Marginal lands for Growing Industrial Crops

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1 Publishable executive summary

The exploitation of industrial crops for the production of ligno-cellulosic compounds and vegetable oil on marginal lands relies on efficient harvesting and logistics' strategies. The present deliverable goes through the difficulties encountered from harvesting to dispatchment of indrustrial crops highlighting prons and cons of the currently available technologies to improve the whole value chain in the following categories: lignocellulosic crops (fiber, herbaceous perennial and Short-Medium Rotation Coppice (SRC-MRC)) and oil crops. The two sections are indipendently investigated focusing on harvesting and densifiction of the biomass to reduce cost and increase profitability. The information provided within the present document was gathered from experimental data collected on fields, from literature review and background knowledge gained from collaboration in previous research projects.

Regarding fiber crop (in particular hemp) it is possible to say that there are several solutions available to harvest this species, which should be properly selected according to the crop features and to the aim of the cultivation, i.e. fiber and seed-fiber.

Focusing on lignocellulosic crops, the present deliverable focused mainly on miscanthus, describing the possible alternative solutions which are generally based on cutting the plants and densify them through chipping and/or baling.

Harvesting systems for SRC and MRC have been instead experiencing a substantial change in the last years, shifting from dedicated systems for biomass harvesting and densification to semi or fully mechanized harvesting approaches, derived from forestry sector, in order to produce fiber wood from the main stem and biomass from branches and tops.

Finally, concerning oil crops, it is possible to say that, among the investigated ones, camelina and castor can efficiently be harvested with conventional combine harvesters equipped with cereal and sunflower header respectively. Castor bean harvesting is instead still a great challenge, indeed the present deliverable highlights how a sunflower header is a better option than a cereal one, but however many concerns are still present regarding seed loss and quality of the collected product.

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2 Introduction

The biomass demand to fuel a growing global bio-based economy is expected to tremendously increase over the next decades, and projections indicate that dedicated biomass crops will satisfy a large portion of it. The establishment of dedicated biomass crops raises huge concerns, as they can subtract land that is required for food production, undermining food security. In this context, biomass crops suitable for cultivation on marginal lands raise attraction, as they could supply biomass without competing for land with food supply.

The term 'marginal land' has entered the wider political debates, and today biofuel crops are generally promoted and supported on marginal land; nonetheless, marginal land has been not yet unequivocally defined, and there is not a clear information on where, when and how much genuine marginal land is available.

A current estimate of marginal land of various types existing in Europe is about 1,350,000 ha, either abandonedbecause its productivity is too low to provide enough income to farmers, or as underused land by farmers whose income is hardly above their opportunity costs. Agriculture on with existing (food) crops has few chances to improve as the crops used are not well adapted to marginal conditions. A large number of industrial crops have been tested on both EU and national projects for bio-based products and energy. Most of these crops are reported as crops with ability to grow on marginal land. Thus, the idea to use this land for growing industrial crops as feedstock for the bio-based industry has the advantage that will not affect the food vs fuel competition. Moreover, part of the marginal land has been recorded as contaminated and polluted being inappropriate for food and feed crops growing for sanitary reasons but can be exploited for industrial crops cultivation.

Industrial crops can provide abundant renewable biomass feedstocks for the production of high added-value bio-based commodities (i.e., bioplastics, bio-lubricants, bio-chemicals, pharmaceuticals, bio-composites, etc.) and bioenergy. They can be broadly categorised as oil, lignocellulosic, carbohydrate or specialty crops. Most of them are multipurpose crops offering the opportunity to follow a cascade bio refinery concept to produce several value-added bio products and bioenergy, thus feeding the bio-based economy.

Prospectively, industrial crops can increase and diversify farmers' income through access to novel bio-based markets (i.e., bulk and fine chemical, biomaterial or bioenergy industries, amongst others), and the possibility to exploit marginal lands with limited value for conventional agriculture. In recent years, a debate has emerged regarding food security and land use for bioenergy/industrial non-food crops. Cultivating industrial crops on marginal land unsuitable for food production is consistently proposed as a viable alternative to minimize land-use competition for food production, and its adverse effects (direct or indirect) on food security, land based GHG emissions and biodiversity loss.

