for clarity with respect to policy incentives such as agri-environmental schemes, planting grants, and any emerging carbon markets.

These studies demonstrate that further social science research is urgently required, involving a wide variety of stakeholders, thus taking a multi-actor approach. As widespread PBC plantings will change the visual landscape it is important to understand the perceptions of all stakeholders, including the public, of this change and its benefits and disbenefits. There is scope to include deliberative techniques with communities to try to reduce or transform specific local economic impacts and enhance community and wider societal 'buy-in'. We recommend that PBC development be community-based with active involvement of local communities in project development with priority given to generating benefits for communities.

2.4 Push factor 4: R&D needed for upscaling production

Over the last 20 years, public-supported research and development (R&D) with industry involvement and coordination between national and EU funded projects has delivered significant advances in our ability to scale-up PBC deployment with R&D on the following steps: genetic resource collection and characterisation, breeding, propagation, agronomy, harvest, transport and storage, pre-treatment and valorisation. In large projects, parallel development in different steps has been attempted to accelerate holistic system developments, making chains that connect production with utilisation. Typical start to finish testing durations to breeding new hybrids ready for widespread testing are 12 to 15 years for the grasses *Miscanthus* and switchgrass and 15 for willow and 22 years for poplar [75].

EU programmes have been effective in building up multi-location trial networks for evaluation of new hybrids and how well they are matched to different environments [76-78]. Continuity of these trials over relevant timescales beyond the EU programmes depends on national funding arrangements which tend to be patchy, jeopardising progress.

Beyond plot trials, there is much to do in agronomy and crop management to upscale to commercial fields. This has been the driver for developing *Miscanthus* propagation by seed which has multiplication rates from 2,000-5,000. This only requires between 10 and 20 ha of land in a southerly location where the parents flower to produce sufficient seed to achieve the UK CCC upscaling target of 23,000 ha yr^{-1}. Large inter-annual variations in weather present new challenges to crop establishment, such as early spring or summer droughts, or floods during planting periods (https://www.ipcc.ch/report/sixth-assessment-report-cycle/). However, innovations in planting and agronomy such as mulch films are being developed to cover these challenges (Fig. 7).

Figure 7: Upscaling: Learning by doing. planting *Miscanthus* at commercial scale. Above shows the start of a 12 ha planting of clonal rhizomes near Limburg, Hessen, Germany in 2023. Below shows 9 ha of seed-to-plug-to field establishment with bioderived and biodegradable mulch film [79] in UK, 2022. (Photos: John Clifton-Brown and Chris Ashman)

Technology readiness levels for the reliable establishment of PBCs, such as *Miscanthus,* range between 4 and 6 for areas up to 10 ha, but higher planting rates still need many innovations. For all PBCs the methods for harvest, storage, and transport logistics need further work in the local context. In addition, spatial harvest yield monitoring in commercial plantings is required to inform these developments to optimise yield and minimise environmental impact. We recommend policymakers put long-term commitments to publicly supported R&D and coordination between national and EU funded projects needs to continue. Industry involvement in projects is essential to the commercial translation of the technologies developed.

2.5 Pull factor 1: Utilisation options

The fifth step identified in Figure 1 is where the biomass enters value chains. The push factors 1 to 4 impact the potential quantity and quality, spatial and temporal availability of biomass, but without the end-to-end value chains this potential will not turn into reality. These currently are: 1) biomass for energy, 2) biomass for energy with carbon capture and storage, 3) biomass for chemicals and materials in bioproducts to replace high carbon alternatives and 4) biomass for livestock bedding and fodder. Cascaded uses for the different biomass fractions are being actively encouraged for the circular bioeconomy.

For bioenergy, there are many national initiatives [80], but it has long been argued that a simpler 'volume market' is a better way to initiate sector growth. In the UK, favourable policies for bioenergy have supported simple straw-burning power stations with a total installed capacity of ~160 MW in 2022 (www.eco2uk.com). These currently capture neither heat nor CO_2 but, depending on transport distances, still only emit 21.3 kg CO_2 MWh^{-1} which is an order of magnitude less than gas [81]; however, more could be done to maximise GHG mitigation. In addition to providing much-needed renewable energy, these straw-burning power stations have established domestic biomass supply chain actors and developed the expertise needed to deliver more ambitious plans for Bioenergy with Carbon Capture Storage. However, incentive schemes that are poorly designed can have serious consequences beyond energy and agricultural policy; the power sharing agreement in Northern Ireland collapsed in 2017 because of a renewable heat incentive scheme [82], paralysing government for almost three years. Reuters poll on carbon price in 2021 indicated that the price must be increased to more than \$100 (up to \$250) per tonne to limit warming to 1.5°C [83]. At this level the carbon price will cover the costs of the carbon capture storage component [84]. As other countries expand biomass use, prices are expected to rise [85] with increasing importance on indigenous biomass production driven by global shocks such as the recent Russian invasion of Ukraine.

