Review

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Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe – a review

Jana Reinhardt[†], **Pia Hilgert**[†], **Moritz Von Cossel**, Biobased Resources in the Bioeconomy (340b), Institute of Crop Science, University of Hohenheim, Stuttgart, Germany

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Abstract: About 8.37 Mha of European agricultural land is affected by low temperature and thus considered marginal agricultural land. This land allows for industrial crop cultivation without competing directly with food security or biodiversity conservation. However, little is known regarding the yield performance of industrial crops under low temperature conditions. This study therefore compiles the available data and discusses them in the context of remaining uncertainties. Overall, 12 industrial crops were identified as relevant for Europe: giant reed (*Arundo donax* L.), camelina (*Camelina sativa* L. Crantz), cardoon (*Cynara cardunculus* L.), crambe (*Crambe abyssinica* Hochst ex R.E.Fr.), cup plant (*Silphium perfoliatum* L.), hemp (*Cannabis sativa* L.), miscanthus (*Miscanthus* spp.), poplar (*Populus* L.), reed canary grass (*Phalaris arundinacea* L.), sorghum (*Sorghum bicolor* L. Moench), switchgrass (*Panicum virgatum* L.), and willow (*Salix* L.). Good or very good growth suitability under low temperature was indicated for camelina, upland switchgrass, reed canary grass, and willow. Nevertheless, it was also found that there are strong variations in yield performance within the selected industrial crops. Little information was found on the effects of marginality constraints on biomass quality. The uncertainty resulting from this fragmentary data situation represents one of the greatest challenges to the large-scale implementation of industrial crop cultivation across European agricultural land prone to low temperatures, especially in the context of climate change. © 2021 Society of Chemical Industry and John Wiley & Sons, Ltd

Key words: environmental thresholds; lignocellulosic biomass; marginal land; oil crops; perennial plants; unfavorable growth conditions

Correspondence to: Moritz von Cossel, Biobased Resources in the Bioeconomy (340b), Institute of Crop Science, University of Hohenheim, Stuttgart, Germany. E-mail: moritz.cossel@uni-hohenheim.de
[†]Authors contributed equally to the work.

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Introduction

Achieving a sustainable bioeconomy is increasingly important to meet the climate protection goals of a greenhouse-gas-neutral global economy by the period between 2050 and 2100.[1] Sustainability encompasses three dimensions: social justice, economic performance, and environmental viability.[2] All of these dimensions must be considered when providing plant biomass for bioenergy and biobased materials production, which are essential components of a bioeconomy. The increasing demand for plant biomass in connection with global population growth and the resulting increase in food demand leads to land-use conflicts between food production, biomass production, and nature conservation measures.[3–5] This conflict is known as the food, energy, and environment trilemma.[6] Climate change intensifies the land-use conflict, as it leads to more challenging conditions for agricultural production, including extreme weather events such as droughts and heavy rain. This, in turn, causes a reduction in land areas suitable for food production.[3,4,7–9] To reduce the land-use conflict, plant biomass should be produced primarily on so-called marginal agricultural land.[3,10,11] As summarized by Haberzettl *et al.*,[12] marginal agricultural land is associated with reduced crop yields in comparison with optimal conditions due to environmental constraints.[12] Demanding food crops are often not suitable for economically profitable cultivation on this type of land due to the limited applicable management practices. More robust industrial crops are therefore currently subject to research to assess their potential as suitable alternatives to make use of this marginal agricultural land.[2] In this study, marginal agricultural sites are defined as areas that are not suitable, or are only slightly suitable, for the cultivation of food and fodder plants due to abiotic site factors, and which would require intensive (above-average) agricultural management to overcome these limitations.[2] This study does not focus on social and political aspects related to marginal land.

Different abiotic (climatic and geophysical) factors such as drought, flooding, unfavorable soil type and high salinity can restrict plant growth, and can thus be reasons for the marginality of an agricultural area.[3,13] This marginality influences the quantity and quality of biomass in relation to the energy and material use of plants, because growth and yield formation are strongly influenced by abiotic factors,[3,14] e.g. unfavorable climate conditions.

Temperature has a significant influence on the growth and development processes of plants and thus also on their biomass production.[15] For each plant species there is a certain optimum, minimum and maximum temperature. At temperatures below 5 °C or above 35–40 °C most plant species show very little growth,[16] and physical damage, including the death of the plants, occurs. Low temperature (LT) stress can be caused by frost (temperatures below −1 °C) and cool temperatures (0–18 °C).[13] These types of low temperature stress limit plant growth through their influence on physiological processes such as photosynthesis and foliation, which are regulated by temperature-dependent enzymes.[17,18] This is especially important during the first winter after planting or sowing perennial crops such as *Miscanthus* (*Miscanthus* spp.), where only the best established individuals survive.[19,20] Late spring frost, on the other hand, can be problematic for both annual and perennial industrial crops and should therefore be considered in crop management, e.g. by a later sowing date or the application of fleece in spring.

The location factor LT for marginal locations is calculated as described by Rossiter *et al.*,[17] with the heat sum and the duration of the vegetation period. The heat sum above a base temperature of 5 °C is calculated by summing the daily differences between average temperature and base temperature (for 1 year). The duration of the vegetation period is calculated by the number of days per year with an average daily temperature above 5 °C. This is thus calculated from the days on which plant growth is possible due to the temperature.[17] Sites whose heat sum is not sufficient to allow food plants to complete their physiological life cycle are disadvantageous for their cultivation and therefore marginal.[17] Sites with a heat sum of less than 1500° days or a vegetation period of less than 180 days are classified as marginal.