In MAGIC the industrial crops will be categorised in four groups: a) the oil crops (camelina, crambe, lesquerella, cuphea, castor, safflower, flax, etc.), b) the lignocellulosic crops that will include the fibre crops (flax, hemp, kenaf, nettle, biomass sorghum, etc.), the perennial herbaceous crops (switchgrass, giant reed, miscanthus, reed canary grass, etc.) and the woody species (willow, poplar, eucalyptus, robinia, etc.) c) the carbohydrate crops (biomass sorghum, cereals, sugar beet, etc.) and d) specialty crops.

3 Lignocellulosic Crops

3.1 Fiber crops

Among the 20 species selected within MAGIC Project the main fiber crop is hemp (*Cannabis sativa* L.). Hemp is considered a multi-purpose crop, considering that the various fractions of the plant can have different uses but among these, fiber is for sure one of the most known and investigated by scientific literature.

Hemp for fiber production is usually harvested at the moment of full flowering of male plants, considering that this represents the point of maximum fiber yield [1]. Harvesting hemp is particularly challenging, considering some features of this crop like high biomass yield and plant height.

There can be three different harvesting strategies for fiber hemp: whole stem; cut stem and combined harvesting for fiber and seed production [2].

3.1.1 Whole stem harvesting

In whole stem harvesting, the stems of the plant are maintained entire or in long sections for collection and processing. The obtained material with this type of harvesting approach consists of long fibers for textile industrial use. This system is not widely applied and there are a few available machineries for this harvesting strategy.

A machine developed for the whole stem harvesting is the model ZK-1,9 (SEL'MASH, Bezheck, Russia). The base version of this machine was designed to cut and arrange the stems parallel to each other in an ordered windrow. After the installation of a special conveyor, the machine was able to replace the operation that was previously performed by hand, i.e. cutting the plants and creating bundles which are left on the ground to be arranged successively by the operators for drying [3].

3.1.2 Cut stem harvesting

In this type of harvesting, the plants are mowed and then sectioned or shredded being left disorderly on the soil by forming windrows or a uniform bed of mowed stems and leaves. There are different machineries to perform this kind of harvesting. The first machine, which is also the most widespread in Europe, is the HempCut 3000/4500 (HempFlax, Oude Pekela, Netherland). The machine was further developed by the company Wittrock (Rhede, Germany), becoming the worldwide sold machine HempCut 3000 or 4500 according to the working width (Figure 1). HempCut has moreover a modified header developed by Kemper (Stadtlohn, Germany) and an adapted one-knife cutting drum. During harvesting operation the stalks of the plant are fed longitudinally into the chopping drum, cut into pieces of 600–700 mm and expelled directly under the drum in a windrow (Mastel and Stolzenburg, 2002). The material capacity of this machine is in the range of 2.1-3.4 ha/h with working speed of 5-10 km/h.

Figure 1. Hempcut machine [4].

Another machine baed on the cut stem strategy is “Bluecher 02/03” (Kranemann, Klocksin, Germany, Kranemann.org, 2014) (Figure 2). The basic concept of this machinery was to preserve the original array of the hemp plant until it is cut into pieces of 600–700 mm. The conveyor system maintains and collects stalks in a vertical position. Successively, through cutting discs located at fixed positions on the drum, the stalks are sectioned being kept upright in their natural position before being set in a swath [5]. Reported material capacity for this system is almost 3 ha/h.

Figure 2. Blücherh 02 mounted on self-propelled New Holland 1905 [2].

A different system consists of simple cutting bars mounted onto a metallic frame, driven and powered by a trac-tor. The bars are located at different heights from the ground; their arrangement has been designed in order to obtain stems portions that satisfy the requirements of the processing facilities. An example of cutting bar system is Clipper 4.3 MMH (Tebeco, Praha, Czech Republic) (Figure 3). Three different cutting bars of this machine are 4 m long; they cut the stems down into parts of 1 m. The machine is equipped with a mowing system based on knives able to cut with high frequency and are continuously sharpened during the operation. In the harvesting system based on cutting bars, the mowed material occupies all the surface of the field (wideswath), this allows for a more uniform and faster retting and drying. The main disadvantage of this system consists of the fact that if the stems are not standing vertical anymore due to wind or other circumstances, the length of the stem sections will increase and with subsequent problems in further processing operations [5]. For this system very high working speed (12.5-16.6 km/h) and high material capacity (4-5 ha/h) are reported.

