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RESEARCH ARTICLE

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Towards identifying industrial crop types and associated agronomies to improve biomass production from marginal lands in Europe

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Abstract
Growing industrial crops on marginal lands has been proposed as a strategy to minimize competition for arable land and food production. In the present study, eight experimental sites in three different climatic zones in Europe (Mediterranean, Atlantic and Continental), seven advanced industrial crop species [giant reed (two clones), miscanthus (*M.* × *giganteus* and two new seed-based hybrids), saccharum (one clones), switchgrass (one variety), tall wheatgrass (one variety), industrial hemp (three varieties) and willow (eleven clones)], and six marginality factors alone or in combination (dryness, unfavorable texture, stoniness, shallow soil, topsoil acidity, heavy metal and metalloid contamination) were investigated. At each site, biophysical constraints and low-input management

practices were combined with prevailing climatic conditions. The relative yield of a site-specific low-input system compared with the site-specific control was from small to large (i.e. from −99% in industrial hemp in the Mediterranean to +210% in willow in the Continental zone), due to the genotype-by-management interaction along with climatic variation between growing seasons. Genotype selection and improved knowledge on crop response to changing environmental, site-specific biophysical constraint and input application has been detected as key to profitably grow industrial crops on marginal areas. This study may act to provide hints on how to scale up investigated cropping systems, through low-input practices, under similar environmental and soil conditions tested at each site. However, further attention to detail on the agronomy of early plant development and management in larger multi-year and multi-location field studies with commercially scalable agronomies are needed to validate yield performances, and thereby to inform on the best industrial crop options.

KEYWORDS

biomass crops, biophysical constraints, contaminated land, farming systems, iLUC-risk, less favored areas, relative yield

1 | INTRODUCTION

Lower-grade agricultural lands, often known as marginal lands, affect crop productivity to a different extent; nonetheless, growth in global population, in food consumption and in feedstock demand for non-food purposes has increased the pressure on prime quality lands, lighting up the concept of marginal and contaminated lands to the scientific and policy interest in the last couple of decades (Evangelou et al., 2015; Mellor et al., 2021). Von Cossel et al. (2019a), reported a marginal area affected by natural constraints across European land surface of 646,833 km^2, while Gerwin et al. (2018) quantified 380,000 km^2 of marginal lands for biomass production in Europe using soil-quality indicators. Furthermore, it has been estimated that 137,000 km^2 of EU agricultural land is contaminated by at least one heavy metal and/or metalloid (HM&M) in concentrations above the guideline value set for agricultural soils (Tóth et al., 2016). This land has to be remediated before re-using for food production to protect human health and the environment. Previous works have demonstrated that several non-food industrial crops have the ability to accumulate HM&M in their aerial biomass contributing to the removal of the toxic elements from the soil (Barbosa et al., 2016; Fernando et al., 2016; Galić et al., 2019; Guo et al., 2019; Luyckx et al., 2021; Nsanganwimana et al., 2014; Witters et al., 2009).

The idea to use industrial crops on marginal and contaminated lands is basically a response to growing concerns about possible food shortages due to land use changes, in combination with the fact that industrial crops are less demanding and more tolerant to adverse climatic and edaphic conditions (Dauber et al., 2012; Gelfand et al., 2013; Gerwin et al., 2018; Qaseem & Wu, 2021). Moreover, these crops in marginal and contaminated lands also offer ecological advantages, such as restoration of soil and water properties and improvement of the biological and landscape diversity (Fernando et al., 2018; Gomes et al., 2022). In addition, industrial crops are able to contribute, even when productivity is low, to the reduction of greenhouse gases and fossil energy savings (Barbosa et al., 2018; Schmidt et al., 2015). Therefore, the cultivation of these crops in marginal/contaminated soils is a win-win process: helps to safeguard the boosted competition for land and the economical exploitation of the produced biomass may bring an additional income to farmers. Nevertheless, it is obvious that the degree of land marginality with reference to a specific industrial crop has a time and space dimension; hence, any criteria used for its identification may change over time (Teuling, 2018), can be influenced by different policy and market forces, including the demand for biomass from industrial crops and also by other agricultural land-uses in the area (Soldatos, 2015).

Therefore, as lands can be marginal from different perspectives, classifying it by means of agronomic criteria would be less sensitive to misunderstandings. The Regulation (EU) 2013 (1305/2013) defined eight biophysical criteria for the delimitation of areas facing natural constraints subjected to payments if land management should be continued to conserve or improve the environment.

Later, the expert panel of the Joint Research Center (JRC) further developed threshold values with a 20% margin in accordance to the agronomic Liebig's law of the minimum, providing a summary of the sub-severe thresholds and pair-wise combinations of criteria that result in a negative synergy (Rossiter et al., 2014). Obviously, any on-site biophysical constraint interact with genotype and environmental conditions, which may exacerbate negative synergies on crop growth and yield (Confalonieri et al., 2014). Therefore, a careful selection of genotype and management strategies suitable to environmental conditions and biophysical constraints (including land contamination), should be envisaged to cope with and/or to overcome yield gaps (Von Cossel et al., 2019a). This is particularly true when low-input practices are set to reduce pressure on natural resources so as to minimize GHG emissions and environmental burdens associated to the cultivation phase (Wagner & Lewandowski, 2017). Unfortunately, there are not specific procedures to correctly apply low-input practices, since levels of production means will greatly change depending on soil type, climate, crop and biophysical constraints, along with farm infrastructure, knowledge and resources availability (Von Cossel et al., 2019b). In the frame of the H2020-MAGIC project (www.magic-h2020.eu), low-input practices are defined as a part of agricultural management systems for sustainable crop production on marginal land. This approach focuses on achieving high output through selection of appropriate crop type or development of new varieties. It takes into account the prevailing marginality constraints and agronomic practices that contribute towards developing farm economy for a specific climatic zone by fulfilling optimal crop requirements and enhancing environmental and ecological services (Von Cossel et al., 2019a).

Gaining knowledge on crop response to a combination of reduced input supply under growing limiting conditions would be a win-win solution that satisfies both the stakeholders (farmers, entrepreneurs, etc.) and the society (due to rural development and low environmental impacts). However, reliable information is still scattered and not well organized to date because many experimental trials usually deal with different definitions of marginal lands and levels of agronomic input (Reinhardt et al., 2021a); hence, comparison among crops and expected results is often questionable. Therefore, the present study aims to present the large group of data obtained in the framework of the MAGIC project, to bring an advancement to knowledge on the suitability of certain industrial crops to marginal and contaminated soils, helping to clarify the constraints associated with their cultivation under low-input practices. In addition, the results obtained will provide hints on how the cultivation of these crops in marginal soils can mitigate indirect land-use change (I-LUC) risks, in accordance with the sustainability criteria laid down in Article 29 of the Directive (EU) 2018/2001 and to meet the European Green Deal towards an EU climate neutral in 2050. To this end, six different sites across Europe presenting different biophysical limitations in accordance with the report of the JRC (Rossiter et al., 2014) and two contaminated sites were investigated to grow industrial crops under low-input cultivation system. Biomass production from field experiments was calculated as relative yield to give equal weight to each site and to allow an easy comprehension of the genotype-by-management-(by environment) structure (Yau & Hamblin, 1994). Ultimately, this can assist to make general recommendations of the most appropriate crop and management options at the different regions, climates, soils and marginal land types.

2 | MATERIALS AND METHODS

Low-input agricultural practices were applied to advanced industrial crops (herbaceous annual, herbaceous perennial and woody species) grown in eight replicated experimental trials across Europe. European countries were grouped, according to the European climatic stratification proposed by Metzger et al. (2005), in three main agro-ecological zone: Mediterranean, Atlantic and Continental (Figure 1). In each zone, experimental field trials were carried out, with the main aim to ascertain the feasibility to grow industrial crops in sites affected by biophysical limitations by applying low-input agricultural practices. Biophysical limitations are essentially those reported in the JRC study (Rossiter et al., 2014), which alone or in combination leads to negative synergies to crop yield. Heavy metal (Cd, Ni, Cu, Pb and Zn) and metalloid (As and Sb) contaminated lands alone or in combination with biophysical limitations are also investigated since not suitable to food production. Low-input practices applied to industrial crops at each experimental site are summarized in Table 1.

2.1 | Mediterranean agro-ecological zone

In this agro-ecological zone, field trials were established at the experimental farms of the: University of Catania (Italy), Centre for the Development of Renewable Energies (Spain), Centre for Renewable Energy Sources and Saving (Greece) and Agricultural University of Athens (Greece).

2.1.1 | Perennial grasses on dryness combined with unfavorable texture

The field trial was carried out at the Experimental Farm of the University of Catania (Italy, 37°24’N, 15°03’E, 10 m a.s.l.) under the following conditions:

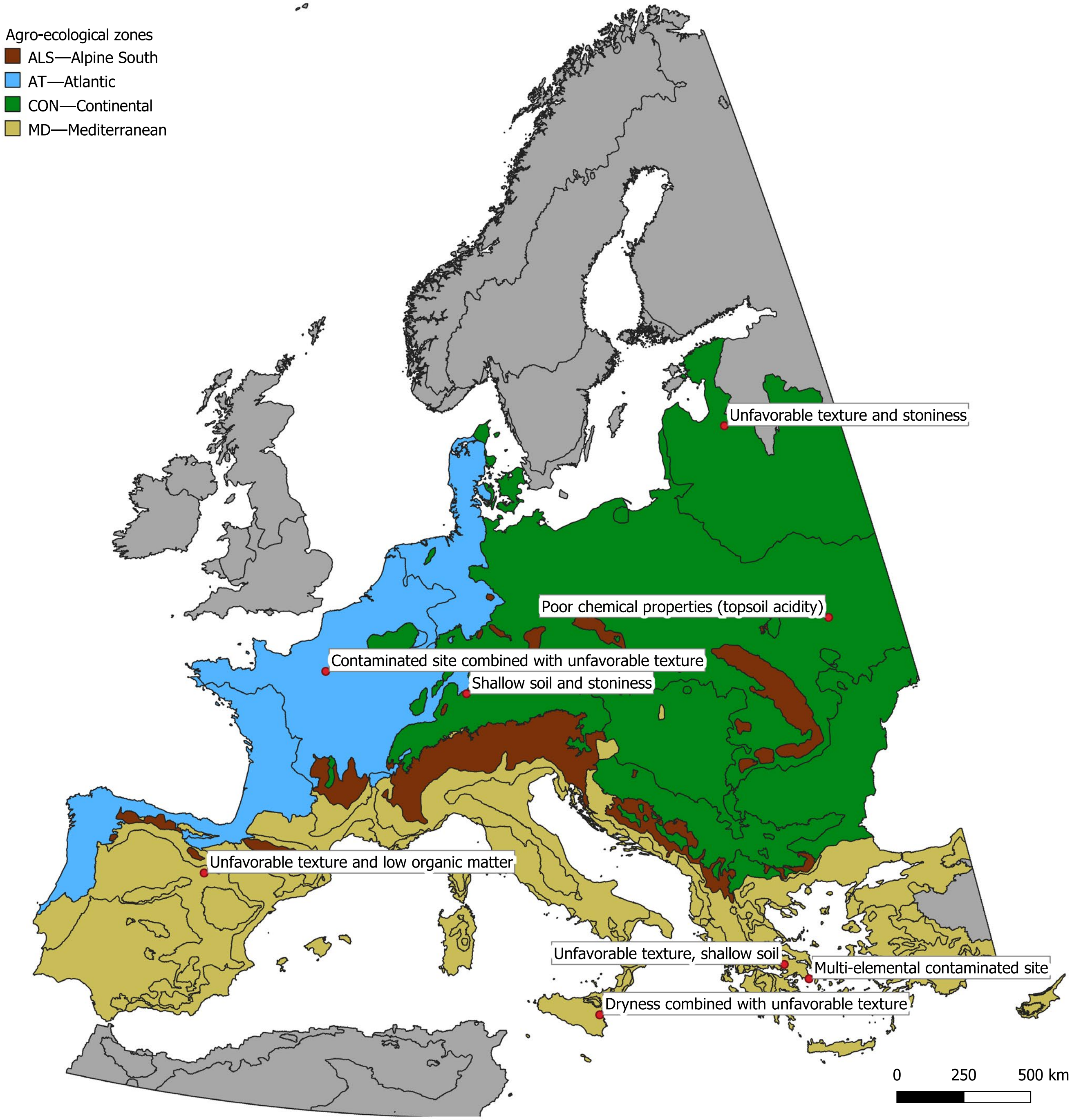

FIGURE 1 Distribution of field trials across agro-ecological zones in Europe and biophysical constraint/s at each site. Mediterranean zone includes South and North Mediterranean; Atlantic zone includes Lusitanian, Central and North Atlantic; Continental zone includes Pannonia, Continental and Nemoral (Metzger et al., 2005). Grey areas are outside the boundaries of this study