The relevance of the LT agricultural marginality constraint can be expressed by the size of the agricultural land affected. As described by Rossiter *et al.*,[17] LT is one of the most relevant marginality constraints. For LT, respective thresholds exist which differentiate favorable agricultural land from marginal agricultural land (adapted from Rossiter *et al.*):[17]

- Annual average temperature ≤5 °C.
- Heat sum ≤1500 growth degree days (GDD) (base temperature 5 °C).
- Length of the growing season ≤180 days.

The total area of European marginal agricultural land characterized by LT accounts for about 8.37 Mha.[21] Gerwin *et al.*[21] indicate that 13.8% of European marginal agricultural land has an unsuitable soil temperature, imposing challenges for crop cultivation. As the suitability of industrial crops for cultivation under LT conditions is unclear,[9,13,22,23] this study focuses on the following main research question: Which industrial crops have the greatest yield potential for the growing bioeconomy in Europe under the marginality constraint LT?

Material and methods

The perspective taken in this study considers the biomass yield as a suitable parameter for assessing the performance of industrial crops.[24] A comparison between yield on marginal agricultural land and agricultural land that is not marginal (e.g. favorable climate and fertile soils)[25,26] was therefore regarded as a first suitable insight into the future potential of biomass yield performance on marginal agricultural land. First, however, a selection of the most relevant industrial crops in Europe had to be made based on current literature.

Identification of most relevant industrial crops in Europe

For the selection of industrial crops relevant for European marginal agricultural land, EU-funded projects investigating industrial crop cultivation were first sought through the Community Research and Development Information Service (CORDIS) of the European Commission.[27] On the CORDIS website (https://cordis.europa.eu/projects/de), a search query was made on December 6, 2019 using the term 'industrial crop'. The filters for projects and date were set from January 1, 2014 to find only projects that were started or finished in the period from January 1, 2014 to December 6, 2019. As a result, 407 projects were displayed. From these, all projects were selected that were primarily concerned with the cultivation of industrial crops in the field of bioeconomy. Twenty-three projects were identified and all the industrial crops examined in them were compiled (n = 48).[28] Industrial crops that were examined in at least four projects were classified as relevant. In total, 12 industrial crops were identified that meet this criterion (Table 1). These industrial crops are examined in more detail in the further course of this work, i.e. the literature search, which is described in the following sections.

Database and literature search approach

To obtain information about the yield performance of the most relevant industrial crops in Europe under different abiotic constraints, an extensive literature search was conducted using the database Scopus®. To make the search queries in Scopus as precise as possible, the advanced search function was used, which enables a complex search order by means of field codes and Boolean operators.[30]

The development and readjustment of the search queries is graphically depicted in Fig. 1. First, the database was searched for papers in which the plant name appears in the title, abstract, or keywords. These fields were selected because only literature about field trials with the plant species was aimed for in this analysis. If the plant is mentioned in one of the described fields, it was most likely also examined in the paper. Keywords were selected for each plant. In most cases these were the botanical and English names, for example TITLE-ABS-KEY ('*phalaris arundinacea*' OR 'reed canary grass').

Based on these results, the algorithm was modified by adding an AND NOT statement to sort out papers containing the keywords tropic* OR model* OR gis OR gene* OR genome in the title, abstract or keywords (e.g. (TITLE-ABS-KEY ('*phalaris arundinacea*' OR 'reed canary grass')) AND

Table 1. Overview of the selected industrial crops, sorted alphabetically by common name.

Botanical name	Trivial name	Life cycle	Photosynthetic pathway	Use	Projects	Frequency of studies
Arundo donax L.	Giant reed	Perennial	C3	L	9	8
Camelina sativa (L.) Crantz	Camelina	Annual	C3	O	5	6
Cannabis sativa L.	Hemp	Annual	C3	L/O	6	10
Crambe abyssinica Hochst ex R.E.Fr.	Crambe	Annual	C3	O	4	3
Cynara cardunculus L.	Cardoon	Perennial	C3	L/O	5	5
Miscanthus ssp.	*Miscanthus*	Perennial	C4	L	12	13
Panicum virgatum L.	Switchgrass	Perennial	C4	L	6	10
Phalaris arundinacea L.	Phalaris	Perennial	C3	L	4	6
Populus L.	Poplar	Perennial	C3	W	7	11
Salix L.	Willow	Perennial	C3	W	5	13
Silphium perfoliatum L.*	Cup plant	Perennial	C3	L/C	2	4
Sorghum bicolor L. Moench	Sorghum	Annual	C4	L/C	5	7

*Cup plant was investigated in only two projects, but it was considered relevant because the European Parliament included it in the list of ecological priority areas in 2017.[29] L = lignocellulose, O = oil, C = carbohydrates, W = wood.

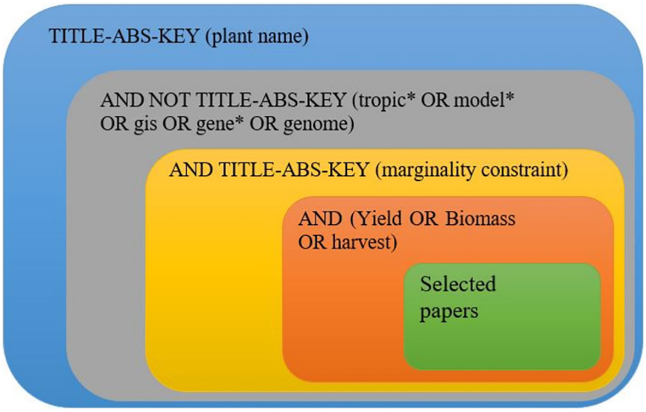

Figure 1. Scheme for the development of the search algorithms used.

