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NON-FOOD CROPS ON MARGINAL LAND: A STUDY CASE OF *CAMELINA SATIVA* (L.) AND *CRAMBE ABYSSINICA* (HOCHST) ON MEDIUM TO STEEP SLOPE IN NORTHERN ITALY

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1 ABSTRACT

The European MAGIC project (H2020) based its research activity on the concept that marginal land could be used to grow industrial crop. This strategy could help satisfying the demand for renewable feedstock, mitigate land competition between food and non-food (iLUC risk), and diversify farmers' income through the access to new markets. However, the assessment of several key aspects (i.e., agronomic, economic, logistic, and environmental) of this ambitious strategy still lacks. The present study was established with the aim to help filling the knowledge gaps about the cultivation of camelina (*Camelina sativa* L.) and crambe (*Crambe abyssinica* Hochst.) in marginal land. For the first time, agronomic performances of these two industrial oilseed crops were assessed in two slope fields (mild and severe slope), in the Emilia Romagna region (Italy). Moreover, camelina and crambe were respectively compared with barley (*Hordeum vulgare* L.) and sunflower (*Helianthus annuus* L.*)* which are typically grown in the internal hilly area of the region. Crop comparison was performed by an index (break-even yield) that aimed to offer a preliminary assessing about the opportunity to cultivate, in a simplified economic framework, the tested industrial crops. The study confirmed that camelina and crambe are suitable for growing in marginal land affected by terrain constraint, proving their adaptability to a wide range of environments. It is noteworthy that qualitative yield traits (i.e., seed oil content, fatty acid profile) of both crops were never negatively affected by the marginal conditions. Nevertheless, marginality reduced seed yield of both oilseed crops, but only under the severe slope condition. Low plant density was one of the main challenging aspects of camelina and crambe cultivation under marginal slope condition. Although under the milder slope field both crops showed the ability to maintain satisfactory yield across a broad range of plant populations, under the severe slope condition poor plant density was a limiting aspect to control weeds and to improve yields. The negative profitability observed for all tested crops under the severe marginal condition questioned not only the opportunity to cultivate camelina and crambe under such a marginal land but even the tested food crops. At the opposite, the positive profitability of camelina in the mild slope field makes its cultivation in such a condition a concrete choice to be further explored.

2 GENERAL INTRODUCTION

2.1 Preliminary concepts

The development of a sustainable and circular bioeconomy has been widely supported by the EU policy as a critical element of a multisector strategy aimed to transform the European economy into a resource-efficient and low-carbon economy (European Commission, 2012).

The transition toward bioeconomy has substantively built on biomass resources (Lewandowski, 2015), therefore the demand for renewable feedstock for bio-based industrial applications has increased over the last years (Gurría P. et al., 2018; Scarlat et al., 2015). Since biomass production is limited by land and resource availability (i.e., water, nutrients), the increase of such a demand has led to controversies in scientific and public debates on the negative effect of land-use change, food security and biodiversity. The competition between alternative uses of biomass (food, feed, fibre, bio-based materials, and bioenergy) can generate adverse social and environmental problems (Pfau et al., 2014).

In this context, the European MAGIC project (Horizon 2020 - Grant agreement ID: 727698) was funded to investigate the suitability of industrial crop cultivation in marginal land, in order to help satisfying the demand for renewable feedstock, mitigating land competition between food and non-food applications (iLUC risk), and diversifying farmers income through the access to new markets. In the project frame, marginal land has been considered as agricultural land affected by biophysical constraints (i.e., steep slope, salinity, dryness) in agreement with different land classification systems, but especially, with the JRC's indicators identifying Areas of Natural Constraints (ANCs) (Terres et al., 2014; Van Orshoven et al., 2012).

2.2 Marginal land

Although several definitions have been proposed and discussed, the term “marginal land” has not been well defined yet. The definition of marginality should consider several aspects, for instance the land use perspective. Dale et al. (2010) indicated that marginal land is a relative term, explaining that the same qualities used to classify a site as marginal in one place or for one purpose can be present in land considered productive in another place or for a different scope. For instance, land considered marginal for cropping can be suitable for grazing or forestry. The marginal land definition should also contemplate the dimension and the temporary character of aspects determining marginality. FAO-CGIAR (CGIAR Technical Advisory Committee, 2000) implied that marginality could be the result of biophysical and socio-economical constraints, that can operate separately or simultaneously. Kang et al. (2013) indicated that marginality could be considered a temporary state since two drivers determine the dynamics in marginal lands: natural process in combination with land management and market changes. For instance, unproper land management can accelerate natural degradation and convert land to the marginal, whereas technical investment can turn marginal land into productive state. Analogously, changes in market may affected profit margins and bring marginal land into use or abandonment. Furthermore, in many studies the term marginal land is often used as synonym or mixed with terms like abandoned, unused, fragile, degraded, or contaminated land, making even more challenging the building of a single definition of the term.

2.2.1 Biophysical constraints

The presence of biophysical constraints is one key characteristic in many definitions of marginal land. Several frameworks have been developed for classifying land suitability for agricultural uses focusing on such limitations.

The USDA (United States Department of Agriculture), for instance, built up a classification system (Land Capability Classification – LCC) with eight land classes defined by limitations (i.e., the susceptibility of erosion, poor soil drainage, low fertility, adverse climate condition). Such framework aims at identifying land capability for agricultural exploitation, as cropping or grazing/pasturing, and land where such activities were precluded and the protection of the Conservative Reserve Program was needed (Helms, 1992).

FAO (Food and Agricultural Organisation of the United Nations) developed a land evaluation system (Framework for Land Evaluation - FLE) based on four different main categories, each one corresponding with a different potential for a particular use. The framework involves the identification of relevant land limitations, for instance, moisture availability, length of the growing season, soil drainage class, depth to water, nutrient availability, salinity (FAO).

Recently, the JRC (Joint Research Centre) provided a common framework identifying significant natural constraints for supporting the designation of the Intermediate Less Favourable Areas (LFAs) in the EU (Van Orshoven et al., 2012). Eight criteria were proposed for classifying LFAs that are defined as lands faced by significant natural handicaps affecting agricultural activities.

2.2.2 Socio-economic constraints

FAO-CGIAR (CGIAR Technical Advisory Committee, 2000) reported that land marginality also depends on the socio-economic parameters of a specific environment. Absence of markets, difficult accessibility, poor infrastructure, restrictive land tenure, smallholdings, and unfavourable output/input ratio have been identified as the main socio-economic drivers of the marginality.

2.3 Marginal land in the MAGIC project

In the MAGIC project, marginal land has been considered as agricultural land affected by biophysical constraints. In Table 1 are listed the biophysical factors and land characteristics used to identify marginal land into the project framework.

Table 1. Biophysical constraints used in MAGIC project to identify marginal land.

CLUSTER	SUB-FACTOR	DEFINITION	THRESHOLD
1. Adverse climate	**Low Temperature**	Length of Growing Period (number of days) defined by the number of days with daily average temperature > 5°C (LGPt5) OR	≤ 180 days
		Thermal-time sum (degree-days) for Growing Period defined by accumulated daily average temperature > 5°C.	≤ 1500 degree-days
	Dryness	The ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET)	P/PET ≤ 0.5
2. Excessive weatness	**Excess Soil Moisture**	Number of days at or above Field capacity	≥ 210 days
	Limited Soil Drainage	Areas which are waterlogged for a significant duration of the year	Wet within 80cm from the surface for over 6 months, or wet within 40cm for over 11 months *or* Poorly or very poorly drained soil *or* Gleyic colour pattern within 40cm from the surface

3. Adverse chemical conditions	**Salinity (Ec)**	Soils with high salinity content	Salinity: ≥ 4 deci-Siemens per meter (dS/m)
	Sodicity (Na – ESP)	Soils with high sodicity content	≥15% (ESP)
4. Low soil fertility	**Soil reaction**	Highly acidic and alkaline soils	pH ≤ 4.5 (in water) pH ≥ 8 (in water)
	Soil organic carbon	Organic matter	SOC <0.5%
5. Limitation in rooting	**Unfavourable soil texture**	The relative abundance of clay, silt, sand.	Topsoil texture class of sand, loamy sand defined as: silt% + (2 x clay%) ≤ 30% *or* Topsoil texture class is heavy clay (≥ 60% clay)
	Coarse fragments/surface stones	Coarse material > 35 cm	Soil surface is covered >35% by coarse material and/or > 15% by stones
	Organic soils	Organic matter	SOC ≥20%
	Shallow rooting depth	Depth (cm) from soil surface to coherent hard rock or hard pan	< 30 cm
6. Adverse terrain	**Steep Slope**	Change of elevation with respect to planimetric distance (%).	≥ 15%

2.4 Marginal land for non-food cropping

Many studies claimed that the cultivation of non-food crops on marginal land could be a win-win strategy for the sustainable production of biomass (Mehmood et al., 2017; Valcu-Lisman et al., 2016; Zegada-Lizarazu et al., 2010). Dauber et al. (2012b), for instance, believed that the inclusion of marginal land in establishing sustainable bioenergy production systems could have social, economic, and ecological benefits at regional scales. However, many challenges must be faced to understand whether this strategy is feasible. Firstly, the identification, localisation and availability of marginal lands are uncertain. According to the MAGIC criteria (Table 1), about 29% of European agricultural area is definable as marginal (Elbersen et al., 2018). However, there is a lack of information about the current and future utilisation of this land. A recent report of EU Commission has estimated 20 million ha of agricultural land at high risk of abandonment in the EU in the period 2015-2030, indicating biophysical constraints as ones of the mean driver factors (Perpiña Castillo et al., 2018). Another challenge is the lack of knowledge about the productivity of industrial crops under marginal condition, as well as about the logistic and crop management system to be used in such land.

2.5 Camelina and crambe

Many industrial crops have been selected by the MAGIC project as promising for feeding the bioeconomy transition in the EU, in relation to their agronomic and industrial characteristics. Camelina (*Camelina sativa* L.) and crambe (*Crambe abyssinica* Hochst) are two of the selected crops that have been already identified as mature oilseed crops for large-scale cultivation and commercialisation in the EU (Zanetti et al., 2013). These crops have attracted the interest of many researchers and industry because of their environmental adaptability and agronomic proprieties, such as short growing season, tolerance to drought and frost, low input requirements (fertilisers, pesticides), beside to a valuable oil composition, suitable for a multitude of bio-based applications (Berti et al., 2016; Righini et al., 2016; Samarappuli et al., 2020). However, the total surface area under these minor oil crops is currently tiny, because of lack of agronomic knowledge and socio-economic lock-in (Leclère et al., 2018).

2.5.1 *Camelina sativa*

Camelina (*Camelina sativa* L.) has recently received the attention of both research and industry because of its unique oil composition combined with relatively large environmental adaptability, low-input requirements and satisfactory yields (Berti et al., 2016). Compared with the most diffused oilseed crops (i.e. soybean, sunflower, oilseed rape, etc), camelina oil presents a singular fatty acid profile characterised by a high content of polyunsaturated fatty acids (PUFAs) (i.e., linoleic acid and linolenic acid), low erucic acid content (<5%), and high eicosenoic acid content (about 15%) (Righini et al., 2016; Zanetti et al., 2013). Furthermore, camelina has a high content of tocopherols (Budin et al., 1995) conferring a relatively high oxidative stability despite the high oil desaturation level. Thanks to these characteristics, camelina oil is a suitable feedstock for a multitude of biobased application (i.e., biofuels, jet fuels, oleochemical compounds, feed and food) (Berti et al., 2016; Righini et al., 2016; Zanetti et al., 2013).