In Germany, it was energy policy rather than agricultural policy that led to the largest recent changes in agriculture. The EEG (Renewable energy law) supported the production of green electricity [86]. Feed-in tariffs were granted to farmers or biogas plant operators for producing electricity from biogas. This policy intervention led to a boost of investments into biogas plants and today Germany has about 8,600, mostly farm-based, biogas plants [87] using manure in combination with maize. As a result, silage maize production for biogas rapidly increased until 2011 and since then remained constant at approximately 2.65 million ha (FNR, 2022). Due to a revision of the EEG in 2012, further expansion of biogas-based electricity generation was largely stopped due to reduced guaranteed feed-in tariffs for biogas electricity from energy crops.

In the EU, the vision for the Biomass Based Industries (BBI) initiative (2014-20) was 'a competitive and sustainable Europe leading the transition towards a bioeconomy, while decoupling growth from resource depletion and environmental impact'. The BBI promoted products not energy, the cascaded use of biomass feedstocks and their use in long lived products such as building materials (Figure 8). This has been recently replaced by the Circular Bio-based Europe Joint Undertaking (CBE) (2021-2031) (https://www.cbe.europa.eu).

Figure 8: Biobased building materials (here from *Miscanthus*) can substitute some -cement-based products and provide long-term carbon sequestration. (Photo: Uwe Kuehn)

In addition to the cascaded uses, the CBE initiative is pushing for whole system circular thinking where the end of life for one product is the beginning of life for another bio-based product. Ambitious projects will be needed to translate these simple concepts into commercial practice.

We recommend that financial and policy support should be underpinned by increasing carbon pricing which will encourage the development and use of low GHG emission energy and materials. This carbon pricing support should be designed in such a way that all actors in the supply chain, including farmers, reap the benefits.

2.6 Pull Factors 2 and 3. Market systems, the socio-economic environment and sustainability goals

Our understanding of the technology and uses of PBCs is documented above. However, a topic that has received far less attention is the role of wider systems and governance in determining whether PBCs become widely planted [88]. Historical studies of rapid and profound transitions occurring in other industries such as energy [89] and transport [90] have demonstrated that transitions are not necessarily led by experts or driven by technology, and are unlikely to be rationally planned or linear. The key feature of many of these studies is an appreciation of the socio-technical regime; the idea that policymakers, technology users and scientists all participate in the co-creation and development of a technology, rather than viewing technology and its uptake as a purely technical issue [91].

Geels & Schot [92] provide a useful (but critiqued) framework for transition using the multi-level perspective. Three levels exist. The highest level is the socio-technical landscape. This consists of overarching factors such as cultural norms, macro-economics and political traditions. These are relatively slow to change and, at least in the short term, are not influenced by other levels. The (second) meso-level is the socio-technical regime: the interactions between science, policy, industry, market preferences, regulation, culture, and technologies in current use. These meso-level regimes are seen as relatively stable and 'locked in' to particular patterns and interactions. The third level is known as niches and is where innovations begin; small networks of innovators act to incubate specific innovations.

For a technological transition to become established (i.e., a breakthrough of an innovation from being niche to being part of the wider socio-technical landscape), interactions between all three levels are needed. When applied to the general question of uptake of PBCs several key themes emerge. Firstly, at the level of the regime, cooperation, and development of understanding between several very different industries is required. Secondly, the lack of understanding amongst innovators about non-technical aspects of the regime is significant. Thirdly, transition to an economy based on biomass is not being driven by the technology, rather it is the socio-technical landscape (e.g., the need to limit climate change) and the regime (e.g., the reconfiguring of the industry towards renewable sources) that are driving the need for innovation. In addition, political events create new requirements that hasten change. Pioneers of change respond to pressures from the socio-technical landscape and regime, accept the need for co-design of systems, and do not consider their work as being a purely scientific endeavour [91, 93].

Current 'landscape' level changes such as rapid global warming and its public awareness, and the global energy crisis, have created a socio-economic environment that supports change. In addition, biomass based energy and products can potentially contribute to eleven of the seventeen UN Sustainable Development Goals [94]. Therefore, we witness an impetus to create policies that support technology to displace fossil resources.