Figure 3. Tebeco Clipper 4.3 MMH [2].

3.1.3 Simultaneous harvesting of seeds and fiber

An innovative harvesting system was developed by HempFlax and named "Double cut system". This machinery consists of the traditional Hempcut 4500 equipped with a modified combine header. The screw elevator is replaced by a conveyor belt which transports the stalks to the side of the machine generating two swats: one is made up of the lower part of the stalks and the other by the upper part (60–70 cm) (Figure 4).

The height of the upper header can be adjusted by a lift. After a short drying period the sections of the stalks with the seeds can be picked up by a normal combine harvester with a conventional pickup header.

Figure 4. HempFlax duble cut system [2].

3.2 Herbaceous perennial crops

As highlighted in Deliverable 5.1 the main harvesting strategies for herbaceous perennial crops are essentially based on two systems: mowing-baling and shredding. The first solution is based on hay-making machineries (mower/mower-conditioner and baler), while the second from forage harvesting systems (self propelled forage harvester, header for silage harvester).
In this deliverable a major focus has been given to a lignocellulosic crop which can be considered as a “standard reference”, considering its wide diffusion and the attention that scientific research has been put on it. This crop is Miscanthus.
In this section, firstly, we will illustrate with a major detail than the one of Deliverable 5.1 the possible harvesting strategies for Miscanthus, and, secondly, we will report a focus on a harvesting trial conducted in 2019 in France.

3.2.1 Harvesting strategies for Miscanthus

There are several harvesting systems for Miscanthus, each of these is based on already existing machineries like self-propelled forage harvesters (SPFH), and other silage making and haymaking machinery. However, these machineries operate usually with a lower working productivity than when used for forage because of the higher density and hardness of Miscanthus stem [6].
As for woody crops (Section 4), the harvesting strategies for Miscanthus can be based on a single passage harvesting or a double passage one.
In single phase harvesting biomass is picked up, chopped or mowed and directly loaded onto a trailer or a baler. The most common single phase harvesting system for miscanthus consists of the application of a self-propelled forage harvester.
Multi-phase systems consist of mowing, conditioning, followed by raking/swathing, picking up and baling. The typical two-step system implies a mower-conditioner which cuts the crop, raking to create a swath on the ground; and baling [7]. For miscanthus conditioning is recommended in order to facilitate the baling operation.
The various harvesting systems for this species derive from hay-making or silage-making machineries, but some modifications are needed to optimize the work performance. Focusing on mower, several studies highlighted that a higher angle of the blades allows to improve working productivity and reducing energy requirements [8,9]. Regarding the modifications needed to balers and forage combines these are needed to facilitate the production of chopped and baled or only baled biomass. For the chopped and baled biomass, the harvested material is blown with a discharge spout into a compression chamber through the discharge basket (funnel), which is placed above the pick-up cylinder. When harvested by a

modified forage combine, the biomass is laid on the ground without being passed through a chopper and is then collected by the baler over the pick-up reel [10]. A vision of two suitable harvesting systems is given in Figure 5.

Figure 5. a) Single passage harvesting and baling with front shredder and baler. b) Production of chopped and baled biomass with forage harvester and modified baler. Both photos are taken from [10].

3.2.2 Harvesting trial (March 2019): evaluating the performance of a Self-propelled forage harvester used to harvest Miscanthus plantations in M-AEZ 2 (north-west France) in a single-passage operation

3.2.2.1 Pre-harvest study: plantation characteristics

The experimental field was located near the village of Grez-en-Bouère (Pays de la Loire, France). The surface of the field was approximately 4.95 ha, flat and regular; the plantation of *Miscanthus x giganteus* was at the first year of production.

According to the farmer, as also confirmed after an overall visual observation, the plantation developed in an heterogenous way, with some areas having a higher plant density. To evaluate the characteristics of the plantation three representative areas were identified and plotted, characterizing an overall surface of 43 m^2 (Figure 6). The mean measurements performed on the sample plots were the following:

- Mean plant height considering 30 plants;
- Plant density at harvest (number of plants per m^2);
- Weight of the biomass inside the plot to estimate biomass productivity.