Camelina is an annual oilseed crop native of southeast Europe and south-west Asia (Larsson, 2013), and belonging to the *Brassicaceae* family. The plant is erect, with a mean height ranging about 0.65-1.10 m (Berti et al., 2011) (Berti et al., 2016). It has branched stems, a variable number of branches (Martinelli & Galasso, 2011), lanceolate leaves, and small yellow flowers arranged in racemes. Fruits are pear-shaped siliques (5-14 mm long), containing 8 to 15 seeds. At maturity, seeds are golden brown and weigh between 0.8 and 1.8 mg seed^{-1}, depending on cultivar and growing conditions during seed development (Zubr, 1997). Camelina is predominately autogamous (Plessers et al., 1962; Zubr & Matthaus, 2002) with low levels of intraspecific outcrossing. It's tolerant to drought stress.

Camelina has a relatively short growing cycle, requiring 1200-1300 GDD with a base temperature of 4°C from sowing to harvest (Gesch & Cermak, 2011). Two biotypes (winter and spring) were identified (Mirek, 1980). Both have a relatively high tolerance to low temperatures, although winter types have proven to be significantly freeze hardier than spring types (Gesch & Cermak, 2011).

Camelina can be cultivated in a wide range of climatic and soil conditions (Righini et al., 2016). In Mediterranean climates, for instance, both autumn or spring sowing is possible, even though the first has shown higher yields (Berti et al., 2011; Masella et al., 2014). Camelina sensitivity to high temperatures stress, especially at flowering stage, has to be taken into account in the choice of sowing period. Gesch et al. (2014) found that seed yield and seed oil content significantly declined when high temperatures coincided with the reproductive phase. Camelina has no seed dormancy, and despite small seed size, it tends to be quite vigorous. Sowing rate commonly varies between 4 and 6 kg ha^{-1} (Dobre et al., 2014). Seed should be shallow planted (≈ 10 mm deep or less), guarantying good contact with soil to enhance good plant establishment (Berti et al., 2016).

Camelina has been tested in rotation with small grain cereals, corn, and soybean and it usually has not affected the subsequent crop seed yield, and in some cases, it has even enhanced yields (Berti et al., 2015; Shonnard et al., 2010). In the semiarid Mediterranean climate, Royo-Esnal & Valencia-Gredilla (2018) showed that its introduction as a rotational crop is a feasible option for helping to suppress winter weeds, as well as to provide seed yield. Several studies were also carried out introducing camelina in double- or relay-cropping systems. In the US, for instance, it was reported as an excellent crop for double cropping with soybean (Berti et al., 2015; Gesch & Archer, 2013).

Camelina has been categorised as a low input crop. Although seed yield increases with nitrogen rate (Jiang & Caldwell, 2016), but in some environments, 60-80 kg N ha^{-1} are enough to reach ceiling seed yields increase (Urbaniak et al., n.d.; Wysocki et al., 2013). Furthermore, high nitrogen rates can increase the risk of lodging (Solis et al., 2013) and disease susceptibility (Jiang & Caldwell, 2016).

Camelina is highly resistant to two of the most important diseases of rapeseed and others brassica: Alternaria black spot and blackleg. However, it is susceptible to some diseases of *Brassicaceae* family, like damping-off, clubroot and white rust (Séguin-Swartz et al., 2013). Weed control is one of the major challenges in camelina production (Lenssen et al., 2012), although a relatively high capacity to compete against weeds has been reported (Royo-Esnal & Valencia-Gredilla, 2018). The cultivation in fields with high-weed pressure can be problematic since no herbicides have been registered for camelina.

Numerous studies have been carried out on camelina in different parts of the world showing varying seed yields. It can vary with cultivar, climate and type of the soil where the crop is grown (Berti et al., 2016). In not-limiting condition seeds production can reach 2.5-3.2 Mg ha^{-1} (Righini et al., 2016). Seed quality can be affected by environmental factors such as temperature, precipitation, evapotranspiration (Zubr, 2003). For this reason, significant variation in seed quality can be expected across different locations and/or sowing time. As reported by Righini et al. (2016), seed oil content can vary from 26 up to 43% across Europe.

2.5.2 Crambe abyssinica

Crambe (*Crambe abyssinica* Hochst) is considered one of the primary "green" sources of erucic acid, besides high erucic rapeseed (HEAR) and other brassicas (Zanetti et al., 2016a). In the last years, the interest in crambe has been renewed just thanks to its oil composition and its relatively low-input requirements. High erucic acid (C22:1) oils are a potential feedstock for oleochemical transformations (i.e., biofuels, lubricants, additives) or for producing erucamide that is used in the plastic industry (Walker & Gunstone, 2004). Crambe oil contains, on average, about 55% of C22:1 (Bondioli et al., 1998; Lazzeri et al., 1994) but it can vary between 50 up to 65% (Samarappuli et al., 2020).

Crambe is a brassica oilseed crop native of the Mediterranean zone and the Eastern region of Africa (Falasca et al., 2010; Zhu, 2016). It is an erected plant with a variable number of branches, depending on plant density and environmental conditions. Plant height generally ranges from 0.6 to 0.9 m (Lessman, 1990), but it can reach over 1 m if growing conditions allow (Zhu, 2016). Crambe has oval-shaped leaves and tiny white flowers, clustered into racemes sited at or near branch terminations. Fruits are spherical pod (silicles) of 2.5 mm diameter on average, which bear a single seed into a hull. At maturity, they are generally indehiscent and change colour into light brown. The hull is considered part of the yield because it remains on the seed at harvest (Papathanasiou et al., 1966), Lessman 1966). Seeds weigh on average between 7.0 to 7.5 mg, including hull that account for 14–40% of the seed weight (Lessman, 1990). Crambe is basically autogamous, but 9–14% cross-pollination was reported by (J Vollmann & Ruckenbauer, 1993). Flowering is indeterminate, but the early formed silicles usually adhere until later ones mature. Crambe requires 90−110 days from sowing to maturity (1300−1500 GDD, with a base temperature of 5°C (Meijer & Mathijssen, 1996). It has a tap-root that can reach 1 m depth (Beck et al., 1975; Zanetti et al., 2016a) giving to the plant a great tolerance to drought.

Crambe is considered a cool-season crop even though it can grow in a wide range of climatic conditions (Righini et al., 2016). At seedling stage, it can tolerate low temperature up to -5°C.

During the mean vegetative stage it needs temperature around 15-25°C, even though it can tolerate higher temperature during blooming (Falasca et al., 2010). In warmer climates it can be cultivated as a winter crop, whereas in colder climates it can be grown as a spring crops (Falasca et al., 2010).

Crambe is generally sown in row. Row spacing ranges between 0.12 and 0.90 m in width. Row spacing of less than 0.30 m improved seed yield by enhancing weed competition, decreasing branching, and promoting uniform maturity (Laghetti et al., 1995; Oplinger et al., 1991). Seeding rate varies with row spacing, higher rate is recommended for narrow spacing. Carlson et al. (1996) recommended a seeding rate between 11 and 22 kg ha^{-1}. Seed germination is hindered by the presence of the hull even though it protects the seed from pathogens and insects.

It is worth noting that optimal planting dates for both crambe and camelina are critical management issues significantly affecting the final yield and oil composition. In particular, as reported by Adamsen and Coffelt (2005) for crambe an anticipation of sowing in autumn could negatively impact seed yield, in case of frost occurrence, conversely also a delay of sowing in spring could lead to lower yield performances

Nielsen (1998) considered crambe a feasible oilseed crops for dryland rotation with winter wheat in the central Great Plains.

3 STUDY CASE

3.1 Preliminary concepts

The European MAGIC project based its research activity on the concept that the use of marginal land could help satisfying the demand for renewable feedstock, mitigate land competition between food and non-food (iLUC risk), and diversify farmers' income through the access to new markets. However, the assessment of several key aspects (i.e., agronomic, economic, logistic, and environmental) of this ambitious strategy still lacks. The present study was established with the aim to help filling the knowledge gaps about the cultivation of camelina (*Camelina sativa* L.) and crambe (*Crambe abyssinica* Hochst.) in marginal land. For the first time, agronomic performances of these two industrial oilseed crops have been assessed in steep slope fields in the Emilia Romagna (ER) region (Italy). About 85% of the regional marginal land, surveyed and mapped by the MAGIC project (Elbersen et al., 2018), is indeed affected by terrain constraint (slope >15%). Moreover, camelina and crambe were respectively compared with two annual food crops generally grown in the internal area of the region, where steep slope land is widespread, namely barley (*Hordeum vulgare* L.) and sunflower (*Helianthus Annuus* L.*)*. According to the regional Land Parcel Information System (LPIS), barley and sunflower are indeed two of the most cultivated annual crops in the ER's internal areas, where a wide process of agricultural land abandonment and land use change has occurred. In the period 2003-2017, about 8500 ha of arable land have been lost in this area, according to data from the Statistic and Geographic Information System of the ER region. The choice of such a reference crops was also made because of the respectively affinity of barley and sunflower to camelina and crambe in terms of agronomic management (i.e., same farm machineries, similar growing season and low input management). Crop comparison was performed through the building of an index (see 2.2.4) that aimed to offer a preliminary assessing about the opportunity to cultivate, in a simplified framework, the tested industrial crops in land affected by slope constraint. Furthermore, several works provided positive evidences in terms of agronomic benefit about camelina and crambe addition to small grain cereals systems (Keshavarz-Afshar & Chen, 2015; Nielsen, 1998; Obour K, 2015; Royo-Esnal & Valencia-Gredilla, 2018) that are widespread in the Emilia Romagna marginal hilly area.

3.2 Material and methods

3.2.1 Experimental Site

The field trials were carried out at Ozzano dell'Emilia, Italy (44°26'42" N, 11°28'35" E) in the organic farm of the University of Bologna (AUB) in two consecutive growing seasons (GS), 2018/2019 and 2019/2020.

A North Mediterranean climate characterises the experimental area. The annual precipitations are about 800 mm, not evenly distributed along the year, and the annual mean air temperature is 13.9°C. The maximum mean daily temperature is 31.1°C, reached in August, while the minimum mean daily temperature is 0.3°C, reached in January. Daily air temperatures and precipitation were collected by a weather station located near to the experimental area.

The experimental fields were placed in the hilly area of Bologna province and were characterised by a different slope severity: severe slope (about 30%) and mild slope (about 20%). The milder slope site was introduced only in the second GS. Furthermore, a third field without biophysical constraints (favourable field) was established as control in the plain area of the same farm as control.

The soil physico-chemical analysis was carried out on representative soil samples of each experimental field (Table 2).

Table 2: Soil analysis report of experimental fields: SS = severe slope field; MS = mild slope field; FF = favourable field.