NOT TITLE-ABS-KEY (tropic* OR model* OR gis OR gene* OR genome)) . In this way papers about yield modeling and genetic experiments as well as field trials under climatic conditions not prevailing in Europe were excluded.

Furthermore, the titles, abstracts and keywords of the remaining papers were searched for the marginality constraints (including synonyms and related words) by adjusting the previously used algorithm.

From these results, papers with at least one of the following keywords were selected: 'yield', 'biomass', or 'harvest'. These keywords were searched in all fields to ensure that a yield was listed in the paper. The final search query had the following algorithm: (((TITLE-ABS-KEY ('*phalaris arundinacea*' OR 'reed canary grass'))AND NOT TITLE-ABS-KEY (tropic* OR model* OR gis OR gene* OR genome)) AND (TITLE-ABS-KEY ('soil moisture' OR 'ground moisture' OR 'soil humidity' OR 'soil drainage' OR waterlogg* OR 'water logged' OR 'field capacity' OR 'poorly drained'))) AND (yield OR biomass OR harvest).

If more than 100 results were displayed, the search algorithm was extended by searching for synonyms and related terms to marginal land in all search fields, to ensure that the most fitting results were obtained.

Selection of the search results

The Scopus database was queried with the search algorithms that were developed. From the results, a selection of papers was made that contained the following:

- Field trials on selected plants.
- Information on yield.
- Information on time and location of the experiment.
- Information on site conditions (soil and climate).
- No soil with high salt content.
- No heavy metal contaminated soil.
- No acidic soil (pH <5).
- No test with waste water.
- Climate comparable to Europe (The assessment of the climatic comparability of a site outside of Europe with European condition was done based on the Köppen–Geiger climate classification – more precisely on the world map of Beck *et al.*[31]).
- Trials only in the northern hemisphere (An exception was made for Brazil for the plant crambe. For this plant, 911 results were found of which 224 papers were from Brazil. Here only Brazilian references with a comparable climate were considered.)
- German- or English-language papers.
- Availability of the full text of the papers.
- For some plants, special selection criteria were applied:
  - For willow and poplar, only trials with short rotation coppice were considered.
  - For sorghum, only papers with the variants forage, biomass and sweet sorghum were further investigated as grain sorghum is primarily used for nutrition.[32,33]

In a next step, the locations and abiotic conditions in the selected papers were examined to determine their marginality and the corresponding yield. If several papers were found for one location, the yields were averaged. The selected industrial crops were mainly used for the extraction of oils and fats, carbohydrates (starch and sugar) and lignocellulose.[34] Further processing for energy (biogas, biofuels and solid fuels) or material (materials and chemicals) purposes[14] then took place.

Suitability evaluation

The suitability of industrial crops for LT conditions was conducted following previous studies by Ramirez-Almeyda *et al.*[22] and Reinhardt *et al.*[28] This evaluation scheme was based on the average level of biomass yield under limited growing conditions (here by LT) in relation to the biomass yield under non-limited growing conditions. Suitability levels range from 0 (unsuitable) to 4 (very suitable). These suitability levels are assigned according to the following scheme: If an industrial crop shows a higher biomass yield under LT conditions than under non-limited growing conditions, then very good suitability exists (level 4). If the biomass yields are comparable between LT conditions and non-limited growing conditions, then level 3 applies (good suitability). If the biomass yields are lower or significantly lower, the suitability for cultivation is rated as average (level 2) or low (level 1). If the industrial crop cannot grow at all under LT conditions, there is no suitability for cultivation (level 0). If no field trial data were found in the literature for a particular combination (industrial crop × LT conditions), the suitability for cultivation was estimated based on comparative literature and the authors' assumptions.

Results and discussion

Overview

Field-trial studies were found for seven dedicated industrial crops: Camelina, hemp, switchgrass, reed canary grass, poplar, willow, and sorghum. The number of studies per industrial crop was rather low (1–3) (Fig. 2, Table 2). Most studies were from North America and few examples from Europe and China. This already indicates the need for a more thorough investigation of industrial crop performance under LT conditions in Europe and worldwide.

This restricts the suitability assessment and, as expected, not all industrial crops shortlisted for this review article were found to be suitable for the LT marginality constraint. No studies were found for the industrial crops cardoon, crambe, cup plant, giant reed, and *Miscanthus*, all of which are known to be hardly suitable for growth under the LT marginality constraint. This variation among industrial crops in terms of their adaptability was already known from previous studies.[35,36] However, some such investigations are taking place, such as with *Miscanthus* at a site in southwestern Germany characterized, among other things, by LT (Fig. 3). Especially with perennial plants like *Miscanthus*, it often takes a long time until results are meaningful and can be published. Many industrial crops such as *Miscanthus* could therefore not yet be considered in this study.

Based on the studies' assessment and additional literature, Fig. 4 summarizes the overall suitability for the 12 crops to grow on soils limited by LT. For those crops for which no field trial data was found, the assessment is based purely on data from the associated literature. Overall, camelina, upland switchgrass, reed canary grass, and willow are most suitable (suitability rank ≥3) for cultivation on soils with low temperature, based on field-trial results from 14 sites published in ten papers (Fig. 4). However, wide ranges of variation in dry-matter yields were discovered (Fig. 5).

For cup plant, for example, only 109 results were published in Scopus, which is a much smaller number than all other crops in this study. Furthermore, no studies including cup plant matched the criteria for the LT constraint. However, cup plant probably has a good cultivation suitability, as it survives temperatures down to −30 °C and starts to grow at a temperature of about 5 °C. Optimal growing conditions are achieved at temperatures of about 20 °C.[37] Again, the great need for further studies to better understand the potential of industrial crops under LT conditions is evident.