Results of the measurements are displayed in Table 1.

Table 1. Crop features in the sample plots.

	fresh biomass/ha (t)	plant height (m)	plant density (n./m^2)
plot1	21,6	2,59	30
plot2	23,7	2,38	40
plot3	22,8	2,56	27
mean	**22,7**	**2,51**	**32,3**
st.dev	1,1	0,1	6,8

Figure 6. Establishment of the sample plots.

3.2.2.2 Machine performance

The machine utilized for the harvest was a Self-Propelled forage harvester model New Holland FR9080 equipped with a kemper 460 head. The characteristics are displayed in the following Figure 7. Chipping rotor was regulated at 454 rpm, while cutting height was regulated at 11 cm from ground level.

MODELS		FR9080
Engine		
Brand / type		Caterpillar / C18
Cylinders / displacement	(n°/ litres)	6 in-line / 18
Rated power ISO 14396 - ECE R120 at 2100 rpm	CV hp (kW)	639 (470)
Max. power ISO 14396 - ECE R120 at 2000 rpm	CV hp (kW)	685 (504)
Max. torque ISO 14396 - ECE R120 at 1500 rpm	(Nm)	2939
Fuel tank capacity (standard)	gal. (L)	291 (1100)
Additional fuel tank (optional)	gal. (L)	75 (285)
Feeding		HydroLoc™ drive
Length of cut adjustment		Infinite
Number of feed-rolls	(n°)	4
Feed opening width	in. (mm)	34 (860)
MetaLoc™ metal detection with position indication		●
Cutterhead		
Cutterhead frame width	in. (mm)	35 (900)
Cutterhead diameter	in. (mm)	28 (710)
Cutterhead speed	rpm	1130
Cuts per minute (2x8 knives)	c/min	9060
Length of cut range (2x8 knives)	in. (mm)	.24 - 1.3 (6 - 33)
Cuts per minute (2x12 knives)	c/min	13,600
Length of cut range (2x12 knives)	in. (mm)	- 44 with only 6 knives fitted
Adjust-O-Matic™ shearbar setting		●
Automatic knife sharpening system with reverse drive		○
Variflow™ System - Standard		minutes
Crop Processor		
Roll diameter	in. (mm)	9.8 (250)
Two-roll system with saw tooth profile	teeth	(99 or 99/126 HD)
Width crop processor rolls	in. (mm)	29.5 (750)
10% speed differential (DIA)		○
22% speed differential		●
50% speed differential (DIA)		○
Roll clearance	in. (mm)	.04 - .39 (1 - 10)
Clearance control		Remote
Blower		
Blower housing diameter	in. (mm)	22.2 (565)
Blower housing width	in. (mm)	30.5 (775)
Spout		
Spout maximum height	in. (mm)	252 (6400)
Rotation angle	degrees	210
Automatic spout functions		●
Spout breakaway protection		●

Figure 7. Vision and technical characteristics of the self-propelled forage harvester used in the harvesting trial.

The performances of the machines were evaluated through the study of the working times (methodology C.I.O.S.T.A.) and using the terms included in standards ASAE S495 DEC99.

The parameters studied were the following: **Field Capacity** (ha/h), **Material Capacity** (Mg/h), **fuel consumption** (l/h).

- **Field Capacity (FC)**: the field capacity of the machine was obtained dividing the hectares completed by the hours of **Operative Time (OT)**.

  FC = *hectares of worked surface / OT*

  The obtained results revealed a field capacity of **2.9 ha/h**; these results were confirmed by the data provided by the on-board computer of the machine.

- **Material Capacity** (Mg/h): to obtain the material capacity, the amount of biomass harvested per ha was quantified through direct weighing of the product harvested. In this regard, all full truks deriving from the fields were weighed using an industrial scale located at the near biomass plant before being unloaded. Total harvested biomass was 82.38 tons, resulting in a real yield of 16,64 Mg/ha. As a consequence, the machine showed a material capacity of **48,2 Mg/h.**

- **Fuel consumption:** the fuel consumption was evaluated utilizing directly utilizing the parameter provided by the on-board. It resulted as 85,7 l/h, meaning that for producing 1 ton of biomass the diesel required, only for harvest operation, was 1,77 liters.