Analysis	Value			U.M.	Method
	SS	MS	FF		
Texture					
Sand	38	22	18	%	M.6 DM11-5-92
Loam	41	43	46	%	
Clay	21	35	36	%	
pH in water	8.09	7.92	6.65		M.III1 DM13-9-99
Total carbonate ($CaCO_3$)	17	20	1.62	%	Dietrich-Fruehling
Active carbonate ($CaCO_3$)	3.69	5.81	1.44	%	Drouineau
Organic Carbon	5.91	11.53	10.19	g/kg ss	Walkley-Black
Organic Matter	1.02	1.99	1.76	% ss	Walkley-Black
Total N	0.78	1.44	1.39	g/kg	Dumas
Available P (P_2O_5)	25	22	145	mg/kg	Olsen
Available K (K_2O)	161	194	246	mg/kg	M.13.5 DM13-9-99
C/N	7.58	8.01	7.33		

3.2.2 Experimental lay-out

At the beginning of the study, the steep-slope field was fallow covered by spontaneous grassland, whereas both the mild-slope field and the favourable field were previously cultivated: winter wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* (L.) Moench), respectively.

A large strip of about 12 x 80 m was established for each crop across both the growing seasons. In the second year, camelina strip was switched with that of barley, and crambe with sunflower.

Crop management was defined according to the organic farming and low input system precepts (Von Cossel et al., 2019). The seedbed preparation started on early autumn through a multipurpose cultivator (disc cultivator along with tine cultivator) at 0.3 m soil depth. In all strips, a pre-sowing fertilization was performed with organic fertiliser (Italpollina, Italy) at 500 kg ha^{-1} dosage (Tab. 3). A second organic fertiliser (Fertben) (Tab. 3) was distributed before the sowing of crambe and sunflower at 350 kg ha^{-1},and it was also applied at 250 kg ha^{-1} as top-dressing fertilization in camelina and barley. If necessary, rolling was carried before sowing to level seedbed.

Table 3. Characteristics of organic fertilisers.

Analysis	**Guanito**	**Biouniversal Super 12**
Total N	6 %	12 %
Organic N	6 %	5 %
P_2O_5	15 %	-
K_2O (soluble in H2O)	2 %	-
CaO	10 %	-
MgO	2 %	-
Organic Matter	55 %	70 %
R.U.	7 %	8%
Formulation	pellet Ø 3 mm	pellet Ø 3 mm

In both growing seasons, barley, camelina and crambe were sown with a mechanical seeder (Damax, Italy) commonly adopted for small cereals. The row distance was 0.17 m. The seed rate was 7 kg ha^{-1} for camelina, 190 kg ha^{-1} for barley and 15 kg ha^{-1} for crambe, and sowing depth was 15, 30 and 20 mm, respectively. Sunflower was sown with a pneumatic seeder (Maschio Gaspardo, Italy) at 0.7 m row distance and 7 plants m^{-2} density. All the sowing dates are reported in Table 4. Mechanical weeding was applied in sunflower by hoeing interrow at six true leaf stage. All the crops were rainfed.

Table 4. Crops, varieties, sowing and harvest dates, GDD and cumulative precipitation for the tested crops in GS 2018/19 and 2019/20.

GS	**Crop**	**Variety**	**Sowing date**	**Harvest date**	**GDD***	**Cumulative precipitation (mm)**
2018/19	Barley	Cometa	16/11/18	20/06/19	2000	468
	Camelina	Cypress	16/11/18	14/06/19	1153	468
	Crambe	Galactica	03/03/19	20/06/19	989	323
	Sunflower	Buffalo RGT	08/04/19	02/09/19	1962	385
2019/20	Barley	Cometa	07/01/20	05/06/20	1649	180
	Camelina	Cypress	10/11/19	05/06/20	1230	315
	Crambe	Galactica	26/02/20	28/06/20	1217	63
	Sunflower	Buffalo RGT	03/04/19	20/08/20	1845	176

*GDD os the thermal time from planting to harvest calculated with the formula: GDD = Σ(Tm - Tb), where Tm is the mean daily air temperature, and Tb is the base temperature for which 0, 4, 5, 7 °C values were used for barley, camelina, crambe and sunflower, respectively.

3.2.3 Surveyed parameters

Ten sampling areas of 4 m^2 were randomly collected for all the tested crops and were considered as replicates. Each sampling area was manually harvested when crop reached physiological maturity (Table 4). The aboveground plant biomass was collected and threshed few days after harvest with a plot combine harvester (Wintersteiger, Austria). Total seed and straw biomass were weighted separately, and sub-samples were oven dried at 105°C for 24 h up to constant weight to calculate the dry matter content (DM). Camelina and crambe plant height and plant density were measured at harvest in representative rows inside the sampling areas. The former was surveyed in ten contiguous plants being part of the same row; the latter was measured in two contiguous row segments of one-meter length. Seed yield per plant was calculated dividing seed yield by plant density, to better understand plant plasticity. Camelina and crambe seed weight (Thousand Kernel Weight - TKW) was determined on representative seed samples after cleaning and counting with a seed counter machine (Data Technologies, Israel) at LARAS laboratory of the University of Bologna.

A complete compact extraction system (Behr Labor-Technik, Germania) was used for the oil extraction using hexane as solvent. After seed oil content determination, the fatty acid profile was determined through a Gas Chromatograph (Agilent Technologies, USA) once accomplished oil transesterification (Christopherson & Glass, 1969). Oil analysis was carried out at the laboratory of CIRI Agri-food of the University of Bologna (Cesena, Italy).

3.2.4 Break-even yield (BY)

Break-even yield (BY) was calculated dividing the cultivation costs by the selling price at farm gate for each crop as showed in Table 5. Costs and selling prices can surely fluctuate over the years according to the market changing. However, BY was proposed in this study to normalise yields and to build an index (expressed as a percentage) (Eq. 1) to compare different crops under marginal conditions. Cultivation costs included both explicit (i.e. fuel consumption) and implicit (i.e., depreciation) costs and it was obtained consulting the annual catalogue of the Provincial Association of Agricultural, Industrial and Building Mechanization Companies (APIMAIE, Bologna, Italy) (Tab. 6). Selling prices of organic barley and sunflower were extracted as a mean of two-year data from the agricultural market reports of the Agricultural Food Market Services Institute (ISMEA, Roma, Italy), whereas camelina and crambe selling prices were extrapolated from literature (Stolarski et al., 2018) since no mature market have been implemented in Italy so far. Both costs and selling prices were considered constant across the two GSs (2018/2019 and 2019/2020). For all the tested crops, straw was not considered in the analysis since it was grinded by combine at harvest to be incorporated into soil.

For each sampling area the yield was normalised using the following formula:

$$NY = \frac{x}{BY} 100 \qquad \text{(Eq. 1)}$$

where *NY* was the normalised yield, *x* was the seed yield (Mg ha^{-1}), and *BY* was the break-even yield of the crop (Mg ha^{-1}).

Net revenue was calculated using the following formula:

$$NR = (x\,P) - C \quad \text{(Eq. 2)}$$

where *NR* was the net revenue (€ ha^{-1}), *x* was the seed yield (Mg), P was the selling price (€ Mg^{-1}), and C was the cultivation cost (€ ha^{-1}).

Table 5. Break-even yield of tested crops. The value of each crop was calculated dividing cultivation cost by selling price. Cultivation cost and selling price were rounded.

Description	**Unit**	**Barley**	**Camelina**	**Crambe**	**Sunflower**
Cultivation cost	€ ha^{-1}	1055	990	1122	1100
Selling price	€ Mg^{-1}	220	700	600	530
Break-even Yield (BY)	Mg ha^{-1}	4.79	1.41	1.87	2.07

Table 6. Cultivation cost of tested crops. B = barley; Ca = camelina; Cr = crambe; S= sunflower.

DESCRIPTION	**MEANS OF PRODUCTION RATE**						**COST (€ ha^{-1})**			
	B	***Ca***	***Cr***	***S***	Unit	€ $Unit^{-1}$	***B***	***Ca***	***Cr***	***S***
Minimum-tillage					ha	150	150	150	150	150
Fertiliser application	0.75	0.75	0.85	0.85	Mg	70	52.5	52.5	59.5	59.5
Harrowing					ha	60	60	60	60	60
Sowing					ha	70	70	70	70	70
Hoeing					ha	60	0	0	0	60
Harvest					ha	250	250	250	250	250
Fertiliser	0.75	0.75	0.85	0.85	Mg	450	337.5	337.5	382.5	382.5
Seed	180	7	15	1*	kg	**	135	70	150	70
TOTAL CULTIVATION COST					€ ha^{-1}		1055	990.5	1122	1102

*Unit of measurement for sunflower was a dose of 70 thousand seeds.

**Seed prices were 0.75 € kg^{-1} for barley, 10 € kg^{-1} for camelina and crambe, 70 € $dose^{-1}$ for sunflower.

3.2.5 Statistical analysis

Statistical analysis were performed using SPSS (IBM, USA). Levene's Test ($P \leq 0.05$) was used to verify the homoscedasticity of the data before the analysis of variance (ANOVA). In some cases, values were transformed using the squared root. Once the homogeneity of variance was respected, data were subjected to ANOVA. Tukey HSD Test ($P \leq 0.05$) was used to perform the separation of the means.

Two-way and one-way ANOVA analysis were carried out for camelina and crambe, separately. The former inspected the data collected in the two-year study in the steep slope field and in the favourable field. Thus, growing season and experimental site were the source of variation. The latter analysed the data gathered only in the second year to compare crop performances in the mild slope field. In this case experimental site was the only source of variation.

Crop comparison (camelina vs. barley, and crambe vs. sunflower) was focused on marginal fields data. Two-way and one-way ANOVA were performed. The former analysed data collected in two-year study in the steep slope field; whereas the latter analysed only the second year data across both the marginal fields.

3.3 Results

3.3.1 Meteorological conditions

Both the GSs were characterised by a lack of precipitation between the late winter and early spring time. The cumulative precipitation from January to April in 2019 and 2020 was 56% and 81%, respectively, lower than the long-term mean (345 mm). May was also very dry in 2020, whereas more than double of rainfall felt in 2019 compared with the long-term mean (81.5 mm).

The winter 2020 was the warmest in the last sixty years in the Emilia Romagna region (ARPAE, 2020). Compared with the long-term climatic means, the mean air temperature registered was, on average, 2.3°C higher than the historical mean. The first GS was instead characterised by a warm late winter and a relatively cool spring (Figure 1).

Thermal time of camelina (GDD) (Table 4) was similar in both GSs, and it was consistent with the range identified by Gesch (2014) (1100 – 1200 °C d). Crambe GDD varied across the two GSs. In 2019, it was 989 °C d, drastically below to the range reported by Meijer and Mathijssen (1996) (1300 – 1500 °C d), whereas in 2020, it was slightly lower (1217 °C d) (Table 4).