- Biophysical constraint: averaged ten-year dryness index of the site 0.48, calculated as the ratio of annual total precipitation over annual total potential evapotranspiration (threshold for marginal conditions: ≤0.6). Unfavorable texture, 55.9% sand as relative abundance within 100 cm surface layer (threshold for marginal conditions: 40%).
- Soil conditions: 11.8% silt, 55.9% sand, 32.3% clay, 1.4% organic matter, 1.4 g kg^{-1} total N, 46.1 mg kg^{-1} available P, 293.3 mg kg^{-1} exchangeable K and pH 7.6. The bulk density was 1.1 g cm^{-3}. The soil moisture contents at field capacity (at −0.03 MPa) and nominal wilting point (at −1.5 MPa) were 27 and 11 g H_2O 100 g^{-1} dry weight, respectively.

TABLE 1 Site description in the three agro-ecological zones (AEZ), marginality factor, industrial crop and low-input agricultural practices

AEZ	Geographic position	Marginality factor	Industrial crop	Agricultural practices
Mediterranean	Italy (37°24′N, 15°03′E, 10 m a.s.l.)	Dryness and unfavourable texture	*Arundo donax* L., *Miscanthus* spp., *Saccharum spontaneum* L. spp. *aegyptiacum* Willd. Hackel	Minimum tillage, no fertilization, no weed and pest control, reduced irrigation
	Spain (41°36′N, 2°30′W, 1100 m a.s.l.)	Unfavourable texture and low organic matter	*Thinopyrum ponticum* (Podp.)	Minimum tillage, rainfed, reduced fertilization
	Greece (38°22′N, 23°06′E, 102 m a.s.l.)	Unfavourable texture and shallow soil	*Cannabis sativa* L.	Minimum tillage, reduced fertilization, reduced irrigation
	Greece (37°43′N, 24°02′′E, 5 m a.s.l.)	Multi-elemental contaminated soil and unfavourable texture	*Cannabis sativa* L.	No weed control, no fertilization, reduced fertilization
Atlantic	France (48°57′N, 2°02′E, 43 m a.s.l.)	Contaminated site and unfavourable texture	*Miscanthus* x *giganteus* Greef et Deuter	Minimum tillage, bio-fertilization
Continental	Germany (48°28′N, 9°18′E, 708 m a.s.l.)	Shallow soil and unfavourable texture	*Cannabis sativa* L.	Reduced fertilization (mineral)
	Ukraine (49°34′N, 28°22′E, 234 m a.s.l.)	Poor chemical properties (topsoil acidity)	*Panicum virgatum* L.	Soil amendments, reduced fertilization (organic)
	Latvia (56°41′N, 25°08′E, 87 m a.s.l.)	Unfavourable texture	*Salix* spp.	Reduced fertilization (mineral and organic)

- Experimental design: split-plot design, with irrigation as main-plot and species as sub-plot. Species were randomly distributed and replicated three times within the main-plot.
- Irrigation: the volume was determined on the basis of the maximum available soil water content in the first 60 cm of soil, according to Cosentino et al. (2014), in three levels of maximum evapotranspiration restoration (ETm): I100 (100% ETm), I50 (50% ETm), and I0 (rainfed condition). Irrigation water was supplied in the summer months (beginning of June to the end of August) when the sum of daily evapotranspiration corresponded to the volume.
- Crop: six perennial grasses, namely ARCT (local clone of *Arundo donax*), ARMO (clone of *Arundo donax* from Morocco), SAC (local clone of *Saccharum spontaneum* spp. *aegyptiacum*), M × G (clone of *Miscanthus* × giganteus), GNT9 (seed-based hybrid of *Miscanthus*), GNT10 (seed-based hybrid of *Miscanthus*).
- Low-input practices: at the establishment a minimum tillage (25 cm depth), under no-fertilization was employed. Weeding was carried out by means of a grass trimmer only at the establishment year when necessary. Each species was transplanted on May 2018 at a density of one plant per square meter, in a single plot of 16 m^2. The irrigation was differentiated from the second growing season; therefore, only two productive years are reported here (the second and the third, 2019/20 and 2020/21, respectively).
- Measurements: aboveground biomass dry matter yield was determined each year at the end of the growing season (approximately end of January), from measurements of the fresh weight of whole plants cut 5 cm above ground level. Border plants were removed and a sampling area of 4 m^2 at the center of each plot was harvested. Representative wet sub-samples were placed in plastic zip bags and weighed and then dried to a constant weight at 65°C to determine the subsample dry weight.

2.1.2 | Perennial grass on unfavorable texture

The field trial was carried out at the Experimental Farm of Centre for the Development of Renewable Energies (Spain, 41º36′N, 2º30′W, 1100 m a.s.l.) under the following conditions:

- Biophysical constraint: unfavorable texture, 84% sand as relative abundance within 100 cm surface layer (threshold for marginal conditions: 40%) and low organic matter.
- Soil conditions: 10% silt, 84% sand, 6% clay, 0.69% organic matter, 0.06 g kg^{-1} total N, 10.25 mg kg^{-1} available P.

- Experimental design: Randomized block design with three inorganic N fertilization levels: 0, 50, 80 kg ha^{-1} yr^{-1}. Plots were randomly distributed and replicated four times. A single plot measured 150 m^2.
- Crop: Tall wheatgrass [*Thinopyrum ponticum* (Podp.)] var Alkar.
- Low-input practices: Soil-bed was prepared according to the minimum tillage practice, and sowing was performed at seed dose of 21.5 kg ha^{-1} in October 2018. Nitrogen fertilization was applied by a complex fertilized NPK (8-24-8) at 300 kg ha^{-1} as base fertilization at the establishment year. Each growing season in the spring, N fertilization levels at 0, 50 and 80 kg ha^{-1} were distributed. A mechanical weed control between plots was done when necessary, and plots were maintained in rainfed conditions throughout the three experimental years.
- Measurements: biomass yield of each plot was harvested and baled in August each year. Then all straw bales were weighed to determinate the fresh weight. Cutting height was done at 7 cm above ground level. Dry matter content was determined by drying representative wet subsamples in a stove at 60ºC until constant weight.

2.1.3 | Industrial hemp on unfavorable texture and shallow soil

The field trial was carried out at the Experimental Farm of the Centre for Renewable Energy Sources and Saving (Greece, 38°22'N, 23°06'E, 102 m a.s.l.) under the following conditions:

- Biophysical constraint: unfavorable texture, 63% sand as relative abundance within 100 cm surface layer (threshold for marginal conditions: 40%) and relatively shallow soil, 50 cm (threshold for marginal conditions: <35 cm).
- Soil conditions: 63% sand, 12% clay, 25% loam with organic matter content of 0.5% and pH 8.0. Below 50 cm soil layer, the texture is predominantly sandy.
- Experimental design: randomized block design replicated three times. Experimental factors included the irrigation in three levels: 400, 200 and 100 mm (I3, I2 and I1, respectively); two industrial hemp (*Cannabis sativa* L.) varieties: Futura 75 and Futura 83; three inorganic N fertilization levels: 0, 30 and 60 kg ha^{-1} (N0, N1 and N2, respectively).
- Low-input practices: The trial was established on 22 April 2021. Before sowing a basic fertilization was applied (200 kg ha^{-1} NPK, 11-15-15). The distances between rows were 70 cm and within the rows were 5 cm. The N application at the N2, N1 and N0 doses were applied through the drip irrigation around 30 days from emergence. Irrigation was provided throughout the cropping season to restore 100% (I3), 50% (I2) and 25% (I1) of maximum evapotranspiration. Weeds were controlled manually when necessary.
- Measurements: The harvest was done on 20 September 2021. At the harvesting time plants within 1 square meter in each plot were cut at 5 cm above the soil surface. The fresh weight of the biomass was measured, and representative subsamples were immediately weighted, placed in paper bags and dried at 65°C till constant weight, to determine the dry matter weight. The biomass dry matter yield (stems + leaves) is reported.

2.1.4 | Industrial hemp on heavy metal and metalloid contaminated soil

The field trial was carried out at the Experimental Farm of the Agricultural University of Athens (Greece, 37°43'59"N, 24°02'40"E, 5 m a.s.l.) under the following conditions:

- Biophysical constraint: long term heavily contaminated soil with Cd, Ni, Cu, Pb, Zn, Sb and As. Unfavorable texture, 47.5% sand as relative abundance within 100 cm surface layer (threshold for marginal conditions: 40%).
- Soil condition: 29.9% silt, 47.5% sand, 22.6% clay, 2.08% organic matter, 1.4 g kg^{-1} total N, 12.1 mg kg^{-1} available P, 330 mg kg^{-1} exchangeable K, 7.4 pH, 51.30 µS cm^{-1} electrical conductivity, 19.6% equal carbonate. Total and DTPA extractable concentrations of heavy metals and metalloids were up to: 25 and 8 mg kg^{-1} for Cd, 182 and 1 mg kg^{-1} for Ni, 138 and 8.8 mg kg^{-1} for Cu, 10797 and 846 mg kg^{-1} for Pb, 4959 and 301 mg kg^{-1} for Zn, 92 and <0.5 mg kg^{-1} for Sb and 590 and 0.7 mg kg^{-1} for As, respectively.
- Experimental design: split-plot design, with two hemp varieties as main-plot and irrigation level as sub-plot. Treatments were randomly distributed and replicated three times within the main plot.
- Irrigation: three irrigation levels were tested based on the potential evapotranspiration (ETP), namely I0 (rainfed condition, 194.0 mm), I50 (50% ETP, 506.5 mm) and I100 (100% ETP, 819.0 mm). Irrigation water was supplied from the sowing (beginning of May) till the end of August through a drip irrigation system.
- Crop: two industrial hemp (*Cannabis sativa* L.) varieties (Futura 75 and Futura 83).
- Low-input practices: Herbicides were not used neither before sowing nor during the growing cycle, and weeds were controlled manually when necessary. Fertilization was not applied, apart from a basic before sowing by a complex fertilizer NPK 16-20-0 and 0-0-30 in quantities of 350 kg ha^{-1} and 300 kg ha^{-1}, respectively.
- Measurements: at harvest, all plants per plot were cut at

5 cm above the soil surface. The fresh weight of the whole plant, as well as stems and inflorescences separately, was measured. Thereafter, representative subsamples were weighted, placed in paper bags and dried at 65°C till constant weight to determine the dry matter weight.