We agree with the six interacting policy approaches identified by Murphy-Bokern [86]: Firstly, for prioritising climate protection, PBCs have the advantage of high output returns relative to input costs, therefore achieving high energy ratios and low embedded GHG emissions. GHG balance and mitigation assessments need to include soil carbon changes due to land use change as well as a comparison with the previous land use (and other opportunity costs). Secondly, market-based interventions or incentives need to ensure adequate profit for all actors in the production and utilisation chains for thermal generation of heat and electricity or biobased products. Contracts for difference (CfD) is the UK's new main mechanism for supporting low-carbon electricity because it guarantees a price reflecting the investment and does not change with market forces over the agreed lifespan. CfD guarantees return on investment for the producer and protects the consumer from unplanned market pressures such as war. We believe that variants of CfD could also effectively support bio-based products because they could be tailored to reward developers for production, conversion, and circularity. Such approaches need to incorporate demand-side innovations with labelling, procurement, and standardisation. Thirdly, standards for bio-based products and circularity are seen as key enabling technologies; however, as biomass types are diverse, standards are difficult to define. Fourthly, long-term commitment and planning are crucial as already highlighted in the Delphi analysis above. This is due to lead in times of 3-8 years for planting of crops and for construction of bioconversion facilities which need to occur at the same time to avoid 'chicken and egg' stagnation. Fifthly, research policies are needed to accelerate PBC breeding and agronomy to reduce establishment times on available land types, improve resilience to drought, frost and heat, increase yields and improve biomass quality. Research is also needed to integrate top-down GIS methods, informed by images from drones and satellites, with bottom-up social science approaches to support land managers who are considering including PBCs in their business portfolios. Land managers need to be included in the development of measurement, reporting and verification systems aiming to quantify environmental, biodiversity and GHG mitigation benefits. This will aid the co-creation of a sustainable and validated carbon market supported by a credible life cycle assessment. Sixthly, land use policies are needed to enable land managers to optimise resources and maximise profitability based on a combination of crop choice, available skill, on- and off-farm infrastructure, personnel values, and traditions. Careful analysis is needed to pitch the levels of payments required to stimulate planting PBCs and avoid triggering unintended consequences on food systems, soils, or ecosystems. Environmental benefits may not be as simple as selecting the most challenging land for PBCs. New forms of farm payment, e.g., UK Environmental Land Management Schemes recognise and reward environmental benefits in line with the principle of public money for public goods. Currently these schemes only make a small contribution to total farm income but should provide a mechanism to promote environmentally sound land use decisions.

All these policies must be concurrent so that landowners, industrialists and their supporting scientists and policymakers join forces to translate PBCs into significant negative emissions technologies to fight the climate emergency. This will require the provision of much-needed information to the general public and an increase in the number of specialists throughout the PBC value chains, achieved through improved education at primary, secondary and tertiary levels, including apprenticeship schemes, with all contributing to 'Shaping the Transition to a Sustainable, Biobased Economy' [95].

3 CONCLUSIONS

Ultimately, land managers will determine how much land is allocated to PBCs for biomass production. Their decisions will be influenced by market demand for feedstock and confidence in the stability of the supply chain. They should be incentivised through specific policy measures coupled to carbon pricing. The percentage allocation of land to PBCs needs to be managed at a government level through incentives to avoid unintended consequences such as loss of biodiversity or reduction in essential food security.

Furthermore, reward mechanisms are required for commercial developers of low carbon bioenergy and bio-based products to encourage investment in a way that rewards actors in the entire value chain, particularly the farmers. Hence, there is a need for further development of measurement, reporting and verification systems to ensure that payments are made for actual long-term GHG emission mitigation. We note that the support for utilisation, both energetic and material, with public-private collaborations should continue until higher technological readiness levels are achieved for the whole value chain including cascaded use of the feedstocks and products. Additional funding is considered necessary to encourage 'on-farm' innovation for agronomy, harvest, transport, and storage with comparative sustainability assessments.

Similarly, continued support for innovation in the R&D of biomass production to increase the availability of planting material to upscale to the hectarage required for net-zero is required. This must include long-term research to quantify the impact and value of large scale PBC introduction into the landscape on ecosystem functions including carbon sequestration to soil, carbon mitigation, flood prevention, erosion control, water cycling, water quality, soil fertility, biodiversity, and cultural values. The value of these ecosystem benefits may be of the same order as the biomass value chain.

Finally, interdisciplinary training and education are required to develop the body of expertise and experience for growing the PBC industry to improve the pool of skilled workers.

Our policy recommendations follow each section, but here we have simplified to just four pointers to help shape the future policy ecosystem:

a) support ramp up of PBC production from less than 1% to 10% of farmed land by 2050 by incentivising farmers in Europe;

b) involve the community during the process of project development (co-creation) and in measurement, reporting and verification;

c) secure long-term commitments to public supported R&D between national and EU funded projects and coordinate between them;

d) support industry involvement in projects for commercial translation of the technologies developed.

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