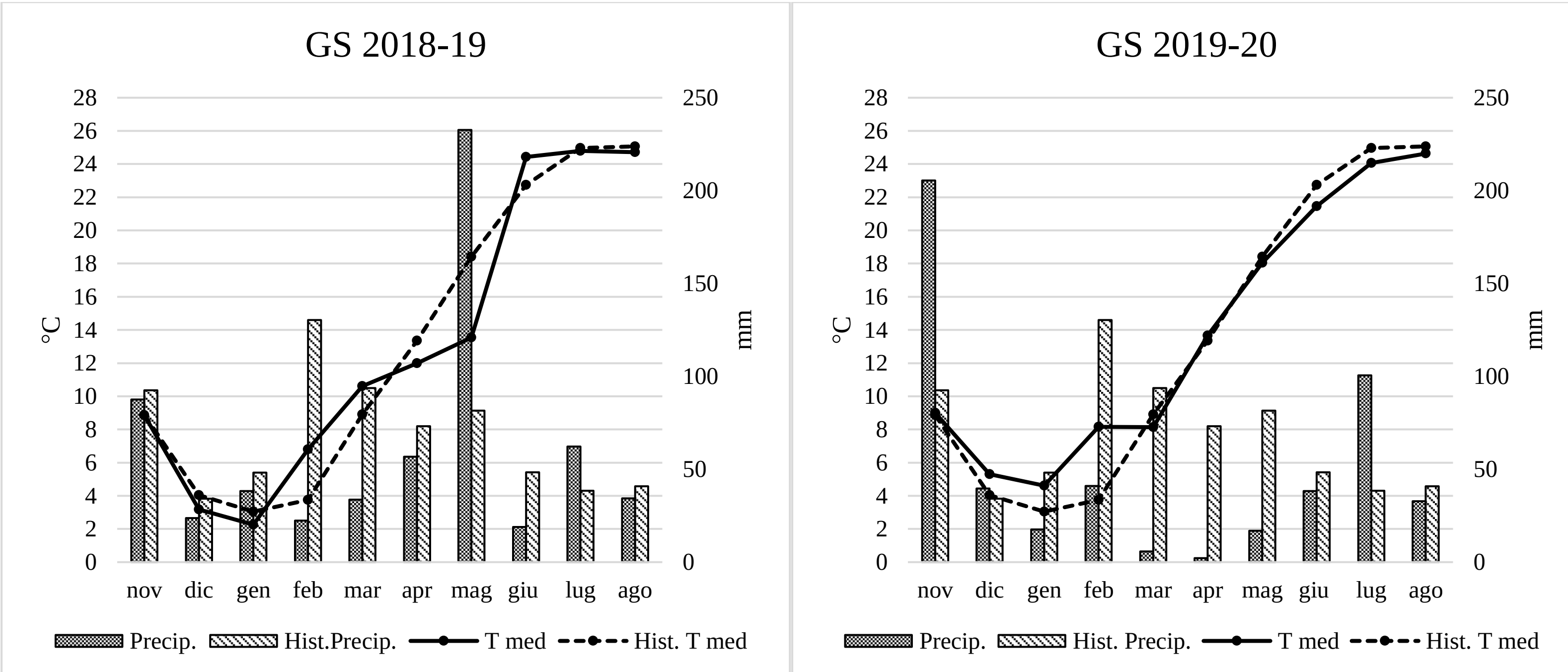

Figure 1. Weather data of GS 2018-19 (left) and GS 2019-20 (right). Precip. = cumulative precipitation, Hist. Precip. = historical cumulative precipitation, Tmed = mean air temperature, Hist. Tmed = historical mean air temperature.

3.3.2 Camelina performances

The two-way ANOVA is summarised in Table 7. Camelina seed yield and plant density were significantly influenced by the experimental field (F) and the growing season (GS). In both years, the mean values of such parameters were lower in the steep slope field than those surveyed in the favourable one, whereas the highest values were observed in the second year (Fig. 2). Seed yield was higher in the GS 2019/20 than the previous GS (1.59 vs. 1.04 Mg) (Fig. 2b), whereas it was 90% lower in the marginal field compared to the favourable ones (Fig. 2a). Similarly, plant density in the second GS was on average 47% higher than that surveyed in the first GS (Fig. 2d) , whereas it was on average 65% lower in the steep slope field than the favourable field despite the same seeding rate was applied at sowing (Fig. 2c). No significant differences were highlighted for seed weight (TKW) that was on average 1.76 g. Plant height and seed oil content depended on the interaction between F and GS (Tab. 7). A significant plant height reduction was observed in the steep slope field in both the GSs (Fig. 2e). In the first and in the second year, plants grown in the marginal field were on average about 53 and 34 cm shorter than those grown in the favourable ones, respectively. Furthermore, a severe weed pressure was surveyed only in the steep slope field during the first GS. In the first GS, seed oil content was relatively high in both experimental fields (42.5%, on average), whereas it was significantly lower in the second GS, especially under favourable condition (about 33.0%) (Fig. 2f). Furthermore, in the steep slope condition, a strong weed pressure was observed only in the first GS. The surveyed fatty acids and fatty acid groups depended on the interaction between experimental field and GS, except for PUFA content that was stable across the different environmental conditions attesting to 57.2%, on average. Slight differences in fatty acid composition were surveyed across the experimental fields, especially in the second GS (Tab. 8). Compared to the favourable condition, MUFA content in the steep slope field was 1.5% higher, whereas SFA content was 6.7% lower (Fig. 3).

*Table 7. ANOVA results. SOV = Source of variation. Considered factors were F = experimental field, GS = growing season. Considered variables were: SY = seed yield, PD = plant density, PH = plant height, OC = seed oil content, TKW = thousand seed weight, C18:1 = oleic content, C18:2 = linoleic content, C18:3 = linolenic content, C20:1 = eicosenoic content, C22:1 = erucic content, SFA = saturated fatty acid content, MUFA= monounsaturated fatty acid content, PUFA = polyunsaturated fatty acid content. * and ** mean significant differences for $P \leq 0.05$ and 0.01, respectively, n.s.= not significant.*

SOV	SY	PD	PH	TKW	OC	C18:1	C18:2	C18:3	C20:1	C22:1	SFA	MUFA	PUFA
F	**	**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
GS	*	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
F x GS	n.s.	n.s.	**	n.s.	**	**	**	**	**	**	**	**	n.s.

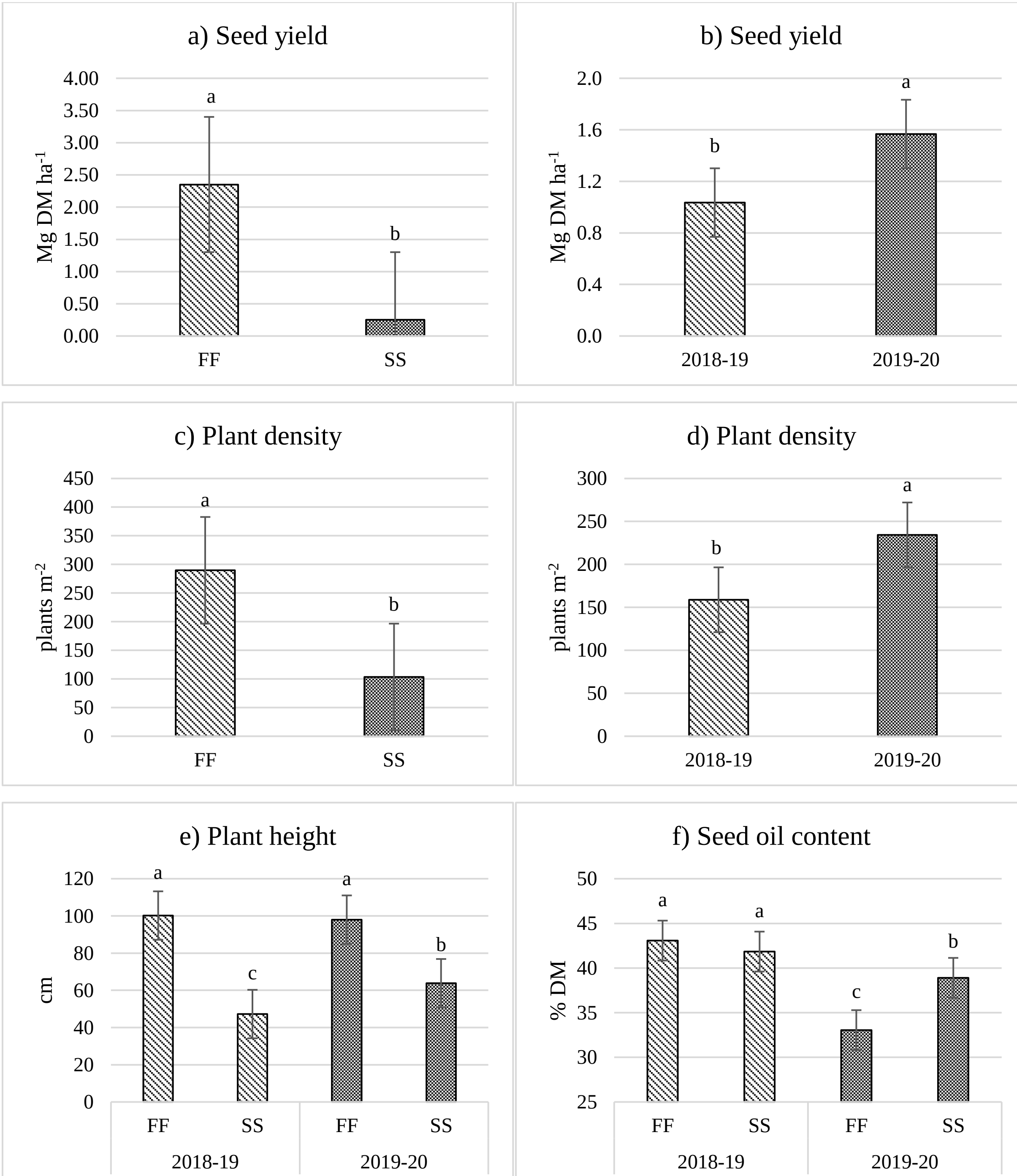

Figure 2. Seed yield, plant density, plant height and seed oil content of camelina in growing season 2018-19 and 2019-20. Charts b) and d) display the average among the favourable field and the steep slope field data in the two examined growing seasons. FF= favourable field; SS= steep slope field. 2018-19= growing season 2018-19; 2019-20= growing season 2019-20. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars= standard error.

Table 8. Average values of the principal fatty acids and fatty acid groups reported as percentage of total oil. GS = growing season, Field = experimental field, C18:1 = oleic content, C18:2 = linoleic content, C18:3 = linolenic content, C 20:1 = eicosenoic content, C22:1 = erucic acid. Different letters within each column mean significant different values (P ≤ 0.05, Tukey HSD test).