2.2 | Atlantic agro-ecological zone

In this agro-ecological zone, the field trial was carried out at an experimental site located in a peri-urban area near Paris (France, 48°57’N, 2°02’E, 43 m a.s.l.) and followed by the French National Institute of Agricultural and Environment Research (France), under the following conditions:

- Biophysical constraint: unfavorable texture, 75% sand as relative abundance within 100 cm surface layer (threshold for marginal conditions: 40%) and multi-contamination by metals after one century of raw wastewater irrigation on market garden soils (mean 570 mg kg^{-1} for Zn, 159 mg kg^{-1} for Cu, 4.3 mg kg^{-1} for Cd and 335 mg kg^{-1} for Pb).
- Soil conditions: 75% sand, 17% silt, 8% clay, 4% organic matter, 24.6 g kg^{-1} organic carbon, 1.6 g kg^{-1} total N and pH 7.5. Cation-exchange capacity is 7.4 cmol kg^{-1}, and field capacity is 26.6 g H_2O 100 g^{-1} dry soil weight.
- Experimental design: randomized block design where two conditions were defined: crop + earthworm inoculations and crop without earthworm inoculation (control). Each condition was performed in three replicates in random selected 1 m^2 parts of the site; therefore, a total of 12 squares were followed over the experiment.
- Crops: two different lignocellulosic crops were studied: miscanthus (*Miscanthus* × giganteus Greef et Deuter) and switchgrass (*Panicum virgatum* L.). Rhizomes of miscanthus were transplanted 50 cm in the row and 60 cm apart (4 rhizomes m^{-2}), while switchgrass was sown at the same density with 10 seeds each time.
- Low-input practices: weed control was carried out only at the beginning of the experiment, to ensure the identification of each square used for the inoculation process; subsequently, another weeding was performed by hand. The trial was irrigated the first year (2019) during four months in summer, then no more water was supplied. No other inputs were provided. Bio-fertilization was carried out by introducing a hundred of earthworms (2/3 endogeic with *Apporectodea caliginosa* and 1/3 anecic with *Lumbricus terrestris*) in each specific quadrat surrounded by a geotextile.
- Measurements: establishment of earthworm's population was followed the second year and the third year after plant establishment (abundance, biomass and diversity in the two favorable seasons of earthworm activity). *M.* × *giganteus* biomass was harvested in October 2020 (second year) and August 2021 (third year). Representative subsamples were weighted, placed in paper bags and dried at 65°C till constant weight to determine the dry matter weight. Switchgrass did not grow in the first year up to June and germinated plantlets were re-transplanted in August. However, this second tentative resulted in an establishment failure; therefore, this crop is not mentioned in the results.

2.3 | Continental agro-ecological zone

In this agro-ecological zone, field trials were carried out at the Experimental farms of the: Universitaet Hohenheim (Germany), Institute of Bioenergy Crops and Sugar Beet National Academy of Agrarian Sciences of Ukraine (Ukraine) and Latvian State Forest Research Institute (Latvia).

2.3.1 | Industrial hemp on shallow soil and stoniness

The field trial was carried out at the experimental farm “Oberer Lindenhof” of the Universitaet Hohenheim (Germany, 48°28′15.2″N, 9°18′06.1″E, 708 m a.s.l.) under the following conditions:

- Biophysical constraints: shallow soil, 26 cm top soil depth above hard rock layer (threshold for marginal conditions: <35 cm); stoniness, 19.6% of topsoil volume is coarse material and rock outcrop (threshold for marginal conditions: >15%).
- Soil condition: 33.0% silt, 8.8% sand, 38.6% clay, 19.6% coarse material and rock outcrop, 49.8 kg ha^{-1} total mineral N (NO_3 and NH_4), pH 7.3.
- Experimental design: completely randomized design with three replications.
- Crop: industrial hemp (*Cannabis sativa* L.) variety Markant (Vandinter Semo B.V., Scheemda, The Netherlands).
- Low-input practices: N fertilization in two levels, (i) control (120 kg N ha^{-1}) and (ii) low input (40 kg N ha^{-1}); sowing density in two levels, (i) high sowing density (20 kg ha^{-1}, or 112.2 seeds m^{-2}, with row distance of 15 cm between rows) and (ii) low sowing density (6.7 kg ha^{-1}, or 37.4 seeds m^{-2}, with row distance of 45 cm between rows). The experiment was performed for two subsequent growing seasons, 2019 and 2020, respectively.

- Measurements: at harvest, plants were cut 5 cm above the soil surface in a sample area of 0.6 m^2 per plot. The fresh weight of the whole plant, as well as separately of the stem, leaves and seeds was measured. For stem and leaves, representative subsamples were weighted, placed in perforated plastic bags and dried at 60°C till constant weight to determine the biomass dry matter content. The seeds were dried at room temperature and weighted up to constant weight.

2.3.2 | Switchgrass on acid soil

The field trial was carried out at the Uladivka-Liulyntsi Experimental Breeding Station of the Institute of Bioenergy Crops and Sugar Beet National Academy of Agrarian Sciences of Ukraine (Ukraine, 49°34'30.7"N, 28°22'39.5"E, 234 m a.s.l.) under the following conditions:

- Biophysical constraint: topsoil acidity, pH 5.1 (threshold for marginal conditions: topsoil pH ≤ 5.5).
- Soil conditions: leached mid-loamy chernozem with SOM content (soil layer 0–30 cm) of 3.9%, pH 5.1, nitrogen (NO_3-N 16.4 mg kg^{-1}, NH_4-N 38.7 mg kg^{-1}), available phosphorus (8.3 mg kg^{-1}) and exchangeable calcium (10.3 mg kg^{-1}).
- Experimental design: randomized block design with three replications, in a single plot area of 35 m^2.
- Crop: switchgrass (*Panicum virgatum* L.) variety 'Morozko', established in 2018.
- Low-input practices: (i) Soil amendment with lime (400 kg ha^{-1}). Lime was applied in the 0–10 cm soil layer 2 weeks before sowing; (ii) hydrogel (150 kg ha^{-1}) was applied (in rows) in the 0–10 cm soil layer two weeks before sowing; (iii) foliar application of organic fertiliser Quantum-Humate (potassium humates, 750 g kg^{-1}) at a dose of 1 kg ha^{-1} alone or combined with Active Harvest Macro 1 L ha^{-1} (amino acids 30%, organic substances 18%, N 5%, P_2O_5 2%, K_2O 4%) at the tillering stage and repeated after 2 weeks. Control conditions (neither lime, nor hydrogel, nor Quantum-Humate alone or combined with Active Harvest Macro).
- Measurements: two subsequent productive years following the establishment of aboveground biomass dry matter yield, determined each year at the end of the growing season (November–December), from measurements of the fresh weight of whole plants cut 5 cm above ground level in a sampling area of 25 m^2. Representative wet sub-samples were placed in plastic zip bags and weighed, and then dried to a constant weight at 65°C to determine the subsample dry weight.

2.3.3 | Willow on stoniness soil

The field trial was carried out at the Experimental Farm of Latvian State Forest Research Institute (Latvia, 56°41'N, 25°08'E, 87 m a.s.l.) under the following conditions:

- Biophysical constraint: high stoniness with small, mostly medium, rarely large stones with 10% volume of coarse material (threshold: ≥10% of topsoil volume).
- Soil conditions: Phaeozems/Stagnosols with a dominant loam (at 0–20 cm depth) and sandy loam (at 20–80 cm depth) soil texture. The content of carbon (C) in soil arable layer was 23 g kg^{-1}, pH 6.1, available P_2O_5 277.1 mg kg^{-1} and exchangeable K_2O 136.8 mg kg^{-1}.
- Experimental design: willow (*Salix* spp.) plant material was collected in an experimental demo field located in the central part of Latvia (56°41'N, 25°08'E) established in the spring 2011, nearby Skrīveri. In the plantation eleven different willow clones (Monika&Visvaldis, S. viminalis, Gudrun, Inger, Klara, Lisa, S. purpurea, Stina, Sven, Swerini, Tora) were planted in a randomized block design three times replicated. Plantation density was 13,000 trees ha^{-1}, planted in double rows, where distance between double rows was 1.5 m and between single rows in double row 0.75 m.
- Low-input practices: willow clones were grown under different fertilization: no fertilization (control), fertilization with wood ash (6 Mg DM ha^{-1}) and sewage sludge (10 Mg DM ha^{-1}), and biomass of willow clones from different stem age was measured and compared. All clones were planted at the same time and biomass was measured for 3-, 4- and 5-year-old stems. Three-year old stems mean that roots are five-year old, while stems grew for 3 years because cutback was done in the first and second growth year. The same for 4-year old stems, but the cutback was done only in the first growth year. Five-year old stems are grown from beginning, and no cutback was done.
- Measurements: stems were cut with motor chainsaw in the spring, when willow stems had no leaves. Biomass measurement was done in double rows in each plot, where row segments of 7.2 meters' length and 2.2 m width were measured and stems weighed. From all stems, that were cut down in one segment, samples for moisture measurement was randomly taken from three different stems from top, middle and bottom part of the stem. The oven-dried biomass was obtained by drying wet-biomass samples at 65°C until constant weight.

2.4 | Statistical analysis

Aboveground dry matter yield data from each experimental trial were calculated as percentage of the inverse relative yield, according to:

$$Y_i = -\left[100 - \left(\frac{\mu_{ln}}{\mu_{cn}}\right) \times 100\right]$$

Y_i = inverse relative yield of ecotype i (in percentage); μ_{ln} = mean biomass production of ecotype i in low-input conditions (g DM m^{-2}) at growing season n; μ_{cn} = mean biomass production of ecotype i in the control condition (g DM m^{-2}) at growing season n.

Data were analyzed according to the experimental design in each site. When assumptions for the analysis of variance (ANOVA) were satisfied, data were analyzed by one, two or three-way ANOVA according to the fixed factor effects used in each experiment. Replications was considered a random effect, while the growing season, when represented a within-subject effect, was tested for sphericity through the Mauchly's test for multiyear trials involving perennial crops grown on the same plot, or as random effect for multiyear trials involving annual crops. Means were then compared for significance using the Tukey test at 95% confidence level with percentage values previously arcsin√% transformed (Minitab, LLC, Statistical Software, Pennsylvania, USA).

Relative yield is displayed by the box-and-whisker diagram to divide the frequency distributions of low-input practices over the control through the median (50th percentile), the first quartile (Q1, 25th percentile), the third quartile (Q3, 75th percentile), the interquartile range (IQR = Q3–Q1), whiskers and outliers. The Pearson's second coefficient of skewness (Sk_2) was calculated to assess data distribution within each site (Doane & Seward, 2011):

$$Sk_2 = \frac{3\,(\mu i - \text{mi})}{\text{si}}$$

where μ_i, m_i and s_i are the mean, the median and standard deviation of the sample i, respectively. If the Sk_2 is within ±0.5 the data are fairly symmetrical, between ±0.5 and ±1.0 the data are moderately skewed, less than −1 or greater than +1 the data are highly skewed.

3 | RESULTS

To account for differences in experimental field trial set-up, crop type and agronomic practices, results are analyzed exclusively by site and comparison of the crop performance is carried out only within site. Data on actual yield of the control condition are reported for each site as g DM m^{-2}. Crop performance was thus assessed through the relative yield of the low-input system against the control condition.