The following sections discuss in detail the extent to which the seven industrial crops for which field trial data are available are suitable for cultivation under LT conditions.

Overall influence of LT on industrial crops growth suitability

Temperature has a significant influence on the growth and development processes of plants and thus also on their biomass production.[15] For each plant species there is a certain optimum, minimum and maximum temperature. At temperatures below 5 °C or above 35–40 °C most plant species show very little growth,[16] and physical damage, including the death of the plants, occurs. Low-temperature

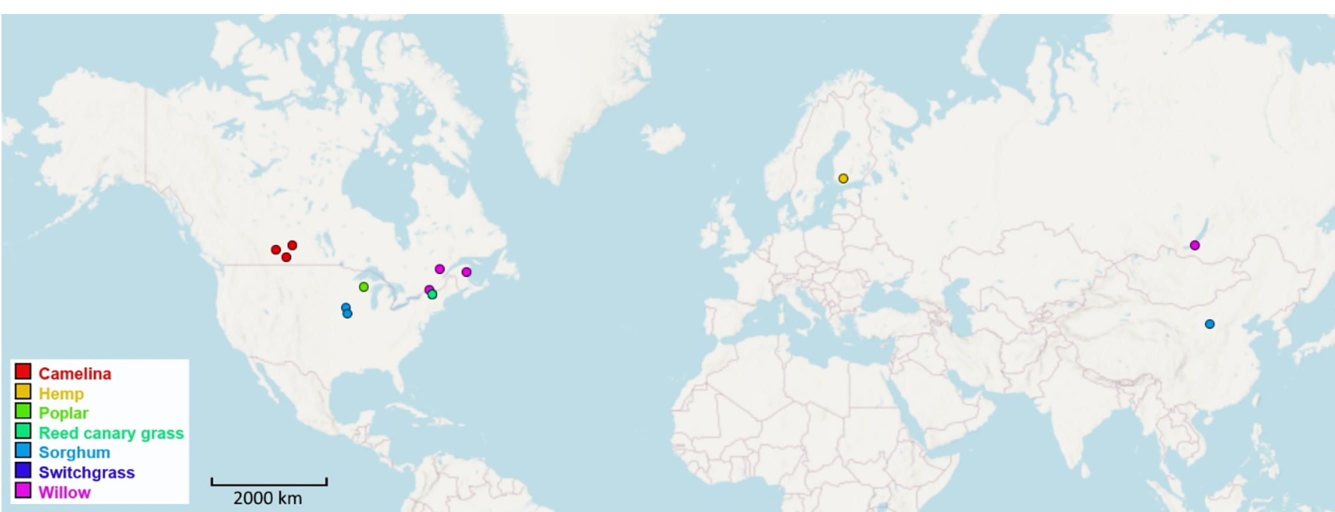

Figure 2. Rough overview of the field trial locations of the papers selected in the literature search conducted in this review. The color of the dots indicates the plant species (in northwestern New York, switchgrass is overlapped by reed canary grass).

Table 2. Overview of average yield performances of the seven crops on marginal agricultural land characterized by low temperature conditions.

Plant	Studies	Other constraints	Average number of vegetation periods	Average above- ground dry matter yield (Mg ha^{-1})	Average seed yield (Mg ha^{-1})	Average stem yield (Mg ha^{-1})	Oil yield (kg ha^{-1})	Nearby City (country)
Camelina	1	DR, UST-CL, UST-S	2.4		1.7		451.4	Saskatoon, swift, current, Oyen (Canada)
Hemp	2	DR,UST-CL, UST-S, UST-ST, LRD	1.6	6.7	0.2	7.0		Jokioinen (Finland)
Poplar	1	DR, UST-CL, UST-S, LRD, SSL	1.6*	7.0				Harshaw (US)
Reed canary grass	1	UST-CL, UST-S, UST-ST, LRD	3.8	4.0				New York (US)
Sorghum	2	DR,UST-CL, UST-S	2.6	11.3		23.8		Wushen (China), Ames, Chariton (US)
Switchgrass	1	DR, UST-CL, UST-S, UST-ST, SSL	4.7	11.3				New York (US)
Willow	3	UST-CL, UST-S, UST-ST, SSL	1.3*	7.0				St Simeon, St Lawrence, Saskatoon, Alma, La Morandiere (Canada)

*Mean number of cuts; LT = low temperature, DR = drought, UST = unfavorable soil type (CL = clay, S = sand, ST = stoniness), LRD = low rooting depth, SSL = steep slope.

stress can be caused by frost (temperatures below −1 °C) and cool temperatures (0–18 °C).[13] These types of low temperature stress limit plant growth through their influence on physiological processes such as photosynthesis and foliation, which are regulated by temperature-dependent enzymes.[17,18] This is especially important during the first winter after planting or sowing perennial crops such as *Miscanthus*, where only the best established individuals survive.[19,20] Late spring frost, on the other hand, can be problematic for both annual and perennial industrial crops and should therefore be considered in crop management, e.g. by a later sowing date or the application of fleece in spring.