GS	Field	C18:1	C18:2	C18:3	C20:1	C22:1
2018-19	Favourable	11.9 c	16.9 c	35.9 a	14.9 a	3.3 c
	Steep slope	11.9 c	17.2 bc	35.9 a	14.1 bc	3.4 b
2019-20	Favourable	13.0 b	18.1 a	34.5 c	14.0 c	3.6 a
	Steep slope	13.9 a	17.5 b	35.3 b	14.2 b	3.1 d

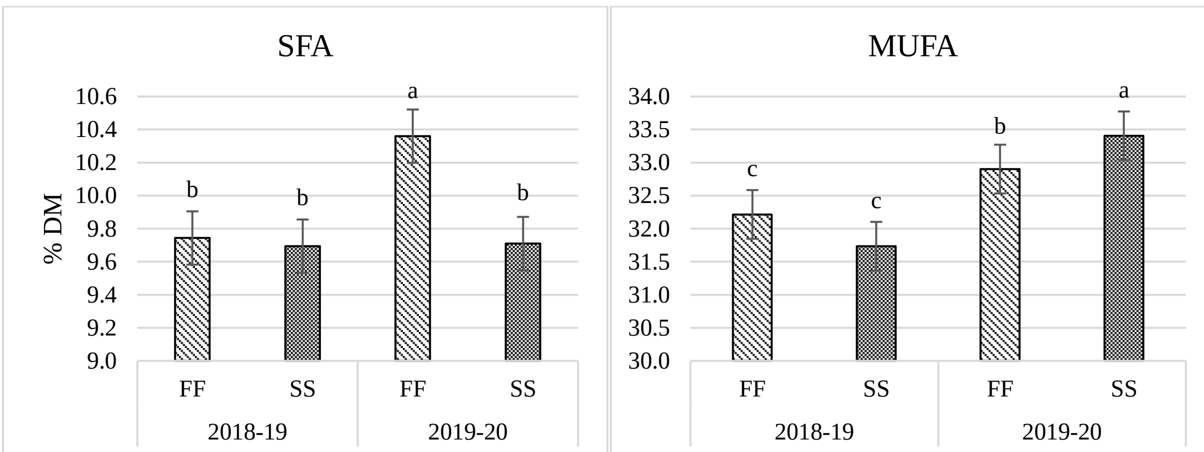

Figure 3. SFA and MUFA contents of camelina in growing seasons 2018/19 and 2019/20. FF = favourable field; MS = milder slope field; SS = severe slope field. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

The one-way ANOVA is summarised in Table 9. Under mild slope condition, seed yield (2.43 Mg ha^{-1}) and plant height (about 1.06 m) were in line with those measured under favourable condition and statistically higher compared to the steep slope field values (+539.5%, +376.7%, +66.1%, respectively). At the opposite, plant density (185 plants m^{-2}) was consistent with that surveyed in the steep slope field and lower than that measured in the favourable condition (329 plants m^{-2}) (Fig. 4). No difference was observed in seed weight (TKW) that was 1.65g, on average, whereas the seed oil content was 36.9 % in the milder slope condition placing between the values of the steep slope and the favourable field (38.9 % and 33.0%, respectively) (Fig. 4). Any difference in oil fatty acid profile was surveyed between the marginal fields (Tab. 10). Compared to the favourable field, MUFA content was on average 1.8% higher but it was partially balanced by SFA level decrease (-6.7%); any significant difference was instead noticed about PUFA content that was 55.4%, on average of the three experimental fields (Tab. 10).

*Table 9. ANOVA results. Considered factor was F = experimental field. Considered variables were: SY = seed yield, PD = plant density, PH = plant height, OC = seed oil content, TKW = thousand seed weight, 18:1 = oleic content, 18:2 = linoleic content, 18:3 = linolenic content, 20:1 = eicosenoic content, 22:1 = erucic content, SFA = saturated fatty acid content, MUFA= monounsaturated fatty acid content, PUFA = polyunsaturated fatty acid content. * and ** mean significant differences for P ≤ 0.05 and 0.01, respectively, n.s.= not significant.*

Source of variation	SY	PD	PH	TKW	OC	18:1	18:2	18:3	20:1	22:1	SFA	MUFA	PUFA
F	**	**	**	n.s.	**	**	**	n.s.	**	**	**	*	n.s.

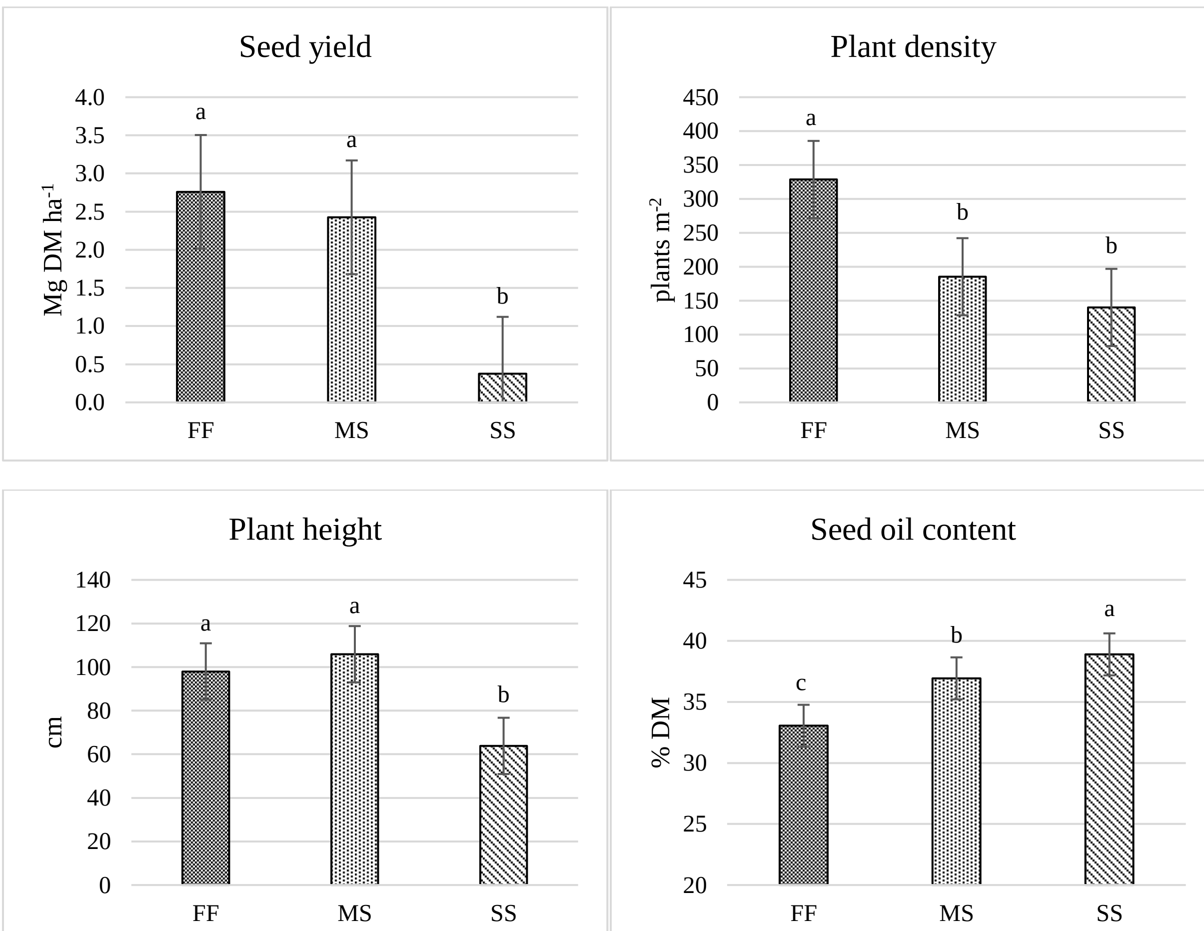

Figure 4. Plant density, seed yield, plant height, and seed oil content of camelina in growing season 2019-20. FF = favourable field; MS = milder slope field; SS = severe slope field. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

Table 10. Average values of the principal fatty acids and fatty acid groups reported as percentage of total oil. GS = growing season, Field = experimental field, C18:1 = oleic content, C18:2 = linoleic content, C18:3 = linolenic content, C20:1 = eicosenoic content, C22:1 = erucic acid, SFA = saturated fatty acid content, MUFA= monounsaturated fatty acid content, PUFA = polyunsaturated fatty acid content. Different letters within each column mean significant different values (P ≤ 0.05, Tukey HSD test).

Field	C18:1	C18:2	C18:3	C20:1	C22:1	SFA	MUFA	PUFA
Favourable	13.0 b	18.1 b	34.5 a	14.0 b	3.6 a	10.4 a	32.9 b	55.3 a
Mild slope	14.2 a	19.0 a	34.1 a	14.2 a	3.0 c	9.8 b	33.6 a	55.4 a
Steep slope	13.9 a	17.5 b	35.3 a	14.2 a	3.1 b	9.7 b	33.4 a	55.5 a

3.3.3 Crambe performances

Despite the thermal sum was below to the value reported by Meijer and Mathijssen (1996) (1300 – 1500 °C d) in both the GSs, crambe was able to complete its cycle. The two-way ANOVA is summarised in Table 11. Crambe seed yield, plant density, and seed yield per plant depended on the interaction between the experimental field (F) and the growing season (GS). Seed yield and seed yield per plant measured under severe marginal condition were always lower than that surveyed under favourable ones (Fig. 5). In the steep slope field, seed yield was 75% lower in both the growing seasons (1.6 vs. 0.4 Mg DM ha^{-1}, and 0.8 vs. 0.2 Mg DM ha^{-1}); a seed yield depression of about 50% characterised both the experimental sites in the second year. Compared with favourable field, seed yield per plant surveyed in the marginal field was 35% and 82.5% lower in the first and in the second growing season, respectively (Fig. 5). In the first GS, plant density under severe marginal condition was 58.3% lower than that observed under the favourable ones (168 plants m^{-2}), whereas in the second GS was observed an opposite behaviour (70 vs. 41 plants m^{-2}, respectively) (Fig. 5). Severe weed pressure was observed in the steep slope field in both the GSs, whereas in the favourable field only in the second year. No significant differences were noticed for seed weight (TKW), plant height, and seed oil content that were on average 5.40 g, 89 cm, and 32.4%, respectively. MUFA and PUFA content depended on the interaction between F and GS, whereas SFA content did not show any significant variation (Tab. 11). The first GS was characterised by the lowest MUFA content (73.3%, on average). The same MUFA and PUFA contents were surveyed in both the experimental sites in the first-year study (73.3% and 16%, respectively). The highest MUFA content beside to the lowest PUFA level were instead surveyed in the samples collected in the steep slope field in the second GS (76.5% and 14.5%, respectively) (Fig.6). Among the main fatty acids, significant differences occurred only in oleic acid (C18:1) and erucic acid (C22:1) content; the former depended on the interaction between F and GS, whereas the latter on the GS (Tab. 11). Oleic acid content was relatively stable in both the experimental sites in the first year (19.75%, on average), whereas in the second GS it was about 16.3% higher in the steep slope filed compared to the favourable one (18.6% vs. 16.0%, respectively). Erucic acid content was 11% lower in the first growing season compared to the second one (49.2% vs. 55.7%, on average) (Fig. 6).