3.1 | Mediterranean agro-ecological zone

3.1.1 | Perennial grasses on dryness combined with unfavorable texture

The experimental area in southern Italy was affected by seasonal precipitation variability, which ratio to the potential evapotranspiration led to a dryness index of 0.37 and 0.62 in the second and third growing season, respectively, namely the seasons after the establishment year when irrigation differentiation started. Mean biomass production of the second and third growing season of giant reed (ACRT, ARMO), saccharum (SAC) and miscanthus (GNT9, GNT10 and M × G) grown in full water restoration (I100) was 3220 ± 320, 3590 ± 170, 3270 ± 430, 1610 ± 190, 1790 ± 90 and 1290 ± 220 g DM m^{-2} yr^{-1}, respectively. Relative yield was significantly affected by irrigation and species main effects and their interaction ($p \leq 0.05$). Pooled data of two growing seasons of rainfed (I0) and mid water restoration (I50) in contrast to the full watering are shown in Figure 2. The least significant reduction was observed in SAC when irrigated at I50 (mean value −17.5%), while the significantly highest in M × G under I0 (mean value −67.2%). Median values were always lower in I0 than in I50. In I0, the median value with the lowest relative yield reduction was observed in the GNT10 (−38.9%), while the highest in the M × G (−68.4%). In I50, the median value with the lowest relative yield reduction was in the SAC (−14.2%) and the highest in the GNT9 (−32.1%). Data distribution was quite symmetric in GNT10 in I0 and I50, M × G in I0 and I50, ARCT and ARMO in I50, and SAC in I50 ($Sk_2 \leq \pm 0.5$). High negative skewness was found in data distribution of ARCT in I0 (Sk_2 −1.14), whereas data were moderately skewed in SAC in I0 (Sk_2 −0.75) and GNT9 in both I0 and in I50 (Sk_2 0.83 and 0.86, respectively). The greatest interquartile range (IQR), showing the largest data distribution was in ARCT in I50 (40.6%) followed by the GNT10 in I50 (35.3%), while distribution of observed data had a quite high level of agreement in most genotypes in I0, namely GNT9 (14.3%), M × G (16.5%), SAC (17.9%), ACRT (18.0%), as well as in SAC and in ARMO in I50 (15.6 and 20.2%, respectively). The overall highest data variability considering also the whiskers was in ARMO and SAC in I0, and in ARCT, ARMO, M × G and GNT10 in I50.

3.1.2 | Perennial grass on unfavorable texture

The experimental area in northern Spain was marginal due to the soil texture with 84% relative abundance of sand and low organic matter. Mean biomass production of the first, second and third growing season of tall wheatgrass unfertilized was 6000 ± 350 g DM m^{-2} yr^{-1}. Relative yield of tall wheatgrass was significantly affected by the nitrogen (N) fertilization main effect ($p \leq 0.05$). Pooled data of three growing seasons indicated that N fertilization significantly improved the relative yield by an average of 43.8% at the highest dose of 80 kg N ha^{-1} yr^{-1} as compared with the unfertilized control but of only 9.9% at the medium dose of 50 kg N ha^{-1} yr^{-1} (Figure 3). The median value was lower in 50 kg N ha^{-1} yr^{-1} (+14.4%) than to the 80 kg N ha^{-1} yr^{-1} in contrast to the control (+42.6%). This latter showed the highest overall data distribution (IQR of 67.0% and whiskers from −12.5% to +121.8%) and a fairly symmetric distribution (Sk_2 0.29). A moderate positive skewness was observed in the N dose of 50 kg N ha^{-1} yr^{-1} (Sk_2 0.68) although distribution of observed data had a lower IQR (30.0%) than the 80 kg N ha^{-1} yr^{-1}. Outliers were very similar to the extreme whisker values in both N fertilization levels.

3.1.3 | Industrial hemp on sandy, shallow soil

The experimental area in south-central Greece was marginal due a 63% sandy textured and relatively shallow soil (50 cm). Biomass production (stems + leaves) of industrial hemp varieties grown in full water restoration (I3, 400 mm) and the highest nitrogen dose (N2, 60 kg N ha^{-1}) was 2030 ± 110 and 3100 ± 90 g DM m^{-2} in Futura 75 and Futura 83, respectively. Relative yield was affected by the water regimes, by the nitrogen dose and by the variety, as well as by the interaction of main effects ($p \leq 0.05$). In Figure 4, the interaction of experimental factors evidenced the significantly highest and similar relative yield mean in Futura 75 at any combination of irrigation and nitrogen dose (relative yield from −2.0% and −3.4% in I2N2 and I3N1 to −15.1% in I2N0 as compared with the highest input combination), except for the I1N0 (−21.5%). In Futura 83, the relative yield mean was maximized at the highest irrigation levels, irrespective of the nitrogen dose (−1.8% and −3.9% in I3N1 and I3N0, respectively). Irrigation water provided at 50% or 25% (I2 and I1) of full watering significantly reduced the relative yield mean in Futura 83 (from −33.5% in I2N2 to −49.0% in I1N0). However, Futura 83 was more stable than Futura 75 under changing irrigation and nitrogen fertilization doses as evidenced by the IQR, which were always higher in Futura 75, meaning that data were more variable between the 25th and 75th percentile (IQR from 22.30% in I1N1 to 7.54% in I1N0). The IQR in Futura 83 ranged from 7.16% in I3N1 to 1.22% in I2N2. In Futura 75, data were highly and negatively skewed in I1N2 (Sk_2 −1.37) and I1N0 (Sk_2 −1.72). Data were moderately and positively skewed in I2N0 (Sk_2 0.67) and I3N2 (Sk_2 0.98), while moderately and negatively skewed in I3N0 (Sk_2 −0.90). Remaining irrigation by nitrogen dose combinations had either a positive or a negative fairly symmetrical distribution ($Sk_2 \leq \pm 0.5$).

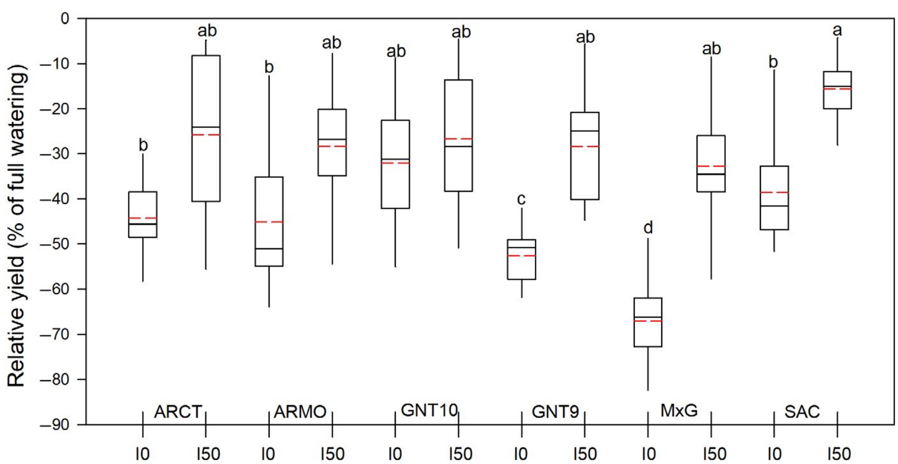

FIGURE 2 Perennial grasses on dryness and unfavorable texture in Italy for two growing seasons (2019/20 and 2020/21) after the establishment. Relative yield (%, $n = 6$) of ARCT (local clone of *Arundo donax*), ARMO (clone of *Arundo donax* from Morocco), SAC (clone of *Saccharum spontaneum* spp. *aegyptiacum*), M × G (clone of *Miscanthus* × giganteus), GNT9 (seed-based hybrid of *Miscanthus*), GNT10 (seed-based hybrid of *Miscanthus*) under rainfed (I0) and mid watering (I50) in contrast to full watering. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \leq 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1). Least significant difference of genotype × irrigation interaction per $p \leq 0.05$ (15.82)

In Futura 83, data were fairly symmetrical in I2N1 (Sk_2 0.35), while moderately and positively skewed in I2N0 (Sk_2 0.87) and I1N1 (Sk_2 0.67). A high and positive skewness was observed in I3N1 (Sk_2 1.07), I1N2 (Sk_2 1.09), and I1N0 (Sk_2 1.18), whereas I3N0 and I2N2 had a high and negative Sk_2 (−1.17 and −1.27, respectively).

3.1.4 | Industrial hemp on heavy metal and metalloid contaminated soil

The experimental area in southern Greece was marginal due to long-term soil contamination with heavy metals and metalloids (i.e. Cd, Ni, Cu, Pb, Zn, Sb and As) in a 47.5% sandy textured soil. Biomass production of industrial hemp Futura 75 and Futura 83 grown in full water restoration was 540 ± 10 and 880 ± 120 g DM m^{-2}, respectively. Relative yield was affected by the water regimes and by the variety, as well as by the interaction of both main effects ($p \leq 0.05$). Irrigation water provided at 50% of evapotranspiration restoration (I50) mitigated yield decrease to an average of −13.3% in Futura 75 in contrast to the full watering (Figure 5). The yields of Futura 83 were more severely affected, and such reduction was −50.2%. Relative yield decreased nearly 99% in both varieties in rainfed conditions (I0) as compared with the full water restoration. Furthermore, median values, whiskers and IQR were very similar between the two hemp varieties in I0, although a moderate positive skewness was observed in Futura 75 (Sk_2 0.87). On the contrary, in I50, Futura 75 had the highest median value (−14.1%) and symmetry of data (Sk_2 0.49, IQR of 14.1% and whiskers from −18.5% to −7.4%) as compared with Futura 83, which showed the highest overall data distribution and skewness (Sk_2 −1.23, IQR of 42.4% and whiskers from −67.8% to −25.4%).

3.2 | Atlantic agro-ecological zone

3.2.1 | Bio-fertilization of miscanthus on contaminated sandy textured soil

The experimental area in northern France was marginal due sandy textured soil of 75% and multi-contamination by heavy metals (mean of Zn = 570 mg kg^{-1}, Cu = 159 mg kg^{-1}, Cd = 4.3 mg kg^{-1} and Pb = 335 mg kg^{-1}). Biomass production of miscanthus unfertilized was 110 ± 30 in the second and 130 ± 70 g DM m^{-2} in the third growing season. Biofertilization through earthworms (2/3 endogeic with *Apporectodea caliginosa* and 1/3 anecic with *Lumbricus terrestris*) significantly improved the biomass yield as compared with the unfertilized control ($p \leq 0.05$). However, the biofertilization was ineffective after one year from the inoculation (relative yield mean −6.2%) but it was outstanding the subsequent growing season (relative yield mean 95.6%). Relative yield (Figure 6) not only changed mean values between growing seasons but also data distribution (IQR of 25.4% and 164.5% in the second and third year, respectively). In the second year, the median value was also lower than the third (2.3% and 60.7%, respectively), data were positively skewed (Sk_2 1.80) and more variable among the least negative quartile group (Q1 of −20.25% and lower whisker −29.9%). In the third year, data were negatively skewed (Sk_2 −1.19) and more variable among the upper positive quartile group (Q3 of 182.9 and upper whisker 235.4%).

3.3 | Continental agro-ecological zone

3.3.1 | Industrial hemp on shallow soil and stoniness

The experimental area in southern Germany was marginal due shallow soil, 26 cm top soil depth above hard rock layer and stoniness, 19.6% of topsoil volume is coarse material and rock outcrop. The average annual hemp biomass dry matter yield of two growing seasons at the high N dose (120 kg N ha^{-1}) was 1130 ± 8.0 g DM m^{-2} yr^{-1} in the 15 cm row distance (R15) and 740 ± 18.5 g DM m^{-2} yr^{-1} in the 45 cm row distance (R45). The average annual hemp seed yield was 262 ± 4.0 and 208 ± 3.5 g DM m^{-2} in R15 and R45, respectively. Relative biomass and seed yield under reduced N fertilization (40 kg N ha^{-1} yr^{-1}) in contrast to high N fertilization (120 kg N ha^{-1} yr^{-1}) of industrial hemp was significantly affected by the row distance main effect ($p \leq 0.05$). Although actual biomass and seed yield of industrial hemp was higher by reducing the row width from R45 to R15, pooled data of two growing seasons indicated that R45 significantly improved the relative yield of biomass (mean value −6.4%) and seed (−14.1%) as compared with the R15 (−21.7% and −25.4% for biomass and seed, respectively) (Figure 7). The median values were also higher in R45 than R15 in both biomass (20.2% vs −5.7%) and seed (−17.9% vs −25.8%). Data distribution was fairly symmetric in all combination ($Sk_2 < \pm 0.5$). However, the largest overall data distribution (IQR of 31.9% and whiskers from −25.8% to +17.6%) was observed in the relative yield of biomass in R45. The IQR in the relative yield of seed was very similar between row distance (8.8% and 8.4% in R15 and R45, respectively); however, the longer upper whisker in R45 suggests that data were more variable among the most positive quartile group; conversely, distribution of observed data had a quite high level of agreement in the relative yield of seed in R15.

