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EDITORIAL

Valorisation of marginal agricultural land in the bioeconomy

1 | INTRODUCTION

The bioeconomy requires more sustainably produced biomass to make a positive societal impact. Sustainable biomass resources must neither compete directly with essential food supplies through competition for production resources, nor through indirect land use change (iLUC) displacing food production elsewhere (Clifton-Brown et al., 2023). Utilization of marginal, abandoned and degraded land can provide low iLUC risk biomass which is in line with the Renewable Energy Directive RED II (European Union, 2018). Marginal land, as defined by Elbersen et al. (2017), is estimated to represent a very large land resource of 38–53.5 million ha in the EU and the United Kingdom (Gerwin et al., 2018; von Cossel, Lewandowski, et al., 2019) and climate warming impacts are likely to speed up degradation of arable into marginal land (European Environment Agency [EEA], 2017; IPCC, 2023). Marginal lands are at particular risk of becoming abandoned and abandoned land areas are projected to increase by 5%–10% (4.8 million ha) in the EU and the United Kingdom by 2030 (Elbersen et al., 2022; Perpiña Castillo et al., 2018).

This Special Issue focuses on the 'valorisation of marginal agricultural land for the bioeconomy' to maximize exploitation of this land resource and is largely based on research performed in two EU-Horizon-2020-funded projects: GRACE (Growing advanced industrial crops on marginal lands for biorefineries, GA 745012, https://www.grace-bbi.eu/) and MAGIC (Marginal Lands for Growing Industrial Crops, GA 727698, https://magic-h2020.eu/). It is divided into four sections: Section 1 consists of seven studies assessing the potential of marginal land for crop production. Section 2 presents extensive field trial results for industrial crop cultivation using the model crop miscanthus and assessing the interactions between Genotype (or hybrid) × Environment × Management (G × E × M). Section 3 introduces results from studies on biomass utilization, ranging from biorefinery approaches for the production of novel biobased platform chemicals to direct material use. In Section 4, results of the environmental, social and techno-economic life cycle assessments of different value chains are presented. Finally, the aggregated 'lessons learnt' in the last decade of perennial biomass crop research are translated into recommendations to shape EU policy for the support of perennial cropping systems.

2 | SECTION 1: ASSESSING POTENTIAL CROP CULTIVATION ON MARGINAL LAND

Early stage identification of land abandonment is necessary to maximize exploitation of marginal land. The study of Meijninger et al. (2022) introduces a novel approach for identifying arable land abandonment using radar coherence data in combination with a Random Forest model. The results of this study show that radar-based analysis is a relatively simple method to detect land abandonment at an early stage and allow monitoring and rapid policy response.

Marginal lands are typically characterized by constraints on plant growth. Perennial biomass crops, such as miscanthus, can produce sufficient biomass yields for commercial use on such conditions with only low input requirements. Awty-Carroll et al. (2023) tested eight intraspecific *Miscanthus sinensis* hybrids and six *Miscanthus sacchariflorus* × *Miscanthus sinensis* hybrids on seven marginal, contaminated and/or abandoned locations across Europe. Average yields ranged from 10 to 13.7 t DM ha^{-1} with large hybrid-specific differences revealing the site-specific suitability of the hybrids. Data collected throughout the third growing season were used for calibration and validation of hybrid-specific early yield models by Shepherd et al. (2023). These models were applied to predict the potential dry matter yield of marginal land across Europe and need to be further improved by continued data generation. The yield potential maps on marginal

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land, although only based on early-cultivation-phase data, allow identification of high-performing hybrids for specific regions and sites.

Marginal lands are strongly affected by changing climate, and crops cultivated on marginal land are often more prone to extreme climatic conditions than those on better land. Ferdini et al. (2023) determined the impact of ongoing climate change on the suitability of the two contrasting perennial biomass crops giant reed (GR) (*Arundo donax* L.) and reed canary grass (RCG) (*Phalaris arundinacea* L.) for cultivation in Europe, including their potential cultivation area on marginal land. The results indicate that potential marginal-land cultivation areas for GR are located in Greece and southern Spain and for RCG in northern Europe, and are likely to increase by 24% and 13%, respectively, by the end of this century. The study shows that crop selection for marginal land will be affected by ongoing climate change and potential utilization pathways need to consider such impacts.