*Table 11. Two-way ANOVA results of crambe (2019 and 2020). SOV = Source of variation. Considered factors were F = experimental field, GS = growing season. Considered variables were: SY = seed yield, PD = plant density, SYP = seed yield per plant, PH = plant height, OC = seed oil content, TKW = thousand seed weight, C18:1 = oleic content, C18:2 = linoleic content, C18:3 = linolenic content, C20:1 = eicosenoic content, 22:1= erucic acid, SFA = saturated fatty acid content, MUFA= monounsaturated fatty acid content, PUFA = polyunsaturated fatty acid content. * and ** mean significant differences for $P \leq 0.05$ and 0.01, respectively, n.s.= not significant.*

SOV	SY	PD	SYP	PH	TKW	OC	C18:1	C18:2	C18:3	C22:1	SFA	MUFA	PUFA
F	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
GS	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**	n.s.	n.s.	n.s.
F x GS	**	**	**	n.s.	n.s.	n.s.	**	n.s.	n.s.	n.s.	n.s.	*	*

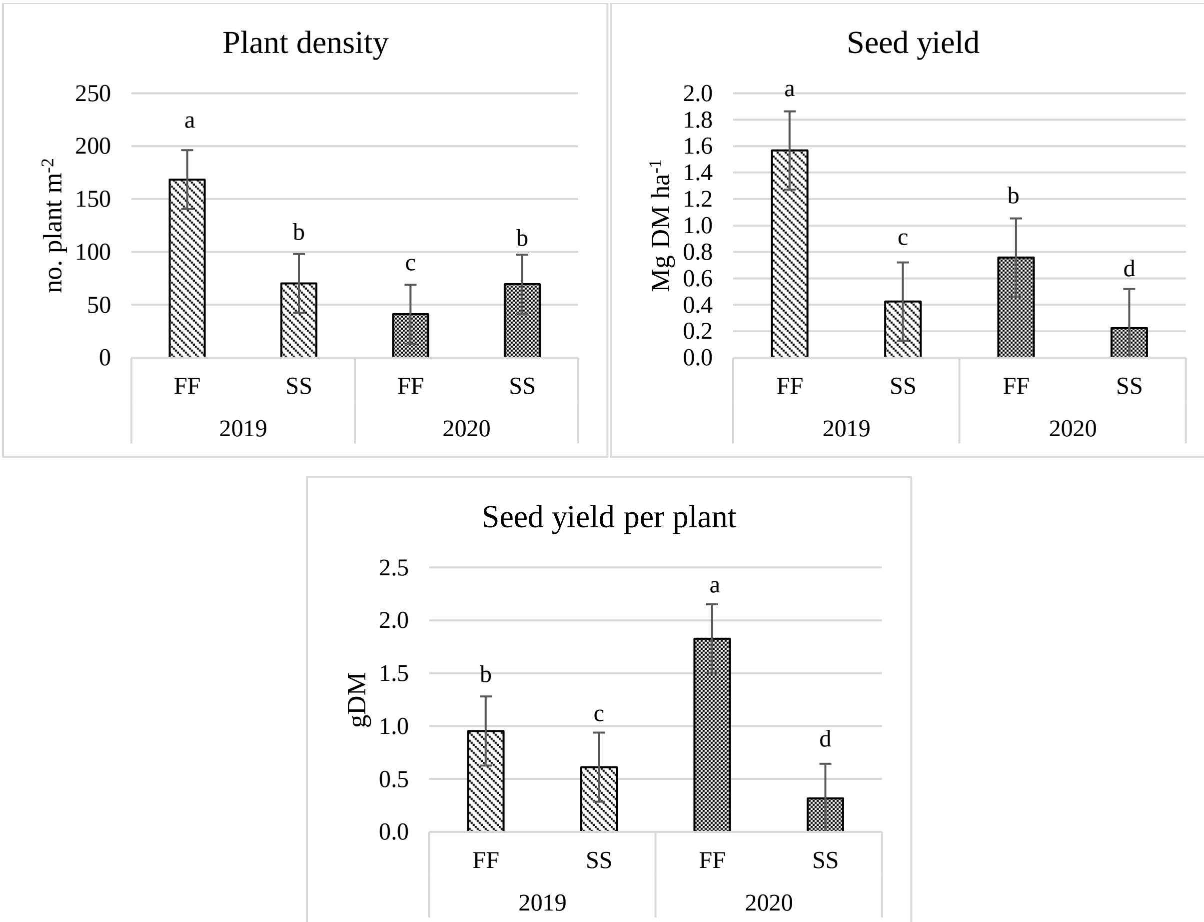

Figure 5. Plant density, seed yield, seed yield per plant of crambe in growing seasons 2019 and 2020. FF = favourable field; SS = severe-slope field. Different letters above each column mean significant different values ($P \leq 0.05$, Tukey HSD test); bars = standard error.

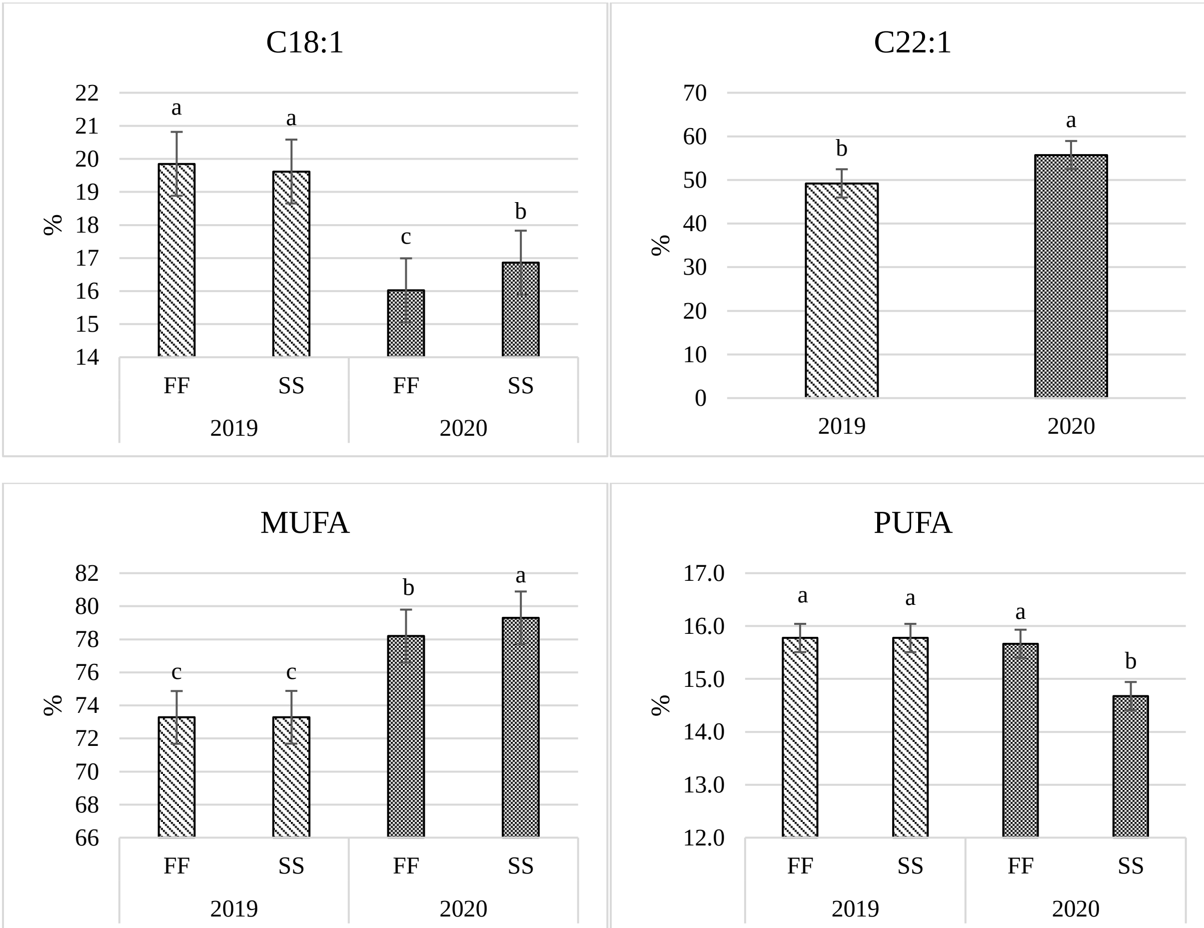

Figure 6. Oleic acid (C18:1), erucic acid (C22:1), MUFA and PUFA contents of crambe in growing seasons 2019 and 2020. FF = favourable field; MS = milder slope field; SS = severe-slope field. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

The one-way ANOVA is defined in Table 12. Under the milder slope condition, it was surveyed the highest seed yield (1.33 Mg ha^{-1}), whereas plant density was relatively low (49 plants m^{-2}) and lower than that measured in the steep slope field (Fig. 7). Any significant difference was observed about seed oil content, SFA and erucic acid level across the experimental fields, that were on average 32.4%, 6.1%, and 55.8%, respectively. MUFA and PUFA content (79.6% and 14.3%, respectively) was consistent with that surveyed in the steep slope field (Tab. 13). Some slight differences occurred in the acidic composition of crambe oil relatively to the minor fatty acids content (Tab. 13).

*Table 12. One-year ANOVA results of crambe (2020). Considered factor was F = experimental field. Considered variables were: SY = seed yield, PD = plant density, SYP = seed yield per plant, PH = plant height, TKW = thousand seed weight, OC = seed oil content, 18:1 = oleic content, 18:2 = linoleic content, 18:3 = linolenic content, 22:1 = erucic acid, SFA = saturated fatty acid content, MUFA= monounsaturated fatty acid content, PUFA = polyunsaturated fatty acid content. * and ** mean significant differences for P ≤ 0.05 and 0.01, respectively, n.s.= not significant.*

Source of variation	**SY**	**PD**	**SYP**	**PH**	**TKW**	**OC**	**18:1**	**18:2**	**18:3**	**22:1**	**SFA**	**MUFA**	**PUFA**
F	**	**	**	**	n.s.	n.s.	**	**	**	n.s.	n.s.	**	**