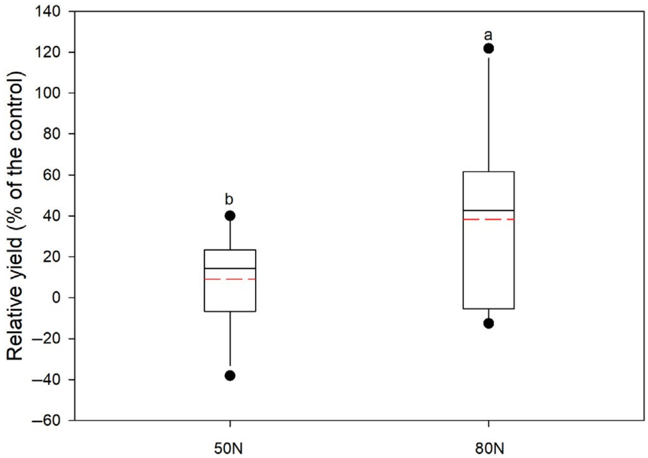

FIGURE 3 Perennial grass on unfavorable texture and low organic matter in Spain for three growing seasons (2018/19, 2019/20 and 2020/21). Relative yield (%, $n = 12$) of tall wheatgrass (*Thinopyrum ponticum*) under mid nitrogen fertilization level (50 kg N ha^{-1} $year^{-1}$) and high nitrogen fertilization level (80 kg N ha^{-1} $year^{-1}$) in contrast to the unfertilized control. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \le 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), vertical black solid lines the whiskers, and solid black circles the outliers. Interquartile range (IQR = Q3–Q1)

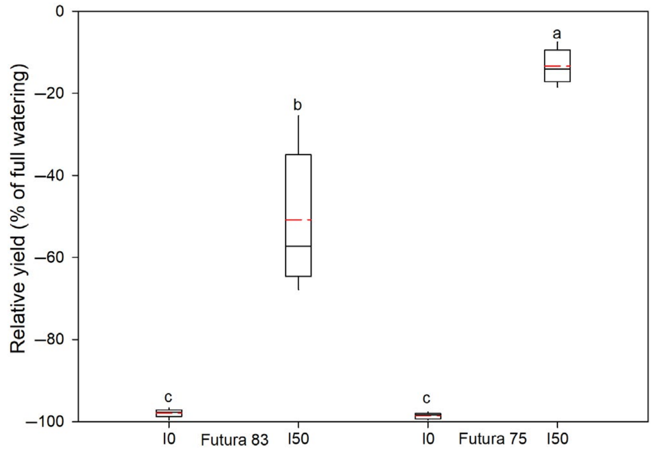

FIGURE 5 Industrial hemp on heavy metal and metalloid contaminated soil in Greece for one growing season (2021). Relative yield (%, $n = 3$) of Futura 75 and Futura 83 under rainfed (I0) and mid watering (I50) in contrast to full watering. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \le 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1). Least significant difference of genotype × irrigation interaction per $p \le 0.05$ (18.08)

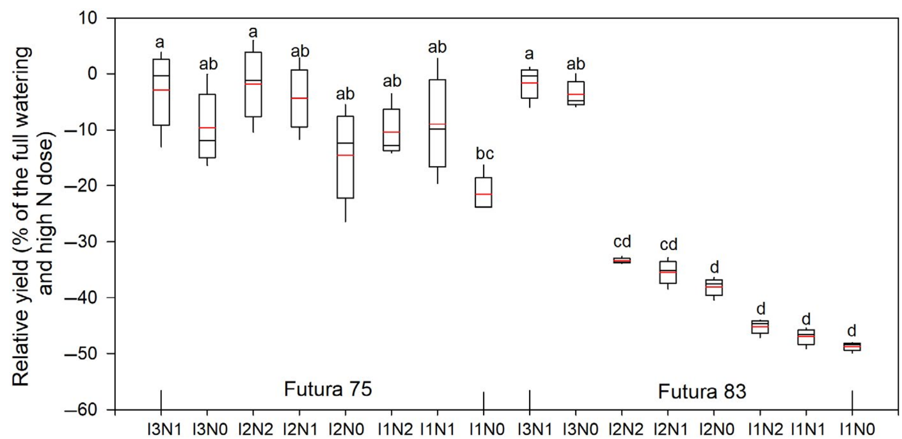

FIGURE 4 Industrial hemp on unfavorable texture and shallow soil in Greece for one growing season (2021). Relative yield (%, $n = 3$) of Futura 75 and Futura 83 under high, mid and no-nitrogen fertilization level (N2, N1 and N0, respectively) and irrigation levels (I3, I2 and I1, respectively) in contrast to the full watering and highest N dose (I3N2). Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \le 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1). Least significant difference of genotype × irrigation × nitrogen per $p \le 0.05$ (8.97)

3.3.2 | Switchgrass in areas with acid soil

The experimental area in central Ukraine was marginal due to soil acidity (pH 5.1). Mean biomass production of the second and third growing season of switchgrass in control conditions was 460 ± 130 g DM m^{-2} yr^{-1}. Relative biomass yield of switchgrass was significantly affected by the amendment/fertilization treatments applied in contrast to the unfertilized control ($p \le 0.05$). Pooled data of two growing seasons of experimental factors showed different relative yield means between the significantly highest quantum-humate application (QH, 18.6%) and the significantly lowest lime application (L, 1.5%). Other combinations were neither different from the highest nor the lowest relative yield mean (Figure 8). A quite high level of agreement in the relative yield was found in the combination of hydrogel and quantum-humate +active harvest macro (HGQH+), quantum-humate alone (QH), quantum-humate +active harvest macro alone (QH+) and lime and quantum-humate +active harvest macro (LQH+). Other combinations had either a highly negative skewness (Sk_2 −1.59 in LHGQH+, −1.32 in LHGQH and −1.02 in HG) or a positive one (Sk_2 1.01 in LQH). The highest overall data distribution (IQR of 27.7% and whiskers from 3.9% to 37.2%) was observed in the relative yield of QH. On the contrary, the lowest data distribution was in QH+ (IQR of 4.2% and whiskers from 3.1% to 8.8%); however, the longer upper whisker suggested more data variability among the most positive quartile group. The longer lower whisker in the lime treatment alone led to negative relative yield (whisker −5.3%) and data variability among the most negative quartile group (Q1 from −2.4% to +2.5%) compared with the control.

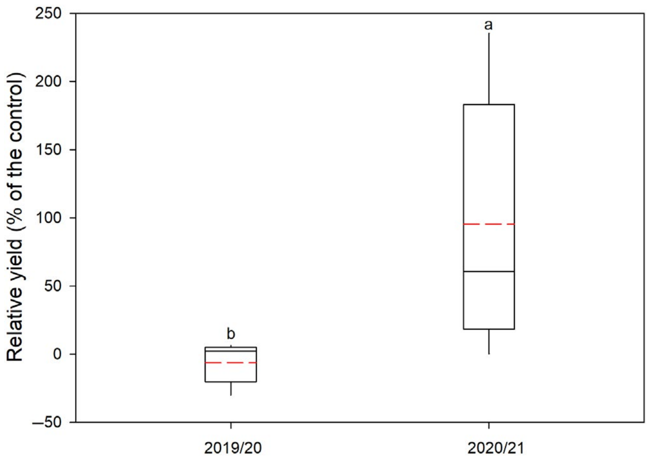

FIGURE 6 Perennial grass on unfavorable texture and multi-contamination by metals site in France for two growing seasons (2019/20 and 2020/21). Relative yield (%, $n = 3$) of miscanthus (*Miscanthus × giganteus*) bio-fertilized with earthworms in contrast to the unfertilized. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \leq 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1)

3.3.3 | Willow in areas with unfavorable soil texture

The experimental area in southern Latvia was marginal due to high stoniness content with small-medium stones with 10% volume of coarse material. Biomass yield of unfertilized willow ranged from 550 ± 190, 660 ± 180 and 810 ± 180 g DM m^{-2} in clone *S. purpurea* at three, four and five-year stem cutting cycle, respectively, to 2270 ± 880, 1970 ± 1060 and 2290 ± 840 g DM m^{-2} yr^{-1} in clone Tora at the same order of stem age. Relative yield of willow was significantly affected by the clone, the fertilizer type, stem age at harvest and their interactions ($p \leq 0.05$). The 11 clones of willow by the fertilizer type by the stem age are displayed in Figure 9. The significantly highest mean value (+210.8%) was in clone Lisa of 5-year stem age and fertilized with sewage sludge compared with the control (SC). The significantly lowest mean (−34.8%) was in clone Swerini of 5-year stem age and fertilized with wood ash as compared with the control (WC). Different responses of data distribution were shown by willow

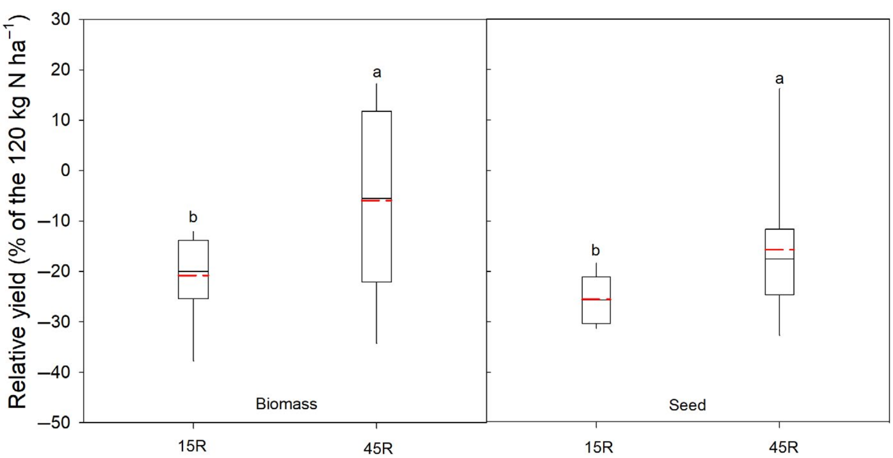

FIGURE 7 Industrial hemp (var. Markant) on shallow soil and stoniness in Germany for two growing seasons (2019 and 2020). Relative yield (%, $n = 6$) of biomass (leaves and stems) and seed under low nitrogen fertilization (40 kg ha^{-1}) in contrast to high nitrogen fertilization (120 kg ha^{-1}), narrow (15R) and wide (45R) row distance. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \leq 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1)

clones and treatments. High level of agreement in relative yield was observed in clone *S. viminalis* at 5-year stem and WC (IQR 11.4% and whiskers from −20.7 to −9.3%) and Monika&Visvaldis at 5-year stem and both WC (IQR 12.1% and whiskers from −4.0 to 8.1%) and SC (IQR 17.6% and whiskers from 83.3 to 100.9%). Data were highly skewed in clone *S. purpurea* at 5-year stem and SC (Sk_2 1.19) and Monika&Visvaldis at 4-year stem and SC (Sk_2 1.01). Remaining clones had from a moderate ($Sk_2 < \pm 1.0$) to a fairly symmetry of data ($Sk_2 < \pm 0.5$). The overall widest distribution in relative yield of willow was in clone Inger at 5-year stem and WC (IQR 150.3% and whiskers from −53.9 to 181.8%) and clone Klara at 5-year stem and WC (IQR 120.2% and whiskers from −49.7 to 233.9%). Wide distribution was also observed in *S. viminalis* at 5-year stem and SC, Inger at 3-year stem and both SC and WC, Stina at 4-year stem and SC, Sven at 3-year and 5-year stem and SC, and in Tora at 5-year stem and SC.