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Industrial crops yield performances under LT conditions

Camelina

Camelina can be grown as a summer or a winter crop.[38,39] On favorable sites, camelina has an average grain yield of about 1.5 Mg ha^{-1}, usually ranging from 0.9 to 2.2 Mg ha^{-1}[38] but can even reach up to 3 Mg ha^{-1}.[40] The average oil content of the grains is 42%,[40] mostly ranging from 35 to 45%.[38] The thousand grain mass is between 0.8 and 1.8 g.[39] At a favorable location in Austria, an average oil yield of 807 kg ha^{-1}, a grain yield of 1.9 Mg ha^{-1}, and a thousand grain mass of 1.4 g was achieved.[41] The results of a trial in Poland on a fertile site showed a grain yield of 1.7 to 2.2 Mg ha^{-1}, an oil content of 39.3–42.2%, and an oil yield of 690 to 930 kg ha^{-1}.[42] The yield

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Figure 3. Impression of an ongoing field trial on the suitability of *Miscanthus* genotypes for cultivation at a marginal agricultural site in southwest Germany, which is characterized by low temperature and a short vegetation period.

of camelina is mainly influenced by the environment and to a lesser extent by the genotype.[43]

Three marginal agricultural lands with the factor LT were found in Canada. Summer camelina was cultivated on all three sites, which each had a low annual average temperature between 3.3 °C for Saskatoon and 4.1 °C for Swift Current and Oyen. The heat totals of the three sites were also below the limit of 1500 GDD during the vegetation period. The yields at Saskatoon and Swift Current were very close to each other at 1.9 and 1.8 Mg ha^{-1}, whereas the yield at Oyen was slightly lower at 1.3 Mg ha^{-1}. Compared with the average yield of 1.5 Mg ha^{-1} on favored sites[38] these were higher in Saskatoon and Swift Current and slightly lower in Oyen. The oil content of 42% (Saskatoon and Swift Current) and 45% (Oyen) was also in the range of that on favored sites.[38,40] Similarly, oil yields on fields in Saskatoon and Swift Current, at 798 and 756 kg ha^{-1} respectively, were similar to those obtained from a favorable location assessed by Vollmann *et al.*[41] These results confirm findings of von Cossel *et al.*[36] who indicate a good suitability for Camelina cultivation at 0–5 °C. Camelina has a short growing period of 85–120 days depending on the location.[38,43–45] This characteristic makes it ideal for marginal agricultural lands with LT, where the growing season does not exceed 180 days. Camelina is also well suited to these locations due to its high tolerance to frost, cool weather, and climate.[38,45,46] Winter camelina can survive frost down to −20 °C.[47] The seedlings of the summer camelina are also frost-resistant and can survive several frost periods in spring.[45] All these factors make camelina suitable for cultivation on marginal agricultural lands with LT.

Hemp

On favored sites, fiber hemp achieves a stalk yield of 10 Mg ha^{-1} DM.[48] Struik *et al.*[49] investigated five different varieties of hemp grown for fiber on three favored sites in Europe (Italy, the UK, and the Netherlands) over 3 years with different fertilization and plant density variants. A maximum above-ground biomass yield of 22.5 Mg ha^{-1} DM and a stalk yield of 18.5 Mg ha^{-1} DM was achieved. The average above-ground biomass yield over all locations, years, varieties and trial variants was 14 Mg ha^{-1} DM and the stalk yield 11 Mg ha^{-1} DM.

Three different locations in Finland characterized by LT were found on which monoecious and dioecious varieties were grown. Each of these locations was also characterized by sandy, silty, or heavy clay. The average yields of all sites were lower than those of favored sites.[49] At the silty site, the dioica variety achieved a yield of 9.9 Mg ha^{-1} DM. This yield is only slightly below the yield on favored sites. The

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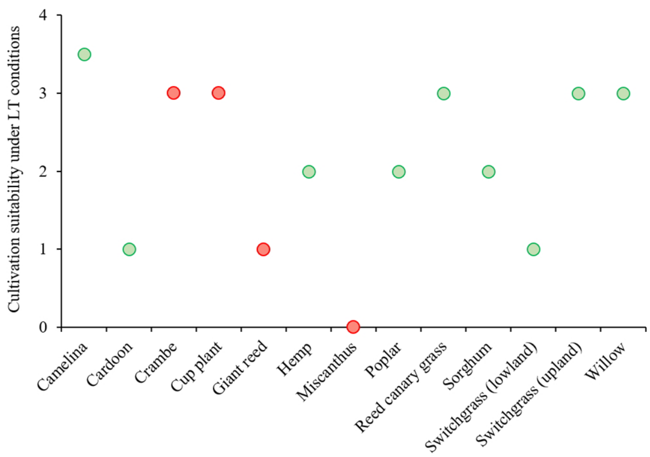

Figure 4. Classification of cultivation suitability of the 12 crops under LT based on field trial results (green dots) or assumptions derived upon associated literature (red dots) e.g. Ramirez-Almeyda *et al*.[22] because no field trial data were found. The ranking values are as follows: 4 = very good suitability for cultivation (much higher yield than the one achieved on favored sites); 3 = good suitability for cultivation (yields of the sites approximately equivalent to average yields on favored sites); 2 = moderate suitability for cultivation (lower yield compared to average yields on favored sites); 1 = poor suitability for cultivation (much lower yields compared to the average yields on favored sites); 0 = unsuitable (cannot grow on sites with the corresponding agricultural marginality constraint). Here, 14 sites in ten papers were found and used to assess the suitability of the respective crop for LT conditions with field trial data.