To achieve full yield potential on marginal sites, the most suitable choice of crop type and its agronomy are essential to ensure economic viability of marginal land utilization. Scordia et al. (2022) performed field trials at eight experimental sites in three different climatic zones in Europe to test the performance on marginal land of a range of advanced industrial crop species. The experimental sites include six marginality factors alone or in combination, and the biophysical constraints at each site were combined with adapted low-input management practices. The yield of the different site-specific low-input management systems ranged from −99% for industrial hemp in the Mediterranean to +210% for willow in the Continental zone compared to the site-specific control management system. These results highlight the importance of running field trials for the selection of the most profitable crop and management practice for each environment.

As a multi-purpose crop, hemp is of high interest for the bioeconomy since it can serve as feedstock for a plethora of biobased products, including long- and short-fibre materials, oil- and protein-based products and pharmaceuticals. In their review article, Blandinières and Amaducci (2022) show that hemp is a species that can be considered particularly susceptible to adverse conditions, especially in terms of soil characteristics and dry climates. With the exception of thallium, heavy metal contaminations do not appear to severely limit hemp's productivity, but might affect its economic viability due to limitations in marketing the produce. While drought conditions have a particularly negative effect on the productivity of hemp, it was identified as an added-value crop for income diversification in mountain environments less susceptible to drought.

3 | SECTION 2: INDUSTRIAL CROP CULTIVATION

Improving the cultivation of industrial crops on marginal land is a fundamental aspect of this Special Issue and the perennial C4 model crop miscanthus has been identified as particularly suitable for marginal land on account of its perennial nature, stress tolerance and high resource use efficiency (Lewandowski et al., 2016).

In general, the establishment period is the most critical and challenging phase in perennial crop cultivation and successful establishment is a prerequisite for achieving timely and high productivity. However, on marginal land in particular, the optimum time window for planting is very narrow and limits upscaling. For this reason, Ashman et al. (2023) tested the application of degradable, transparent mulch film on newly planted miscanthus plantlets to de-risk and optimise establishment success and extend the suitable planting window for commercial upscaling using plantlets pre-grown in the glasshouse. The transparent mulch film protects the plantlets from damage by late frosts, drought and grazing and stimulates early growth by increasing soil temperature and moisture. Novel biobased, truly biodegradable mulch films were also tested successfully, helping to minimize the risk of microplastic pollution.

In-depth knowledge on site-specific early-season growth, canopy development and end-of-season ripening of novel hybrids is essential for continued breeding success and site-specific productivity optimization. The study of Magenau et al. (2023) assessed the early-season regrowth in different miscanthus hybrids cultivated across Europe. Significant differences in early canopy development were identified between the *M. sacchariflorus*×*M. sinensis* hybrids and the *M. sinensis*×*M. sinensis* hybrids. The study showed that the current breeding strategy of extending and maximizing radiation interception through the selection of early-emerging *M. sacchariflorus*×*M. sinensis* genotypes and fast canopy closure is only suitable for marginal land to limited extent, in particular for locations prone to late frost. Late-emerging and more frost-tolerant *M. sinensis*×*M. sinensis* hybrids are better adapted to such locations and a promising strategy for increasing productivity of such sites.

Drought is a very relevant constraint on marginal land and development of miscanthus hybrids with improved drought tolerance a promising mitigation and climate change adaptation strategy. Al Hassan et al. (2022) explored the genetic diversity present in 23 *M. sinensis* genotypes exposed to artificial water deficits to better understand the underlying response and drought tolerance mechanisms. A strong negative correlation was found between yield stability under stress conditions and yield in

favourable conditions, showing that the most productive genotypes suffered most from stress conditions in terms of yield reduction and chlorophyll degradation. Lazarević et al. (2022) quantified drought-induced changes in eight novel *M. sinensis* seed-based hybrids at a juvenile seedling stage using non-destructive multispectral 3D imaging of plant morphology, colour and chlorophyll fluorescence imaging. While a sharp decline in Normalized Difference Vegetation Index (NDVI) was observed for the drought-sensitive hybrids compared to the control, the drought-resilient hybrids showed a stay-green strategy resulting in only a slight NDVI decline and a lower phenotypic plasticity. The multispectral imaging allowed rapid and non-destructive quantification of plant morphological and physiological responses under drought conditions and proved to be a rapid tool for effective screening of drought susceptibility traits.