4 | DISCUSSION

In Europe, marginal arable lands due to biophysical constraints account for the 28% of the total agricultural area (Von Cossel et al., 2019a,b). In addition, 6.24% of European agricultural area is somehow affected by high concentrations of soil heavy metal that needs remediation action for a safe food production (Tóth et al., 2016). According to current EU policies (i.e. EU 2018/2001), low-iLUC risk energy crops, which are generally less demanding on natural resources, would comfortably be accommodated on such marginal lands, provided that yield gap is sufficiently offset by significant input reduction or by financial incentives.

Experimental field trials investigated in the present study spanned three different climatic zones in Europe (Mediterranean, Atlantic and Continental) in eight sites, seven advanced industrial crop species [giant reed (two clones), miscanthus (*M.* × *giganteus* and two new seed-based hybrids), saccharum (one clones), switchgrass (one variety), tall wheatgrass (one variety), industrial hemp (three varieties) and willow (eleven clones)] and depending on the site, six marginality factors alone or in combination (dryness, unfavorable texture, stoniness, shallow soil, topsoil acidity, heavy metal contaminated soil). At each site, biophysical constraints and low-input management practices were combined with prevailing climatic conditions and crop requirements.

4.1 | Mediterranean agro-ecological zone

In the Mediterranean environmental zone, the most significant limiting factor is the low rainfall amount and distribution, particularly in the spring-summer growing season, coupled with the high evapotranspiration. Other climatic parameters, such as air temperature, killing frost, active temperature for growth and length of the growing season are quite favorable (Cosentino et al., 2012). Estimated marginal arable lands in the Mediterranean zone account for

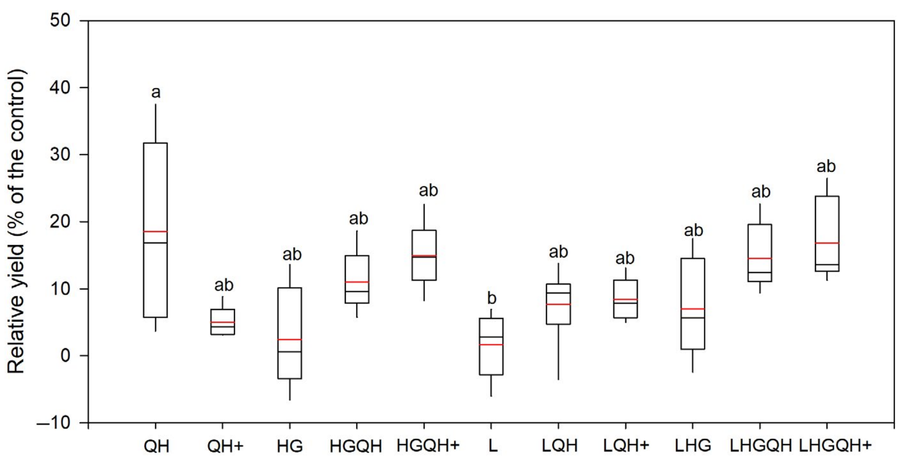

FIGURE 8 Perennial grass on topsoil acidity soil in Ukraine for two growing seasons after the establishment (2019/20 and 2020/21). Relative yield (%, $n = 6$) of switchgrass (*Panicum virgatum*) fertilized with Quantum-Humate (QH), Quantum-Humate + Active Harvest Macro (QH+), Hydrogel (HG), Hydrogel and Quantum-Humate (HGQH), Hydrogel and Quantum-Humate + Active Harvest Macro (HGQH+), Lime (L), Lime and Quantum Humate (LQH), Lime and Quantum-Humate + Active Harvest Macro (LQH+), Lime and Hydrogel (LHG), Lime and Hydrogel and Quantum-Humate (LHGQH), Lime and Hydrogel and Quantum-Humate + Active Harvest Macro (LHGQH+) in contrast to unfertilized control. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \le 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1). Least significant difference of liming × hydrogel × foliar fertilization interaction per $p \le 0.05$ (15.93)

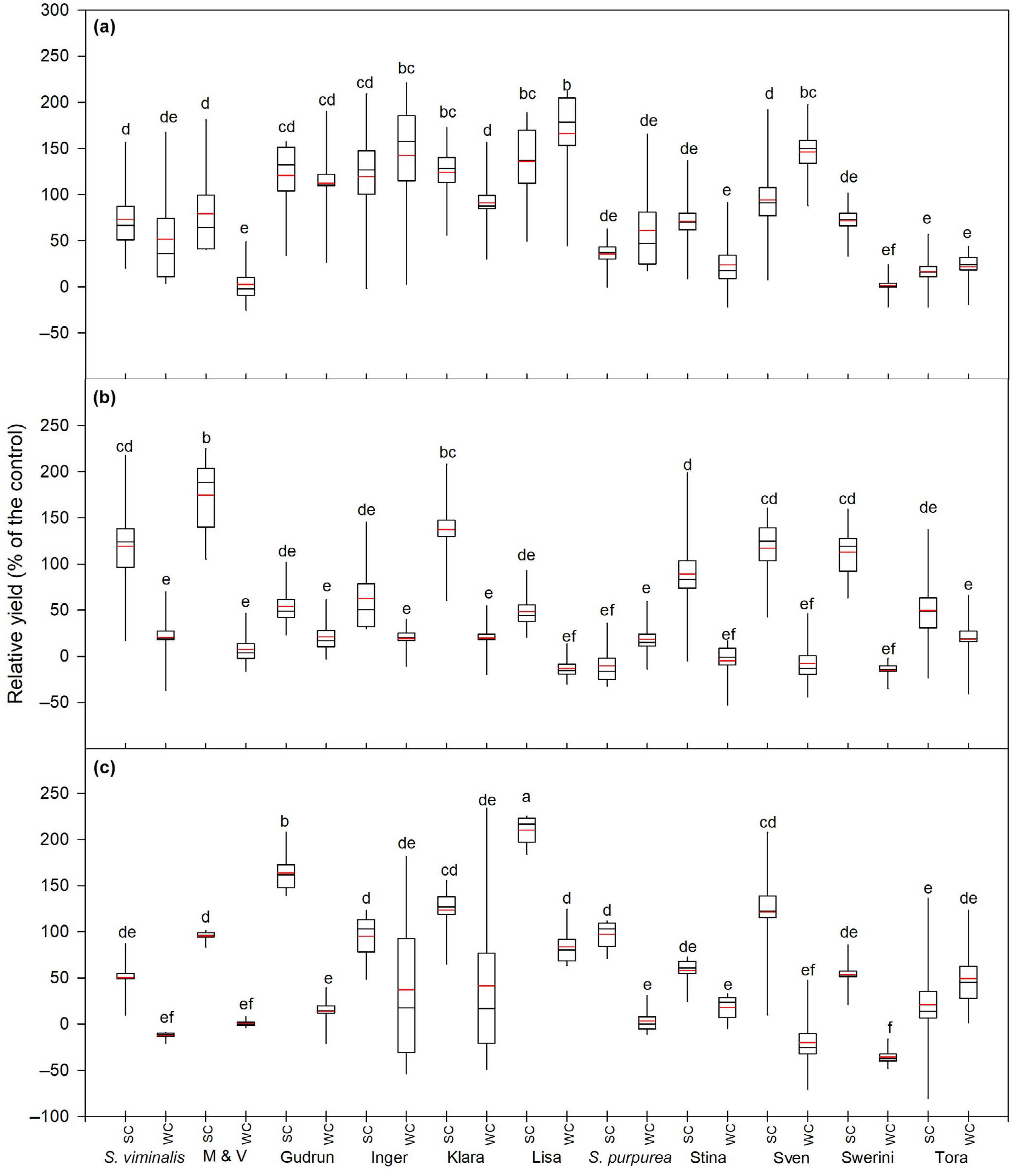

FIGURE 9 Willow (*Salix* spp.) on stoniness soil in Latvia for 3 (a), 4 (b) and 5-year (c) stem cutting cycle. Relative yield (%, $n = 3$) of willow clones fertilized with sewage sludge (SC) or wood ash (WC) in contrast to unfertilized control. Different letters indicate significant different means (horizontal red line) according to the Tukey test at $p \leq 0.05$. Horizontal black line shows the median (50th percentile) above the 25th percentile (Q1) and below the 75th percentile (Q3), and vertical black solid lines the whiskers. Interquartile range (IQR = Q3–Q1). Least significant difference of clone × fertilization × stem age interaction per $p \leq 0.05$ (72.28)

the 34% of the total European marginal agricultural area, and nearly 41% of it is affected by adverse rooting conditions, unfavorable texture and adverse climatic conditions (Von Cossel et al., 2019a). According to the prevailing marginality factors, it was investigated: (i) irrigation water regimes in six perennial grasses in an area affected by adverse climatic conditions (dryness) in southern Italy; (ii) fertilization levels in one perennial grass species in an area affected by unfavorable texture and low organic matter in northern Spain; (iii) irrigation water regimes by nitrogen fertilization doses in two industrial hemp varieties in a sandy, relatively shallow soil in south-central Greece; (iv) irrigation water regimes in two industrial hemp varieties in a heavy metal and metalloid contaminated site in southern Greece.

4.1.1 | Perennial grasses on dryness combined with unfavorable texture

In southern Italy, the uneven seasonal rainfall amount varied the dryness index in the two growing seasons (0.37 and 0.62, respectively) impacting on relative yield and its variability. Investigated perennial grasses are warm-season crops, with vegetative development matching the most frequent dry summer events in this area (Scordia & Cosentino, 2019). Combined with a sandy textured soil, the full irrigated treatment – 100% ETm restoration – improved the biomass yield in all species; hence, the relative yield decreased but to a different extent when irrigation water was provided at 50% of ETm or crops were rainfed. This reflects the significant effect of species but also the different mechanistic responses to drought of each species. The irrigation by species interaction confirmed the non-conservative growth strategy of M × G (Stravidou et al., 2019), with profligate water use during severe drought (Scordia et al., 2020a) but also at the onset of mild drought (i.e., 50% of ETm) as suggested by the negatively skewed distribution of pooled data. In rainfed conditions, the seed-based miscanthus hybrid GNT9 can be considered of the same group; however, at 50% of ETm the positive skewness indicated more data consistency for the upper quartile group. On the other hand, the seed-based miscanthus hybrid GNT10 had a more conservative growth strategy under drought, and the relative yield was similar under rainfed and 50% of ETm, although data variability was quite high; therefore, a growing season effect, given by stand age and climatic parameters other than rainfall and evapotranspiration cannot be ruled out. GNT10 has never been tested in drought areas of south Mediterranean; however, at higher latitudes falling into the Continental zone (near Poznan, Poland), on a light sandy soil where long drought periods occurred during mid-growing, Clifton-Brown et al. (2019) reported five times higher biomass yield of GNT10 compared with M × G, which confirms the different growth strategies between this two miscanthus hybrids.

Mediterranean endemic grasses, giant reed (ARCT and ARMO) and saccharum (SAC), were amongst the least variable in rainfed conditions; these ecotypes strongly responded to water availability having the lowest relative yield decrease, from −17.5% in SAC to −24.1% in ARCT, at 50% ETm. In previous studies an asymptotic relationship between crop water use and biomass yield demonstrated the linear biomass increase up to mid-levels of water restoration and the asymptotic phase at the highest water restoration of giant reed (Cosentino et al., 2014) and saccharum (Cosentino et al., 2015). Physiological (e.g., highly effective stomata control, reduced transpiration, net photosynthesis maintenance, isoprene emission to stabilize photosynthetic membranes) and morphological adjustments (e.g. leaf rolling, stem height and thickness, xylem morphology) to optimize water use at the onset of mild drought indicated mechanisms for drought avoidance of both species (Cosentino et al., 2015, 2016; Haworth et al., 2017, 2019; Scordia et al., 2015a,b; Scordia et al., 2017, 2020b). Overall, present results indicated that a reduced irrigation (from 100 to 50% ETm restoration) can be a suitable approach to save irrigation water on marginal land with water scarcity. However, site-specific genotype selection still remains a basic issue for growing in rainfed cropping systems. It is worth mentioning that adjacency of plots between the endemic species, which were taller than miscanthus, might have caused competition effects for light and nutrients. Although genotypes were randomly set up within the main plot, this spatial distribution could have biased present results suggesting that further experiments in larger plots would be necessary to validate crop performances.