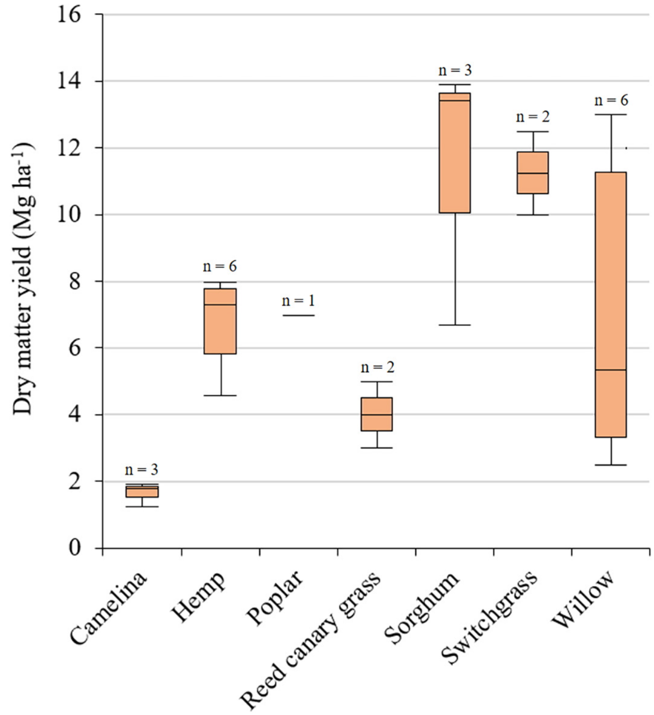

Figure 5. Overview of the average annual aboveground dry matter yields (minimum, first quartile (Q1), median, third quartile (Q3), and maximum) under marginality constraint 'low temperature' of those of the selected crops which were found to be most suitable (suitability rank ≥3) ('n' denotes the number of yield values). For camelina, the seed yield is shown.

yields of the dioecious varieties were higher than those of the monoecious varieties on all three sites (on average 7.8 Mg ha^{-1} DM compared to 5.7 Mg ha^{-1} DM). The yield span for the dioecious varieties was also much smaller (0.6 Mg ha^{-1} DM) whereas the for the monoecious varieties the yield range covered 2.5 Mg ha^{-1} DM.

If a variety adapted to the southern European climate is grown in northern Europe, short growing seasons and frosts at the beginning and end of summer can restrict plant growth. The northern limit for hemp production in Europe is 64 to 65 °N.[50] Hemp is generally considered a frost-sensitive plant,[50] but there are exceptions for the early growth stage. Hemp survives frost down to −5 °C until the four-to-five paired leaf stage but does not grow under these conditions.[48] Hemp only starts to grow at a temperature of at least 1 °C.[35] Despite climatic restrictions on growth, large areas of hemp cultivation in the last century have shown that the production of good-quality hemp is also possible under northern conditions[50] where especially dioecious varieties provide higher and more stable yields. Hemp requires a growing season of at least 90 days and a heat sum of at least 1400 GDD.[23] Fiber hemp needs about 110–115 days and a heat sum of 1900–2000 GDD until harvest.[48] The length of the vegetation period of hemp grown for fiber, matches that of sites that are marginal due to their short vegetation period (limit ≤180 days). Hemp grown for fiber grows best between 19 and 25 °C.[48] The results show that hemp can be suitable for cultivation on marginal agricultural lands with LT, provided that appropriate varieties are selected.

Poplar

On average, the poplar yield is in the range of 7–10 Mg ha^{-1} DM.[51] Berendonk *et al*.[52] indicates that a yield of 8–12 Mg ha^{-1} DM can be expected for short-rotation plantations. On a favorable location in Mira in northern Italy, a yield of 20 Mg ha^{-1} DM in the second rotation and 15 Mg ha^{-1} DM in the first rotation was achieved.[53]

One site in northern Wisconsin was found in the study review that meets the criteria for LT as it has only 100 frost-free days. Genotype NC-9922, *Populus deltoides* var. Angulata × *Populus trichocarpa* was grown on this site and harvested after 5 years. A yield of 7 Mg ha^{-1} DM was achieved and a survival rate of 77% was determined.[54] This yield is slightly below that reported by Berendonk *et al.*[52] and corresponds to only half the yield of the first rotation in Mira.[53] According to von Cossel *et al.*,[36] poplar requires a growing season of at least 180 days. The results from northern Wisconsin show that a shorter growing season is also sufficient for cultivation, but that yield and biomass losses are to be expected. Poplar has a high tolerance to cold,[13] it can grow at temperatures of 0 °C and survives temperatures as low as −20 °C.[22,23] *Populus deltoides* ssp. monilifera survives even temperatures down to −70 °C.[55] However, annual average temperatures of 8.5 to 17 °C are optimal for poplar.[53] Overall, it can be assumed that the suitability for cultivation on sites with LT is mediocre.

Reed canary grass

Reed canary grass achieves biomass yields of 5–13 Mg ha^{-1} DM.[56–58] On four different favored sites in the Czech Republic it achieved an average yield of 8 Mg ha^{-1} DM (yields of 3.9 to 13.8 Mg ha^{-1} DM were measured) from the second to the sixth year of cultivation.[59]

Two sites were found that meet the LT criteria. The use of NPK fertilization resulted in higher yields on these sites, with the sandy site achieving at 9 Mg ha^{-1} DM (compared to 3 Mg ha^{-1} DM without fertilization) and the clay site 11 Mg ha^{-1} DM (compared to 6 Mg ha^{-1} DM without fertilization).[60] Without fertilization, the yields are markedly lower than on favored sites.