The end-of-season ripening behaviour of miscanthus is a main driver for maintaining a high harvestable yield quantity, while achieving biomass quality requirements and minimizing nutrient offtakes by the harvested biomass. Magenau et al. (2022) studied the dynamics of the senescence processes of different miscanthus hybrids. Generally, it was found that delaying the harvest until spring reduced overall yield, moisture and nutrient contents for all novel hybrids tested. However, the late-ripening *M. sacchariflorus*×*M. sinensis* hybrids showed combined high yields and low nutrient contents only at lower latitudes. At higher latitudes, elevated nutrient contents and offtakes were observed due to too late and incomplete senescence, while the earlier-ripening *M. sinensis*×*M. sinensis* hybrid combined high yields with low nutrient offtakes. The results of this study allow for the development of site-specific adapted novel hybrids and provide valuable information for the sustainable crop management of these novel hybrids.

Moisture content at harvest in spring is not only influenced by miscanthus hybrid-specific senescence, but also by winter weather conditions, especially temperatures. The climate change-induced mild winter temperatures require increased breeding and selection to ensure low moisture contents are reached before harvest. Impollonia et al. (2022) assessed the dynamics of moisture content during senescence and overwinter ripening using unmanned aerial vehicle-based remote sensing for high-throughput plant phenotyping (HTPP) in 14 novel miscanthus hybrids. Machine learning and generalized additive modelling proved to be a powerful tool for HTPP and for the support of future field phenotyping for breeding selections.

In addition to hybrid and over-winter ripening characteristics, harvesting procedure can also impact biomass yield and quality. Magenau et al. (2021) assessed the impact of cutting height on biomass yield and nutrient offtakes in miscanthus hybrids with different morphologies. An average yield loss of 270 kg ha^{-1} (0.83%) with each 1-cm increase in cutting height up to 40 cm was determined. Interestingly, the mineral (N, P, K, Ca) concentrations did not differ significantly in the lower basal sections and cutting height had only a limited influence on moisture content. Therefore, low cutting heights (e.g. 15 cm) appear a suitable approach to maximize utilization of the site-specific yield potential and maintain long-term productivity, but the potential long-term impacts on soil organic carbon also need to be monitored.

4 | SECTION 3: BIOMASS USE AND PROCESSING IN BIOREFINERIES

Industrial crops from marginal lands can be a relevant, low iLUC feedstock source for the developing bioeconomy, but their suitability for downstream processing and conversion into added-value biobased products, materials and biochemicals needs to be confirmed. Świątek et al. (2022) demonstrated and assessed all steps required for the production of 5-hydroxymethylfurfural (HMF) using miscanthus biomass and chicory roots to replace industrially applied hexose sugars. The paper presents the technical potential of utilizing biomass, including lignocellulosic biomass such as miscanthus, as a feedstock for HMF production in an environmentally friendly biorefinery process.

Building on this technological approach, Götz et al. (2022) presented a techno-economic analysis for processing miscanthus into high-value chemicals, including HMF, using process simulation. The techno-economic analysis was based on a regional, modular on-farm biorefinery concept for the production of platform chemicals (HMF), furfural and phenols from miscanthus biomass. It was shown that, with an accuracy of ±15%, regional biorefineries could currently already provide platform chemicals at prices of 2.21–2.90 EUR kg^{-1} HMF. This demonstrates the strong technical potential of modular lignocellulosic biorefineries, but at still higher costs than fossil-based platform chemicals.