4.1.2 | Perennial grass on unfavorable texture

The present area is characterized by unfavorable texture and low soil organic matter; however, in Spain, marginal agricultural land is usually rainfed arable lands where annual herbaceous crops often provides low economic returns caused not only by edaphic but also by climatic constraints (Ciria et al., 2019). Deeply investigated perennial bioenergy grasses (i.e. miscanthus, switchgrass, giant reed, etc.) are all warm-season crops, and depending on the species water requirements are from moderate to high in the Mediterranean area (Scordia & Cosentino, 2019).

The three growing seasons had cold winters (absolute minimum temperature −8.8°C averaged 3 years), long dry summers (absolute maximum temperature 37.9°C averaged 3 years) and an average annual precipitation between September and August of 466.9 mm. Unlike warm-season perennial grasses, tall wheatgrass is a cool-season that can be established in autumn, it grows on semiarid sites (with at least 300 mm of annual precipitation) due to its summer dormancy characteristics and leaf morphology (Asay, 1985; Hafenrichter et al., 1968). Previous studies spanning eight years with three varieties of tall wheatgrass in rainfed marginal lands in Spain had an average biomass yield of 4.4 Mg DM ha^{-1} yr^{-1}, which varied according to the precipitation between March and June (Ciria et al., 2020). Similar biomass yields were obtained with other annual grasses (Sanz et al., 2011). However, comparing tall wheatgrass with rye, the reduced field works and input consumed for cultivation resulted in remarkable better carbon footprint (≈200% less), reduction of the primary energy consumption (≈40%) and an increase of soil organic matter, making tall wheatgrass a sustainable option in rainfed marginal lands where winter cereals are traditionally grown (Ciria et al., 2020).

In the present study, 3-year mean biomass production of rainfed, unfertilized tall wheatgrass was slightly higher than that achieved previously (6.0 ± 3.5 Mg ha^{-1} yr^{-1}). Under these unfavorable texture and low soil organic matter conditions it would be necessary to apply more than 50 kg N ha^{-1} yr^{-1} to further increase the biomass yield. Indeed, 80 kg N ha^{-1} yr^{-1} improved the relative yield by an average of 43.8% compared with the 9.9% increase at the dose of 50 N ha^{-1} yr^{-1}. These results are in line with Pedroso et al. (2014) and Cicore et al. (2017), who found that the higher the N mineral fertilization dose, the higher the biomass yield of tall wheatgrass in the United States and Peru, respectively. Contrarily, Barro et al. (2014) showed no effect on biomass yield using a maximum of 80 kg N ha^{-1} during the first 3 years. Although we found a significant effect of N fertilization at the level of 80 kg N ha^{-1} yr^{-1}, the high data distribution with pooled data of three growing seasons (IQR of 67.0% and whiskers from −12.5% to +121.8%) suggests that further investigations are still necessary to ascertain the N requirements of tall wheatgrass on specific marginal lands.

4.1.3 | Industrial hemp on sandy, shallow soil

The experimental field was located in a site owing unfavorable texture for crop growth in south-central Greece. The soil texture was extremely sandy below 50 cm soil depth, holding low water capacity and nutrient availability although it does not constraint root development of hemp. This contrast with the optimal soil for hemp growth, which should be deep, rich in capillary and aeration, rich in nutrients and with a good water-holding capacity (Amaducci et al., 2015). Although, the determined soil organic matter was only 0.5%, which is much lower than typical arable soils in the Mediterranean, biomass yield was quite high when irrigation was supplied to cope with full water requirements (i.e. 400 m) in both hemp varieties. Futura 83 outyielded Futura 75 in well water conditions and nutrient availability; however, yield decreased dramatically when the irrigation was reduced to 200 or 100 mm in Futura 83; contrarily, Futura 75 was more stable reducing input supply. This was reflected by the relative yield reduction, which was quite consistent reducing input levels (from −2.0% and −3.4% in I2N2 and I3N1 to −15% in I2N0 as compared with the highest input combination), and significantly reduced only at the lowest combination of input (I1N0, −21.5%) in Futura 75. A higher reduction was observed in Futura 83 when irrigation water was provided at 50% or 25% (I2 and I1) compared with the full watering (from −33.5% in I2N2 to −49.0% in I1N0), while relative yield mean was maximized at the highest irrigation levels, irrespective of the nitrogen dose (−1.8% and −3.9% in I3N1 and I3N0, respectively). On the other hand, Futura 83 appeared more stable than Futura 75 under changing irrigation and nitrogen fertilization doses (as indicated by the less spread IQR). In view of input reduction Futura 75 seems a better option than Futura 83. However, Futura 83 appeared less variable under changing cultivation strategies. It is worth mentioning that unfertile soil and low-fertilizer application (22, 30 and 30 kg NPK ha^{-1} as basic fertilization) might have not support the potential growth of Futura 75, even at the highest N dose in top dressing (only 60 kg ha^{-1}). Finnan and Burke (2013) showed a stem yield increase (as high as 60 kg of stem per kg of N) by increasing N fertilization from 0 up to 120 kg N ha^{-1} in more fertile soil; therefore, under present circumstances, N application was rather far than optimal to still enhance biomass yield and might have contributed to the differences in yield and genotypic responses varying input supply.

4.1.4 | Industrial hemp on heavy metal and metalloid contaminated soil

The experimental field was located in southern Greece, in a site contaminated with Cd, Ni, Cu, Pb, Zn, Sb and As in total concentrations exceeding the common values defined by Kabata-Pendias and Mukherjee (2007). The level of soil burden differed among the elements, which exceeded the common value: Cd 8.3-fold, Ni 2.4-fold, Cu 1.2-fold, Pb 36-fold, Zn 16.5-fold, Sb 92-fold and As 236-fold. Nonetheless, the soil texture and the increased pH reduced the bioavailability of the trace elements resulting in a plant exposure mainly to Cd (8 mg kg^{-1}) and to Pb (846 mg kg^{-1}). Generally, hemp is considered as a promising candidate for the restoration of contaminated sites as it is tolerant to heavy metals, and

– in a certain degree – can uptake them to its aerial biomass (Angelova et al., 2004; Fernando et al., 2015; Pudełko et al., 2021; Shi et al., 2012). Specifically, for the bioavailable elements Pb and Cd affecting the present field trial, it has been reported that hemp could accumulate them mainly in the leaves, in concentrations reaching 22.4 mg Pb kg^{-1} and 3.5 mg Cd kg^{-1}, respectively (Linger et al., 2002).

Investigated hemp varieties Futura 75 and Futura 83 are monoecious, originated from France, and in the Mediterranean zone they are sown in spring with great part of their vegetative growth during the dry summer months (Amaducci et al., 2015; Blandinieres et al., 2021). In the present work, both varieties could germinate and grow in the contaminated soil of the experimental field, but their performance was significantly affected by the applied irrigation treatment. In the rainfed plots, a severe reduction of the relative yield (99%) was observed in both varieties compared with the full water treatment (I100), indicating their sensitivity to drought conditions. The annual cumulative precipitation in the area was 399.6 mm, well below the available moisture of 500–700 mm needed for an optimum yield; the precipitation during the vegetative growth stage was 194.0 mm, also lower than 250–300 mm of water needed for this period (Amaducci et al., 2015; Cosentino et al., 2013). The defined statistical parameters for I0 (median values, whiskers and IQR) indicated the strong influence of the low water availability on the yield of both varieties since there was a very small variability of data. In I50 treatment, Futura 75 showed to be more tolerant and better responded to water scarcity than Futura 83, giving a relative yield decrease of 13.3%, while the corresponding reduction for Futura 83 was 50.2%. Furthermore, the yield variability of Futura 83 was higher than Futura 75, indicating the former more affected by the irrigation treatment and more sensitive to water scarcity. Genotypic difference might be ascribed - but not limited – to the crop water use efficiency (WUE). Under full water availability Futura 83 had a higher WUE than Futura 75; however, when irrigation was reduced to 50% of ETP, Futura 75 used the available water more efficiently than Futura 83 (data not shown) minimizing yield losses.

4.2 | Atlantic agro-ecological zone

In the Atlantic environmental zone rainfall is usually well distributed in the spring-summer growing season; however, the length of the growing season and killing frost events, along with excessive soil moisture might be a significant constraint (Cosentino et al., 2012). Marginal arable lands in this zone account for the 26% of the total European marginal agricultural area and for the 27% is represented by adverse rooting conditions and unfavorable texture (Von Cossel et al., 2019a). The unique experiment reported in this environmental zone dealt with an unfavorable texture (i.e. sandy soil) with a low field capacity soil contaminated by heavy metals in northern France. On the contrary, the content in organic matter is rather high (4%), which originated from the raw wastewater spreading during one century (Lamy et al., 2006). A strong correlation of organic carbon and trace elements was found, mainly ascribed to their simultaneous introduction in the soils via irrigation (Bourrenane et al., 2006; Dère et al., 2007). Organic matter can, thus, play the role of ligand for trace elements decreasing their bioavailability and phytotoxicity, but also as source of nutrients leading to a soil rather rich for organisms and plant growth. Therefore, we hypothesized that the soil texture was the main issue with unstable soil moisture depending on the weather conditions, while contamination should play a minor role. Furthermore, crops like miscanthus or switchgrass are known to be tolerant to soil contamination (Barbosa et al., 2015; Fernando et al., 2004; Guo et al., 2019; Pogrzeba et al., 2018). The second main issue on this site was the weed pressure. In this field trial, minimum maintenance costs were implemented throughout the experiment to cope with realistic economic and practical conditions for farmers for the development of both miscanthus and switchgrass. Thus, irrigation was only applied in the first year to ensure plant establishment (one day long each week during the summer season), otherwise the plants were rainfed.

This irrigation practice, however, favored weed growth, which strongly competed with perennial grasses. As result, switchgrass was not able to grow, neither at the first year when it was sown nor after a second attempt when germinated plantlets were transplanted. This result was rather surprising given the fact that this species is known to be adapted to dry conditions in a wide soil types. However, similar findings were highlighted by McLaughlin and Adams (2005), who explained that one of the most significant issue for switchgrass establishment is the susceptibility to weed competition and the risk of "assumed failure". Due to the willingness of maintaining minimum maintenance farming costs, weeds were not removed except before the start of the experiment. However, weed proliferation on the site was too problematic for switchgrass during the experiment, resulting in a failure.

Concerning the miscanthus growth, our results did not highlight a biofertilization by earthworms the second year of growth. While irrigation was suspended after the first year, the second year had a very hot spring season. Due to the low field capacity, earthworms were not found in the soil surface, and miscanthus yield was not impacted by the presence or not of earthworms in the soil. The population of earthworm, monitored with an electrical sampling, showed that the number of earthworms was lower than expected with a maximum of 13 earthworms found in one geotextile (=1 m^2). Besides, van Groenigen et al. (2015) showed in their meta-analysis that sandy soils are the less suitable textures for biofertilisation with less than 20% of earthworm effect on the aboveground biomass. Therefore, drought and a low presence of earthworms in the surface horizon could explain the biofertilisation inefficacy at the second year. On the contrary, the third year of growth revealed a high effect of earthworm biofertilisation. Indeed, the year 2021 had a rather wet spring, with rainwater favoring miscanthus growth but also earthworm movements towards the surface. Thus, with a good soil water availability, the presence of earthworms near the rhizomes was found beneficial. In addition, the organic matter made up from miscanthus litter layer at senescence after two subsequent growing seasons has likely provided a more suitable environment for earthworm's growth and efficacy. Nonetheless, the large variability between growing seasons hints at further investigations to understand the effectiveness of biofertilization technique under the present marginal conditions.