Reed canary grass can grow well on sites with LT, as it is native to northern Europe[56] and can therefore produce high biomass yields in cool climates.[57,61–63] It requires a minimum growing season of 111 days and grows at temperatures of 5–30 °C. It has mediocre growing conditions in locations with winter temperatures below −20 °C.[22,23]

Sorghum

In a meta-analysis by Laurent *et al.*,[51] average sorghum yields were found to be in the range of 14–19.5 Mg ha^{-1} DM. Under favorable conditions, sorghum has above-ground biomass yields of 15–20 Mg ha^{-1} DM.[64] For example, on a favored site in Cadriano, Italy, fiber and sweet sorghum yielded an average of 20.8 Mg ha^{-1} DM.[65]

Three sites were identified that met the criteria of the agricultural marginality constraint LT; two of them were located in the US (Ames and Chariton) and one was located in China (Wushen). The Chariton site has 165 frost-free days, Ames 160, and Wushen 120–160, so the length of the vegetation period of all three sites is less than the favorable 180 days. The yields in Ames (13.4 Mg ha^{-1} DM) and in Chariton (13.9 Mg ha^{-1} DM) are slightly below those on favored sites. The yield of Wushen of 6.7 Mg ha^{-1} DM is significantly lower.[64] Wushen also meets the marginality constraints of drought and sandy soil, which is probably why the yield achieved was significantly lower. Confalonieri *et al.*[66] highlight that drought and sandy soil texture lead to a negative synergy, thereby worsening the site's marginality and imposing more challenging conditions for crop cultivation.

As indicated by the results from Ames and Chariton, sorghum can be grown in locations with a short growing season due to its short growing cycle of approximately 100 days from sowing to harvest.[67] The reduced length of the growing season is closely linked with the average temperatures during this period. As sorghum is very sensitive to frost, cold damage can occur at temperatures below 4 °C.[33] Cold weather in early spring can therefore have a significant impact on plant growth, leading to considerable yield losses.[68,69] Consequently, a minimum soil temperature of 10–15 °C is important when sowing,[64,70] whereas the optimum air temperature for sorghum is 30 °C.[33] Sorghum therefore has a medium suitability for locations with a short growing season.

Switchgrass

Laurent *et al.*[51] investigated switchgrass yields, which on average are in the range of 7–12 Mg ha^{-1} DM. In Europe, switchgrass yields range from 5–23 Mg ha^{-1} DM.[56] According to Parrish and Fike,[71] switchgrass produces yields of about 15 Mg ha^{-1} DM on favored sites over a longer period of time, while, according to Panacea,[72] switchgrass gives yields of 10–25 Mg ha^{-1} DM on these sites.

Two sites in the USA with the factor LT were found; both also show limited drainage. One of the sites was characterized by high sand content and the other one by a high clay content in the soil. On both sites the variety Cave-in-Rock (Upland) was cultivated. The yield was 10 Mg ha^{-1} DM on the sandy site and 12.5 Mg ha^{-1} DM on the clay site. With NPK fertilization, higher yields were produced on both sites: on sandy fields 12.5 and 14.5 Mg ha^{-1} DM on fields with the increased clay content in the soil.[60] These yields are very similar to those on favored sites.[72] Switchgrass grows at temperatures of 6–35 °C and survives temperatures of −10 to −20 °C.[22,23] This plant requires a growing season of at least 140 days.[23] When sowing, soil temperatures should be around 15 °C.[72] Quinn *et al.*[13] indicate that switchgrass has a moderate cold tolerance. Parenti *et al.*[9] confirm a good cultivation suitability on sites with LT. The upland ecotype is more adapted to northern latitudes and lowland to southern latitudes. The latter has a rather poor winter survival rate at low temperatures.[73]

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Table 3. Comparison of willow yields ($Mg\,ha^{-1}\,year.^{-1}$) on different Canadian sites.

Site	St Simeon	La Moradiere (clay)	Alma (clay)	St Lawrence (clay)	St Lawrence (sand)	Saskatoon (clay)
Average temperature (°C)	4.8	1.5	3.7	6.4	6.4	2.0
pH	5.24	5.55	7.96	6.7	5.75	—
Yield ($Mg\,ha^{-1}$ DM)	4.0	2.5	13	12.8	6.7	3.1

The upland varieties Cave-in-Rock and Sunbrust are better adapted to locations in north-western Europe.[74] Lowland varieties can be grown in northern Europe, but have particular difficulties surviving the winter in the year of establishment.[74] Nevertheless, switchgrass varieties of the upland ecotype are well suited for cultivation in locations with LT. Lowland varieties are less suitable for cultivation there.

Willow

A systematic literature search and meta-analysis indicates that half of all willow yield data are in the range of 8–13 $Mg\,ha^{-1}$ DM.[51] On short-rotation plantations according to Berendonk *et al.*,[52] a yield of 8–12 $Mg\,ha^{-1}$ DM is expected. Under optimal conditions willow can achieve yields of 20–30 $Mg\,ha^{-1}$ DM.[75] On a favored site in Poland, willow produced an average yield of 13.7 $Mg\,ha^{-1}$ DM and a maximum yield of 16 $Mg\,ha^{-1}$ DM.[8]

Six locations in Canada were identified for willow cultivation under LT conditions (Tables 2 and 3). Four of these locations are also characterized by a high clay content in the soil and a fifth site has a sandy soil (Table 3).

St Simeon exclusively fulfills the criteria of factor LT. Its annual average temperature is 4.8 °C. There, five different willow varieties achieved an average yield of 4 $Mg\,ha^{-1}$ DM. This yield is significantly lower compared to yields on favored sites.[52] In La Moradiere (clay), a site with a very low average annual temperature of 1.5 °C, five different willow varieties achieved a low yield of 2.5 $Mg\,ha^{-1}$ DM. The two sites La Moradiere (clay) and St Simeon have very low pH values of 5.24 and 5.55. Lafleur *et al.*[76] could demonstrate that the yield of willow is positively correlated with the pH of the soil, the annual average temperature, and the average temperature within the growing season, explaining the low yields in St Simeon and La Moradiere (clay).