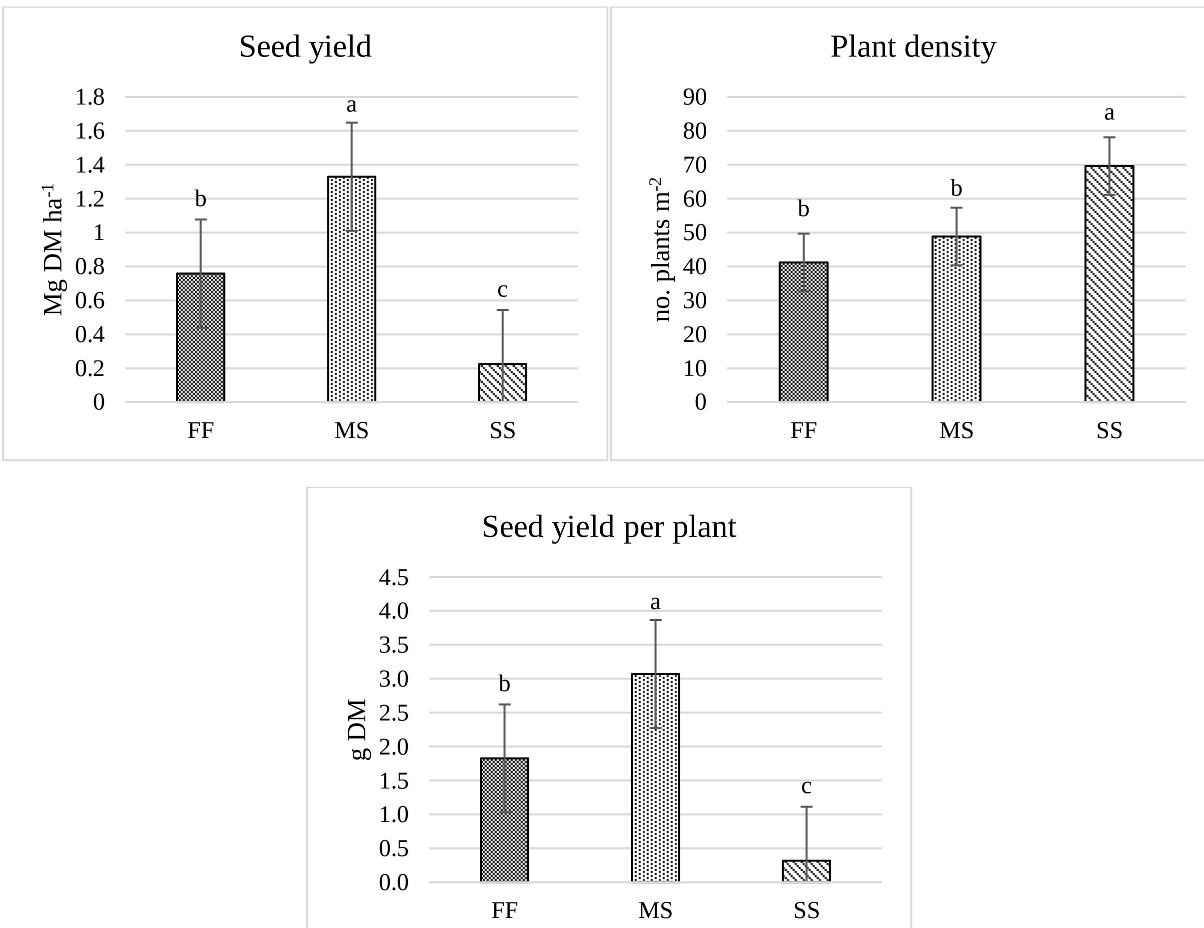

Figure 7. Plant density, seed yield, seed yield per plant of crambe in growing season 2020. FF = favourable field; MS = milder slope field; SS = severe slope field. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

Table 13. Average values of the principal fatty acids and fatty acid groups reported as percentage of total oil of crambe in growing season 2020. Field = experimental field, C18:1 = oleic content, C18:2 = linoleic content, C18:3 = linolenic content, C20:1 = eicosenoic content, C22:1 = erucic acid, SFA = saturated fatty acid content, MUFA= monounsaturated fatty acid content, PUFA = polyunsaturated fatty acid content. Different letters within each column mean significant different values (P ≤ 0.05, Tukey HSD test).

Field	C18:1	C18:2	C18:3	C22:1	SFA	MUFA	PUFA
Favourable	16.0 b	9.0 a	5.7 a	55.5 a	5.6 a	75.3 b	15.5 a
Mild slope	17.2 a	8.0 c	5.4 b	56.0 a	5.6 a	77.0 a	14.1 b
Steep slope	18.6 a	8.5 b	5.3 b	55.9 a	5.5 a	76.5 a	14.5 b

3.3.4 Crop comparison

3.3.4.1 Camelina vs. Barley

In the two-way ANOVA, normalised seed yield (NY) and net revenue (NR) depended on the interaction between crop (C) and growing season (GS) (Tab. 14). In both GSs, seed yield of camelina and barley were substantially below to their break-even yield (BY) value (1.41 and 4.79 Mg ha^{-1}, respectively) and net revenues were negative for both as shown in Figure 8. In the first GS, camelina achieved the lowest normalised yield (9.8%) and negative net revenue (-899 € ha^{-1}), whereas in the second year both values were comparable with those calculated for barley (27% vs. 30.1% and -724 € vs. -738 € ha^{-1}, respectively) (Fig. 8).

*Table 14. Two-way ANOVA results of camelina and barley comparison (two-years analysis, GS 2018/19 and 2019/20). Considered factors were: C = crop, GS = growing season. Considered variables were: NY = normalised seed yield; NR = net revenue. * and ** mean significant differences for P ≤ 0.05 and 0.01, respectively, n.s.= not significant.*

Source of variation	NY	NR
C	n.s.	n.s.
GS	n.s.	n.s.
C x GS	**	**

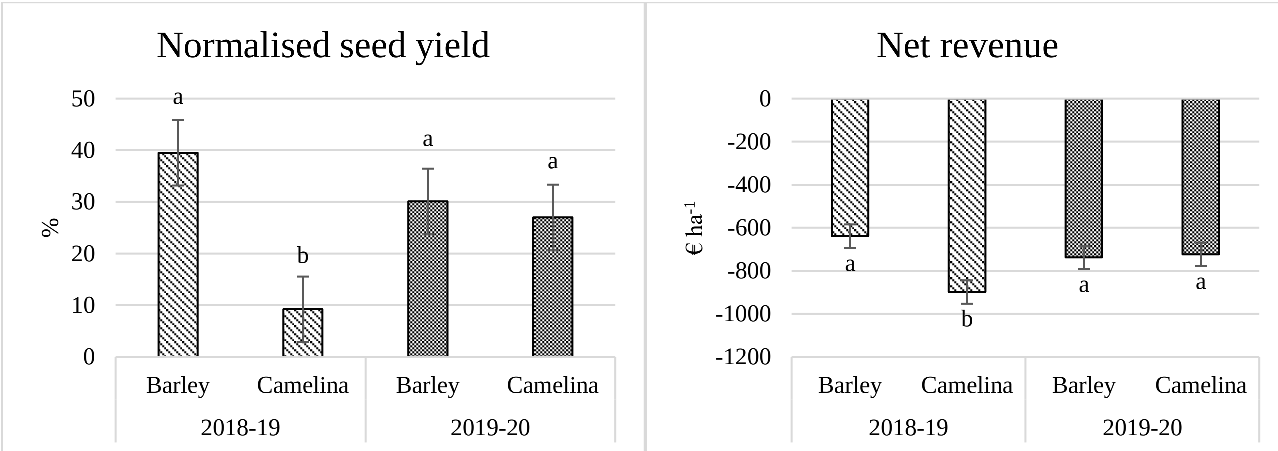

Figure 8. Normalised seed yield, net revenue of camelina and barley under the severe slope field in GS 2018/19 and 2019/20. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

The one-way ANOVA is reported in Table 15. NY and NR depended on the interaction of crop (C) and experimental field (F). Under mild slope condition both camelina and barley normalised yields were higher than those surveyed on the steep slope field (538% and 87%, respectively). However, only camelina exceeded its BY in the mild slope field obtaining a positive net revenue (711 € ha^{-1}) (Fig. 9).

*Table 15. One-way ANOVA results of camelina and barley comparison (one-year analysis, GS 2019/20). Considered factors were: C = crop, F = experimental field. Considered variables were: NY = normalised seed yield; NR = net revenue. * and ** mean significant differences for P ≤ 0.05 and 0.01, respectively, n.s.= not significant.*

Source of variation	**NY**	**NR**
C	**	**
F	**	**
C x F	**	**

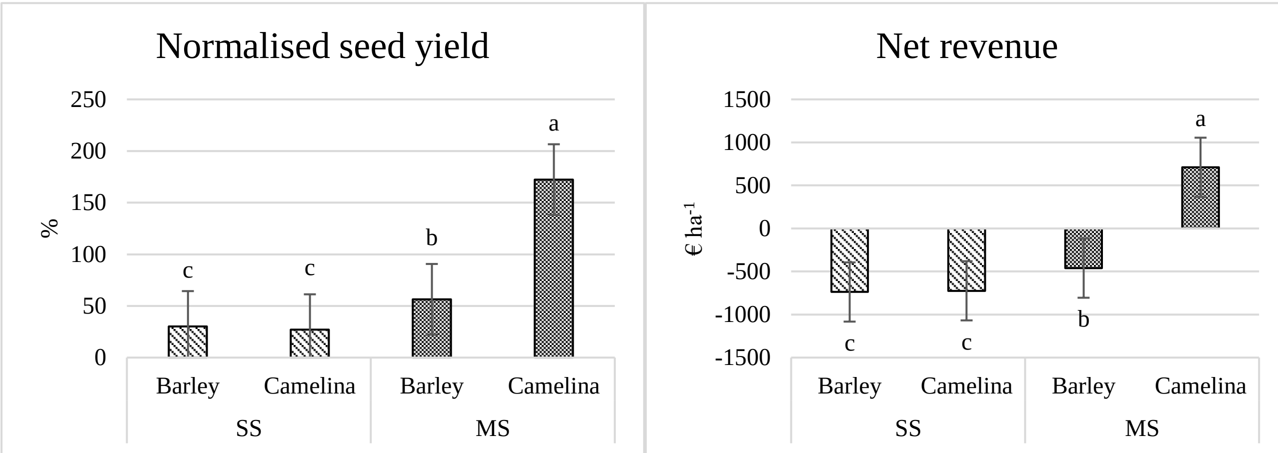

Figure 9. Normalised seed yield and net revenue of camelina and barley in growing season 2019/20. SS = severe slope field; MS = milder slope field. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

3.3.4.2 Crambe vs. Sunflower

No significant difference was surveyed about normalised yield (NY) and net revenue (NR) in the two-way ANOVA (Tab. 16). In both the GSs, normalised yield of crambe and sunflower was greatly below to their respective BY (1.87 and 2.07 Mg DM ha^{-1}, respectively) (Table 17). Crambe was 74.7% and 86.7% lower than its BY in the first and in the second growing season, respectively, whereas sunflower was 42% of its BY in both the GSs.

*Table 16. Two-way ANOVA results of crambe and sunflower comparison (two-years analysis, GS 2019 and 2020). Considered factors were: C = crop, GS = growing season. Considered variables were: NY = normalised seed yield, NR = net revenue. * and ** mean significant differences for P ≤ 0.05 and 0.01, respectively, n.s.= not significant.*

Source of variation	NY	NR
C	n.s.	n.s.
GS	n.s.	n.s.
C x GS	n.s.	n.s.

Table 17. Normalised seed yield and net revenue of crambe and sunflower under steep slope field in GSs 2019 and 2020. GS = growing season; BY = break-even yield. Different letters within each column mean significant different values (P ≤ 0.05, Tukey HSD test).

Crop	**GS**	**Seed yield** Mg ha^{-1}	**BY** Mg ha^{-1}	**Normalised seed yield** %	**Net revenue** € ha^{-1}
Crambe	2019	0.42	1.87	22.6 a	- 870 a
	2020	0.22		11.8 a	- 990 a
Sunflower	2019	0.87	2.07	42.0 a	- 639 a
	2020	0.87		42.0 a	- 639 a

In the one-way ANOVA (Tab. 18), normalised yield and net revenue depended on the two studied factors (crop and experimental field) and their interaction. Compared with the steep slope field results, both crops improved their NY in the milder slope field; for instance, in crambe increased about 5 times and in sunflower doubled (Fig. 10). However, only sunflower exceeded its break-even yield in the milder marginal condition, providing a positive net revenue of 299 € ha^{-1} (Fig. 10).