4.3 | Continental agro-ecological zone

In the Continental environmental zone, while rainfall is rather well distributed in autumn-winter and spring-summer, the killing frost can last 4 months, shortening significantly the length of the growing season (Cosentino et al., 2012). Marginal arable lands in the Continental zone account for the 25% of the total marginal European agricultural area and for the 54% is affected by adverse rooting conditions and unfavorable texture, adverse climatic conditions and poor chemical properties (Von Cossel et al., 2019a). According to the prevailing marginality factors, it was investigated: (i) fertilization levels and row distance in industrial hemp in a shallow soil combined with stoniness in southern Germany; (ii) soil amendment on switchgrass in a site affected by soil acidity in the central Ukraine and (iii) stem age and organic fertilization in 11 willow clones in a stoniness site in southern Latvia.

4.3.1 | Industrial hemp on shallow soil and stoniness

Results from the field trials in southern Germany indicated that a reduced N fertilization rate (from 120 to 40 kg N ha^{-1}) can be a suitable approach to lower the input intensity of hemp cultivation on marginal land characterized by shallow stony soil. It has been reported that in soil with a compaction layer root development of hemp is strongly constrained and takes on a L-shape, which negatively affects nutrients and water uptake (Amaducci et al., 2015). Hemp plasticity varying planting density has been demonstrated in a wide range of environmental conditions. At high seed density, canopy closure is faster, which is an advantage in terms of competition with weeds and biomass yield in the first growth phases (Amaducci et al., 2002; Van der Werf et al., 1995); however, intense interplant competition might impair incoming light and triggers a process that Cerdán and Chory (2003) described "shade avoidance syndrome", leading to earlier flowering and self-thinning in turn decreasing biomass yield at later stages (Ballaré, 1999; Campiglia et al., 2017; Cerdán & Chory, 2003; Van der Werf et al., 1995; Werf, 1994). On the other hand, plants grown at low densities are usually higher and have larger diameter compared to those grown at high density (Amaducci et al., 2008; Struik et al., 2000; Westerhuis et al., 2009).

Overall, the hemp biomass yield found in this study is in line with Baldini et al. (2018), who reported an average stem dry matter yield of hemp grown under shallow soil conditions of 6.1 Mg ha^{-1}. Further comparisons cannot be made due to scare information about present marginal conditions, particularly for seed yield (Reinhardt et al., 2021b).

The reduction of sowing density (from 112 to 37 seeds m^{-2}) by widening the row distance (from 15 to 45 cm) negatively affected the actual yields. On the contrary, the relative yield reduction mean, based on low N input to high N input, was lower with the wider row distance; however, it was more variable both for biomass and seed. This difference between actual and relative yield varying plant density can be partially explained because during the summers in 2019 and 2020, the field trials were affected by strong wind events and birds feeding on the seeds. Both led to much stronger damages in the low row width treatments, because of thinner stems compared with those of hemp grown at wide row distance. Given that extreme weather events are likely to increase in Europe in the future due to climate change (Teuling, 2018; Von Cossel et al., 2019a,b), the wide row distance may be more promising under aspects of resilience. Furthermore, shallow soil and stoniness restricted vertical growth of hemp and roots spread out in the horizontal plane. Accordingly, a higher row distance and less seeds sown are expected to support this growth. However, while the space and plant available N was assumingly sufficient for hemp grown under narrow row width, it seems that it was not sufficient for the wider one.

4.3.2 | Switchgrass in areas with acid soil

Although switchgrass tolerates soil with pH from 4.9 to 7.0 (Moser & Vogel, 1995), soil acidity significantly affects the course of chemical reactions in the soil and the availability of nutrients to plants (Jensen, 2010). Switchgrass grown in unlimed (pH 4.9) and limed (pH 5.9) sandy soil demonstrated tolerance to soil acidity in the short term. However, the influence of acidic soil significantly reduced the plant height, leaf area, aboveground and root biomass in the long term (Bona & Belesky, 1992). Therefore, even a partial deoxidation of the soil is an effective practice to increase the productivity and longevity of the plantation.

Here, lime treatment increased the relative yield of only 1.5% compared with the control; nonetheless, this could be a strategy to extend the life-span of switchgrass.

Mineral fertilization was not applied since nitrogen ends up in even lower soil pH. Under these circumstances, humic substances used as fertilizer are capable of forming complexes with Na, K, Mn, Zn, Ca, Fe, Cu and make them available to plants. The use of humic products is practiced both for plant nutrition and to improve the physical, chemical and biological characteristics of the soil (Canellas & Olivares, 2014). Foliar fertilizer application of humic substances (Potassium humates) at a dose of 1 kg ha^{-1} in unlimed soil enhanced the relative yield of switchgrass by an average of 18.6% as compared to the control. Further foliar application (e.g. Active Harvest Macro) did not improve the relative yield of switchgrass either in unlimed and limed soil. Hydrogel is a moisture-retaining agent useful to overcome uneven rainfall distribution at the germination phase (Mangold & Sheley, 2007). When it was used alone in unlimed soil it was mostly ineffective on relative yield (only 2.4% increase in the non-limed control); however, in the limed soil it increased the relative yield up to 7%. In general, it enhanced the germination by an average of 15–20% as compared with the control in the present marginal conditions (data not shown). Since germination and seedling development of switchgrass is the most critical phase (Scordia et al., 2015a,b), the use of moisture-retaining agents should be carefully evaluated as a possible solution to obtain the desired plant density, particularly under marginal conditions. Overall, different treatments used had a rather limited effect on switchgrass productivity most likely for the shorth timeframe analyzed. It is presumptive that soil amendments may take longer for significant effects to appear, therefore, further growing seasons would be worth to be observed for both yield and stand persistence.

4.3.3 | Willow in areas with unfavorable soil texture

The high stoniness content did not affect the willow growth in southern Latvia, rather a large effect of clone, fertilizer type and stem age was found. Clone selection is important to secure high yields because not all clones are equally good for a particular site (Karp et al., 2011; Larsen et al., 2014; Sevel et al., 2012). Present results indicated better performances by the 5-year old Lisa clone fertilized with sewage sludge, while the worst with the five-year old Swerini clone fertilized with wood ash. In general, however, average yields per year were higher for 3-year-old stems, followed by the 4- and by the 5-year-old stems. Therefore, the best plantation age for higher biomass yields with willow in the present environmental and marginal site conditions is the 3-year; hence, cutback is necessary in the first two plantation years, which leads to biomass robustness due to stem re-sprouting. Biomass measurements were done after one rotation; it is worth noting that after several rotations yields could level off; however, a yield increase up to 61% from first to second harvest rotation has been found in willow (Mola-Yudego & Aronsson, 2008). Willow clones and fertilization treatments showed highly variable responses and data distribution. To improve willow yields in long-time period, it is advised to perform soil improvement that enhances plantation profitability (Verwijst et al., 2013). At present, soil fertilizers that could be used for a biomass crop in Continental marginal lands are wood ash and sewage sludge (Lazdiņš et al., 2005), and both could be obtained for free, usually covering only transportation costs. Sewage sludge showed a positive impact on biomass yield compared with the unfertilized control. Wood ash also improved biomass yield compared with the unfertilized control, except in some circumstances (like the 4-year-old stem Sven, Stina, Lisa and Swerini, and the 5-year old stem S. viminalis, Sven and Swerini). Overall, willow clones could be successfully used on marginal lands with high soil stoniness content in the Continental zone. Furthermore, willows are considered a good choice for heavy metals contaminated sites in the Northern European region (Hall & House, 1994; Mola-Yudego & Gonzalez-Olabarria, 2010), contribute to the overall reduction of natural pollution (Harvey, 2010), diversify the rural landscape and show a positive CO_2 balance (Gonzalez-Garcia et al., 2012).

4.4 | Summary and outlook

Less favored areas and anthropogenic contaminated sites leading to unsuitable land for food production is on the rise. This study may act to provide hints on how to scale up investigated cropping systems, through low-input practices, under similar environmental and soil conditions tested at each site.

In the Mediterranean zone, dryness, unfavorable soil texture and adverse rooting conditions represent significant constraints to crop production. Under dryness conditions, investigated warm-season perennial grasses seems to be a suitable option, although genotype selection still remains a fundamental issue for rainfed cropping systems. Reduced irrigation (from 100 to 50% ETm restoration) can be recommended on marginal lands with water availability; however, genotype with a conservative growth strategy is preferable to save irrigation water while limiting yield decreases. Irrigation water can also be significantly reduced with industrial hemp but genotype selection for tolerance to water scarcity is key, particularly under sandy textured and relatively shallow soil, as well as on heavy metal and metalloid contaminated sites. These conditions, however, does not support the growth of investigated industrial hemp varieties in rainfed systems and at least 100 mm of irrigation water is necessary. On the other hand, tall wheatgrass, a cool-season perennial grass benefits from autumn-winter rainfall, which is quite favorable in the Mediterranean area. This species can be grown in rainfed cropping systems and less fertile soil (sandy soil with low organic matter) provided that N-fertilization of at least 80 kg N ha^{-1} yr^{-1} is applied to sustain biomass growth while preventing long-term soil N-impoverishment.

Adverse rooting conditions, unfavorable texture and soil poor chemical properties affect a vast area of the Continental environmental zone examined in this study. Results of the industrial hemp cultivation on shallow stony soil indicated that N fertilization rate can be reduced (from 120 to 40 kg N ha^{-1}) to lower the input intensity. The wider plant density seems to better support the root growth of hemp in shallow soils and can represent a promising approach under aspects of climate-change resilience (e.g. strong wind events). However, optimization of N-fertilization to offset yield gaps between the two row distances is still required. In acid soil, switchgrass productivity and the stand longevity can be improved with lime treatment before sowing. Moisture-retaining agents resulted useful to enhance the germination and seedling development of switchgrass under present marginal conditions. When mineral fertilization is too risky for soil pH, foliar application of humic substances at the tillering stage and repeated in two weeks' boosts availability of nutrients to plants, improving the yield of switchgrass on acid soils. Willow can be successfully used on marginal lands with high soil stoniness content in the northern Continental zone. However, clone selection and management are important issues to secure high yields. According to present results, stem cutback the first 2 years after transplant (i.e. 3-year-old stem) enhances plant robustness and yield, and sewage sludge and wood ash as fertilizer ameliorated willow performances compared with the unfertilized control; nonetheless, sewage sludge seems a better approach.

In the sandy textured and heavy metal contaminated soil in the Atlantic zone, bio-fertilization through earthworm's inoculation in miscanthus is encouraging. Despite unfavorable conditions at the second year (dryness), earthworms were still present the year after, where a more typical spring rainfall distribution—and probably more organic matter from miscanthus litter – significantly improved biomass yield of miscanthus biofertilized with earthworm as compared with the unfertilized control. Nonetheless, the strong growing season effect hints at further investigations to understand the effectiveness of this technique on present marginal conditions.

Taken together, this study proved that growing industrial crops on marginal lands adapting low-input agriculture practices could be an option; however, genotype selection and further attention to detail on the agronomy of early plant development and management in larger multi-year and multi-location field studies with commercially scalable agronomies are needed to validate yield performances, and thereby to inform on the best industrial crop options.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Zenodo repository (https://doi.org/10.5281/zenodo.6245498).

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