The Alma site with a soil pH of 7.96 and an average annual temperature of 3.7 °C was also investigated by Lafleur *et al.*[76] There the highest yield of 13 $Mg\,ha^{-1}$ DM was achieved, which is slightly above the yield in Berendonk *et al.*[52] indicating that the soil pH is more determining for the cultivation of willow than the low temperature.

The yield of 12.8 $Mg\,ha^{-1}$ DM achieved in St Lawrence (clay) is also slightly higher than that in Berendonk *et al.*[52] This yield increased to 23.5 Mg DM ha^{-1} with a fertilization of 100 $kg\,N\,ha^{-1}$.[77] St Lawrence (clay) has 182 frost-free days, just like the St Lawrence (sand) site. On St Lawrence (sand), willow achieved a yield of 6.7 $Mg\,ha^{-1}$ DM, which is roughly half of the yield obtained at the clay prawn site at the same location.

The trial on the Saskatoon site (clay) produced an average yield of 3.1 Mg DM ha^{-1} (3.7 $Mg\,ha^{-1}$ DM in the first rotation, 2.7 $Mg\,ha^{-1}$ DM in the second rotation) over two rotations and 30 grazing varieties. This site has a growing season of 112 days and an average annual temperature of 2 °C. The annual precipitation of 375 mm in the experimental period was also significantly lower than at the other locations (average 770 mm). The survival rate here was 80% on average, as some varieties showed a high mortality rate over the winter. In the second rotation on fields in Saskatoon (clay) the Taberg, Tully Champion, and Otisco varieties were the most productive, with a yield of 6.4–7.1 $Mg\,ha^{-1}$ DM. All three varieties were derived from *Salix viminalis* × *miyabeana*.[78,79] Overall, the lower yield in Saskatoon in comparison with the other Canadian sites characterized by clay soil might be due to the reduced precipitation and the lower amount of only 112 frost-free days.[78,79]

According to von Cossel *et al.*,[36] willow requires a growing season of at least 180 days. The Saskatoon site shows that, depending on the variety, a shorter vegetation period may result in yield losses. Willow can grow at temperatures of 0–30 °C according to Ramirez-Almeyda *et al.*[22] and has a high frost and cold tolerance.[13,75] *Salix matsudana* 'Navajo,' in particular, is extremely resistant to cold.[80] The northern willow species *Salix sieboldiana* can survive temperatures as low as −50 °C. Other species also survive down to −30 °C.[81] Overall, it can be assumed that willow is well suited for cultivation in locations with LT, especially on soil with an almost neutral pH level.

Conclusions

For a sustainable bioeconomy, industrial crops should mainly be grown on marginal agricultural land to avoid land-use conflicts with food crop cultivation or biodiversity conservation. However, different marginality constraints

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require different solutions with the best crop selection being a major task. This study sheds light on reliable data regarding the yield performance of dedicated industrial crops under the LT marginality constraint. Camelina, upland switchgrass, reed canary grass, and willow were found to be suitable for European marginal agricultural land characterized by LT. Furthermore, reed canary grass and switchgrass can also cope with six other marginality constraints. This high adaptability renders them most suitable for upscaling because LT often comes along with other marginality constraints. There is also the possibility that cup plant and crambe are well suited for cultivation on such sites as indicated by their short vegetation period and frost resistance. However, as no suitable field study data were found, this could not be proven within this review. Further investigations and a broader analysis of the growth conditions of cup plant and crambe are required to obtain insight into potential reasons for the absence of field trial data of these presumably well suitable crops.

It was also found that there are strong variations in yield performance both between and within the selected industrial crops. This can be explained, for example, by the large site and year effects between the studies and by the low number of studies (1–20) per crop that included clear details on both the constraint's marginality thresholds and the dry matter yield of the crop(s).

Another important point is that marginality constraints not only influence biomass quantity but also biomass quality. In this study, the influence of marginality constraints on biomass quality is not presented because too little data were found. Here, too, it is evident how limited the data basis for large-scale implementation of industrial crops appears to be. The uncertainty resulting from this fragmentary data situation represents one of the greatest challenges to large-scale implementation of marginal agricultural land low-input systems for industrial crop cultivation across European agricultural areas prone to low temperature, especially in the context of climate change.

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Data availability statement

Data sets for this research are included in the references.

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Jana Reinhardt

Jana Reinhardt obtained her MSc in agricultural sciences from the University of Hohenheim in 2020. She received a bachelor's degree in geoecology at the Technical University of Freiberg (Saxony) in 2016. This interdisciplinary course of study is focused on environmental problems. For her thesis she specialized in the effects of organic acid on the mobility of germanium in soil and uptake in *Phalaris arundinacea* L. Her areas of interest include marginal agricultural land, industrial crops, interdisciplinary cooperation, soil protection, and geoinformation systems.

Pia Hilgert

Pia Hilgert is currently pursuing her master's degree in bioeconomy at the University of Hohenheim. She obtained a BA in international management from the University of Flensburg in 2018, specializing in Hispanic culture and business. During several internships she gained experience in corporate controlling, international development cooperation, and knowledge management. Her areas of interest include the circular economy, biodiversity conservation, and social transformation.

Moritz von Cossel

Moritz von Cossel studied at Kiel University where he obtained a bachelor's degree (2010) and a master's degree (2012) in agricultural sciences. He then joined the chair of Biobased Resources in the Bioeconomy at the University of Hohenheim where he received his doctorate in agricultural sciences in 2019. He is currently engaged in research on improving the long-term socio-ecological sustainability of land-based biomass production, in addition to his teaching at the University of Hohenheim. His research interests include agroecological intensification, biobased products, bioeconomy, bioenergy, climate change adaptation, ecosystem services, farming concepts, intercropping, perennial crops, permanent grassland, precision farming, and wild plant species.