*Table 18. One-way ANOVA results of crambe and sunflower comparison (one-year analysis, GS 2020). Considered factors were: C = crop, F = experimental field. Considered variables were: NY = normalised seed yield, NR = net revenue. * and ** mean significant differences for P ≤ 0.05 and 0.01, respectively, n.s.= not significant.*

Source of variation	**NY**	**NR**
C	**	**
F	**	**
C x F	*	*

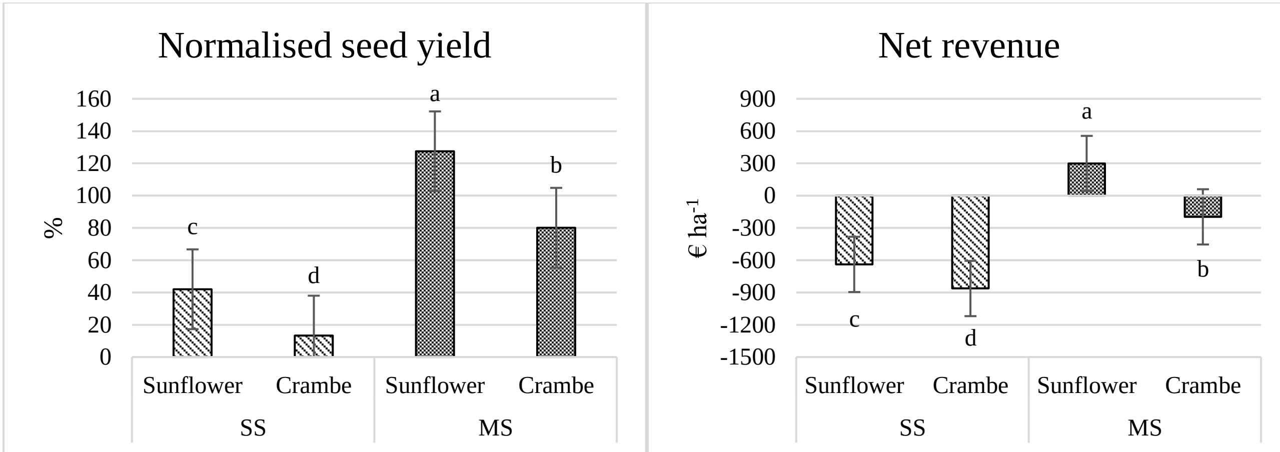

Figure 10. Normalised seed yield and net revenue of crambe and sunflower in growing season 2020. SS = severe slope field; MS = milder slope field. Different letters above each column mean significant different values (P ≤ 0.05, Tukey HSD test); bars = standard error.

3.4 Discussion

3.4.1 Camelina

The results showed that camelina was able to grow under steep slope field, confirming its wide adaptability to different environments (Berti et al., 2016). However, camelina cultivation under such a severe marginal condition might be limited by the unsatisfactory seed yield that was significantly lower than that reported by the literature for the North of Mediterranean area. A seed yield of about 1.80 Mg DM ha^{-1} was indeed identified as average among different camelina genotypes in three year-study carried out near Bologna (Zanetti et al. 2017), whereas the seed yield under steep slope condition was 0.25 Mg DM ha^{-1}, on average of the two-year of study. Although only one year of study has been carried out under milder slope condition, the preliminary results showed how camelina productivity could broadly vary between the two slope fields even though both were considered marginal according to the MAGIC project approach. Slope angle indeed affects soil erosion and water availability (Cerdà & García-Fayos, 1997; Nadal-Romero et al., 2014) causing changing in soil fertility. The poor physico-chemical proprieties of the steep slope field soil (see Table 2) rationally caused the surveyed seed yield loss and plant growth reduction, according to that described by Waraich et al. (2017). The severe marginal condition indeed compromised camelina growth, affecting plant height and plant density, and reducing the crop capacity to compete against weeds described by Royo-Esnal & Valencia-Gredilla (2018). At the opposite, in the mild slope field camelina was able to maintain a really good seed yield despite the relatively low plant density, confirming its plasticity (McVay & Khan, 2011). However, the low plant density surveyed in both the slope fields underlined how plant establishment still represents a challenge for the cultivation of camelina under such a marginal condition. Especially in the severe slope field, an improvement of plant establishment methods (i.e., seeding rate, sowing method) could help achieve higher plant density at harvest and, consequently, improve weeds control and enhance seed yield (Johnson et al., 2009). Despite the smaller plant size, plant height in severe marginal field was compatible with mechanical harvest. 1000-seed weight (TKW) was not instead affected by the marginality and it was in line with the literature evidence (0.8-1.8 g) (Berti et al., 2016). The seed weight stability across different experimental sites represented a positive agronomic trait since seed uniformity could ease harvest operations at farm scale. Compared to the seed yield, seed oil content was never negatively affected by the slope condition. At the opposite, the exceptional drought that characterised the second growing season produced the overall seed oil content decreasing in all the experimental fields, confirming that such trait can vary broadly because of the meteorological conditions (Berti et al., 2016; Budin et al., 1995). Although differences in oil fatty acid profile across the experimental fields were slight, the results underlined a small increase in oil's desaturation level under marginal conditions that could be due to temperature differences in the experimental fields during the reproductive phase (Righini et al., 2019). That could be rationally caused by the slope angle and orientation (South, South-East) of fields and consequently by the higher solar radiation incidence (Mcaneney & Noble, 1976) that could have increased temperature locally. However, considered the relatively low magnitude of the variations, camelina showed the capacity to maintain the oil composition relatively stable across the experimental fields, that represents a positive crop trait, since industry generally looks for standardised feedstock. In general, the oil fatty acid profile was in line with the literature evidence (14–16% C18:1, 15–23% C18:2, 31–40% C18:3, 12–15% C20:1) (Berti et al., 2016; Vollmann et al., 2007), except for oleic acid (C18:1) content that was below.

3.4.2 Crambe

Although crambe was able to grow under marginal conditions, the suitability of its cultivation in such a condition was uncertain. In all the experimental fields, seed yield was clearly below to the mean value reported by Zanetti et al. (2016) for the same cultivar (Galactica) in the North of Italy (2.68 Mg DM ha^{-1}). Analogously to camelina, although both the slope fields were affected by the same biophysical constraint and were equally defined as marginal according to the MAGIC project approach, crambe productivity widely varied across them. The hard growing condition of the severe marginal field (high slope angle and poor soil fertility) affected plant growth, confirming the large influence of the environment on crambe productivity (Meijer et al., 1999). Plant height was lower than the average reported by Righini et al. (2016) (1.0 - 1.2 m) even though it was compatible with mechanical harvest. Plant density was affected by marginality. Thus, as discussed in camelina section, an improvement of plant establishment in slope fields, especially under severe marginal condition where plant plasticity (Zoz et al., 2018) is limited by marginality, could promote reducing weed pressure and improving seed yield as a consequence of higher plant density at harvest. Compared to the first year, the overall yield loss (about 50%) surveyed in the second growing season was due to the severe drought that characterised the spring time, confirming crambe's sensitivity to drought (Dias et al., 2015). Seed weight (TKW) was slightly lower than the literature evidence (6 – 10 g) (Samarappuli et al., 2020), and it might be due to a lack of sulphur fertilisation (Ropelewska & Jankowski, 2020).

At the opposite of the seed yield, seed oil content of the two-year study was positively stable across all the experimental fields, also in the severe marginal condition. However, the mean value surveyed was below to that observed for Galactica in the North of Italy (~45% DM) (Zanetti et al., 2016a), even though some differences in methodology occurred. The relatively low seed oil content might be due to the weather pathway that characterised plant reproductive stage in both the GSs (rainy and cool in 2019 and dry in 2020) confirming the influence of climatic conditions on crambe oil content (Lalas et al., 2012; Lazzeri et al., 1994). The erucic acid was consistent with the literature evidence (50-65%) (Samarappuli et al., 2020) except for the first GS. There, the relative lower content of C22:1 (~49%), surveyed beside to a relative higher oleic acid (C18:1) content, might be due to the strong temperature rise occurred during the seed ripening stage at the beginning of June 2019 after a relatively cool May (see 2.3.1). Yaniv et al. (1995), indeed, reported that high temperatures could differently affect erucic and oleic acid biosynthesis in high-erucic acid *Brassicaceae* by determining an increase of the latter to the detriment of the former. The reduction in C22:1 content was not completely balanced by C18:1 biosynthesis, so that, in the first GS, the MUFA level was relatively lower than that surveyed in the second year. Therefore, anticipating the sowing could help to improve erucic acid content, anticipating the reproductive and ripening plant stages, and avoiding their occurrence during the warmer periods (Zanetti et al., 2016b). Despite some significant differences, PUFA level was always consistent with the literature evidence (Samarappuli et al., 2020). As described in camelina section, the relative stability of crambe oil quality across different growing conditions was an advantageous trait from the industry point of view, and it could enhance the cultivation of such crops under steep slope marginal fields.

3.4.3 Crop comparison

The comparisons between camelina an barley, and between crambe and sunflower were carried out to better understand whether, in a simplified market framework, industrial crops can represent a suitable alternative to help diversifying farmer income in marginal land reducing arable land abandonment, and at the same time to help decreasing iLUC risk providing renewable feedstock for the bioeconomy transition. It is worth noting that all the studied crops were unprofitable under the severe steep slope condition without any form of public subsidy. As described in camelina section (see 3.4.1), the poor physico-chemical proprieties of the steep slope field soil (see Table 2) rationally caused the recorded seed yield loss of the two tested food crops. In the second growing season, the low results in terms of normalised yield (NY) and net revenue (NR) surveyed in barley was rationally distorted by the delay in sowing that can affect negatively seed yield as described by Green et al. (1985), hiding the actual crop productivity. It forced to reconsider the gap between barley and camelina in the second GS, nevertheless the good profitability surveyed in the mild slope field for the industrial crop enhanced the attractivity of camelina to be grown in such a marginal condition. At the opposite, the negative net revenue of crambe surveyed also in the milder slope field suggested a low suitability of such crop in marginal slope condition. It was strengthened by the comparison with sunflower that instead showed a positive profitability in the mild slope field despite to the drought conditions that characterised the GS 2019. Only one year of data was available for the analysis; thus, further studies will be necessary before further conclusions can be made.

3.5 Conclusion

The study confirmed that camelina and crambe are suitable for growing in marginal land affected by terrain constraint (slope >15%), confirming their adaptability to a wide range of environments. It is noteworthy that qualitative yield traits (i.e., seed oil content, fatty acid profile) of both crops were never negatively affected by the marginal conditions. Nevertheless, marginality reduced seed yield of both oilseed crops, but only under severe slope condition. Low plant density was one of the main challenging aspects of camelina and crambe cultivation under marginal slope condition. Although under the milder slope field both crops showed the ability to maintain satisfactory yield across a broad range of plant populations, under the severe slope condition the poor plant density was a limiting aspect to control weeds pressure and to improve yields. The negative profitability observed for all the tested crops under the severe marginal condition questioned not only the opportunity to cultivate camelina and crambe under such a marginal land but even the tested food crops. At the opposite, the positive profitability of camelina in the milder slope field made its cultivation in such a condition very interesting. Finally, the study implies that marginality should be better defined to help identifying the different marginal areas and locate the most suitable crops in the context of a sustainable biomass production that cannot be separated from a development of special agronomic measures under steep slope fields.

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