For direct material use, the physical and mechanical properties of the biomass play a dominant role in determining its suitability for specific applications. Brancourt-Hulmel et al. (2021) assessed the impact of genotype-specific biomass quality on the mechanical properties of polypropylene composite materials reinforced with miscanthus particles. The results of this paper showed that genotype-specific biomass quality

parameters impact tensile strength of the composite material. In particular, large cross-stem sections, plant height, lignin and *p*-coumaric acid contents had a positive impact, and need to be considered in composite value chains.

5 | SECTION 4: EVALUATION AND POLICY RECOMMENDATIONS

The transition to a green bioeconomy needs to be monitored closely to ensure environmental, economic and social soundness of the proposed solutions. Life cycle assessment (LCA) is a tool widely recognized for the assessment of potential environmental impacts, but is labour-intensive, costly and requires expert knowledge. To overcome these aspects, Lask, Kam, et al. (2021) developed a simplified, practice-oriented LCA model for the computation of greenhouse gas (GHG) emissions associated with commercial miscanthus cultivation. The following six of 38 parameters were identified as relevant for the overall results: soil carbon sequestration, harvestable yield, duration of cultivation period, quantity of nitrogen and potassium fertilizer applied and distance between the field and the customer. Such a simplified 'parsimonious' model allows practitioners an easy, rapid but still relatively accurate first assessment of the GHG emissions associated with the production and supply of miscanthus.

In addition to this simplification approach, Lask, Rukavina, et al. (2021) also performed a detailed assessment of a bioethanol value chain using the feedstock miscanthus in a realistic biorefinery project scenario in Croatia. The assessment evaluated the GHG reduction potential of miscanthus ethanol, taking into account biological carbon sequestration in soil during miscanthus cultivation and the technological carbon capture and storage (CCS) of CO_2-rich fermentation off-gas in exploited oil reservoirs. Lask, Rukavina, et al. (2021) showed that an ethanol biorefinery combined with CCS could achieve a GHG reduction potential between 104% and 138% and thus make a significant contribution to EU emission reduction targets in the transport sector.

In addition to low-emission biofuels, novel biobased platform chemicals are also required to achieve 'de-fossilization' of the chemical industry. The platform chemical HMF is expected to play a major role here, but is currently mainly produced from edible biomass, such as high-fructose corn syrup (HFCS). Götz et al. (2023) assessed the potential environmental benefits of replacing HFCS by lignocellulosic miscanthus as feedstock in HMF production. The miscanthus-based biorefinery concept had advantages over the HFCS-based approach in all analysed impact categories, except land occupation, clearly showing the benefits of shifting from edible, first-generation feedstocks to food-first compliant, lignocellulosic ones.

Social aspects play a major role in the holistic sustainability and social acceptance of innovations, but sustainability assessments often focus merely on environmental aspects. Marting Vidaurre et al. (2023) investigated the willingness of farmers in Croatia to cultivate miscanthus for provision as feedstock in biobased industries, considering both challenges and opportunities. Their study revealed that the farmers were mainly concerned with the following social aspects: health and safety, access to water, land consolidation and rights, income and local employment and food security. In the case of miscanthus in Croatia, a major barrier identified was the loss of agricultural subsidies paid per unit area of agricultural land if converted to miscanthus cultivation. This shows the importance of agricultural policy for the implementation of biobased value chains.

For the technical R&D concepts presented in this Special Issue to contribute to a thriving bioeconomy, policy measures need to be given careful consideration at all stages from biomass production to end use. Clifton-Brown et al. (2023) produced a balanced review of the environmental benefits and ecosystem services of perennial biomass crops (PBCs) and also their disbenefits. The authors recommend the following policy recommendations: (1) incentives for farmers and land owners for the establishment of PBC on land of low productivity; (2) carbon credit markets for carbon sequestration in biomaterials; (3) innovation support in biobased value chains; and (4) continued long-term, strategic R&D in agricultural and biomass sectors. All policies need to make sure that farmers, land owners, industrialists, scientists and policy makers join forces to implement PBC as a significant negative emission technology and to shape our transition to a sustainable bioeconomy.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data are made available within the original publications of this Special Issue.

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