3.2.2.3 Post-harvest measurements

The difference between the biomass yield estimated with plot measurement (22,7 Mg/ha) respect to that evaluated through direct weighing of the product collected in the trucks (16,64 Mg/ha) resulted equal to 6,3 Mg/ha, corresponding to 27,7% of the total. Theoretically, these could be considered as general harvest loss, because the machine was not able to collect all potential biomass available. However, the biomass yield evaluated through plot estimation considered the full stem of the plant, i.e. the stem cut at soil level. For obvious risks of machine damages, the plant cannot be cut at soil level, therefore a certain amount of biomass should remain in the soil and this is called stubble. For this reason, an evaluation of the quantity of biomass left on the soil due to cutting height was performed through plotting three areas of 2,75 m^2 each after the machine passage (Figure 8).

Figure 8. Post-harvest sample plots establishment.

Results from plot analysis displayed an average biomass amount of 4 Mg/ha in the form of stubble. Therefore, considering the 6,3 Mg/ha of estimated losses and subtracting the 4 tons represented by stubble, we can consider a theoretical 10,1% remaining, that could represent the proper harvesting loss; a very small part of this percentage is attributable to uncollected canes (0,22 Mg/ha), while the remaining part is represented by uncollected leaves. In fact, several leaves were blown away by the shaking action of the machine header before reaching the feeding systems.

3.2.2.4 Biomass characteristics

Bulk density, particle size and moisture content were evaluated for future considerations related to logistic and cost analysis. Moisture content was calculated according to the current ISO standards at the lab of CREA IT, utilizing harvested samples of miscanthus chips appositely sealed in plastic bags. Considering the average of three replications, the moisture content resulted in 26%. The bulk density was calculated on the base of three replicates according to the current standards UNI EN 15103, using a metal cylinder with an internal volume of 0,026 m^3. The measurements revealed an average bulk density of 151 kg/m^3. The particle size was performed at the CREA IT biomass lab using samples of biomass sealed in plastic bags. The protocol utilized followed the current standard UNI EN 17225-1. The product was composed by fine fractions, mainly 3 and 18 mm; the results of the particle size analysis are displayed in the graph below (Figure 9).

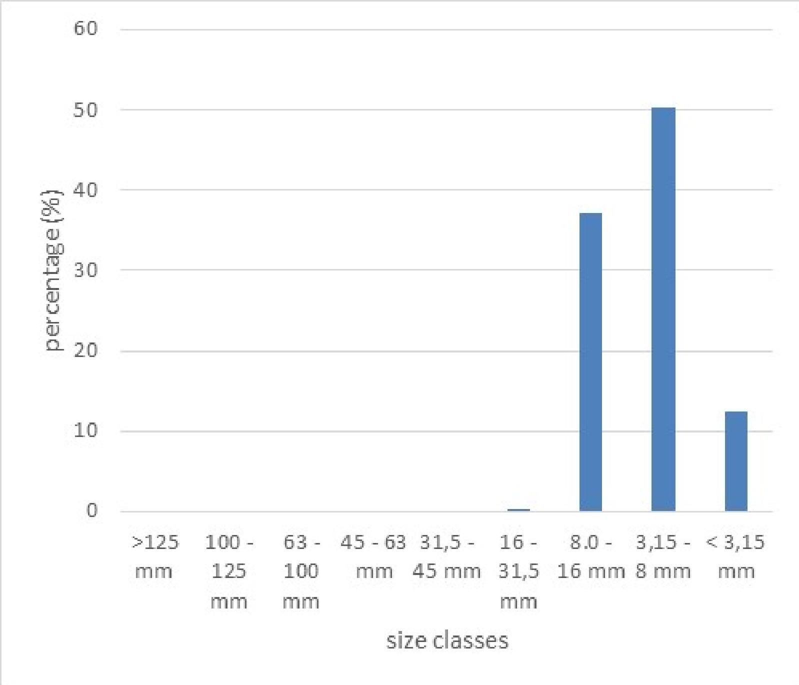

Figure 9. Particle size distribution of chopped miscanthus biomass.

3.3 Harvesting strategies for short and medium rotation coppice

The terms Short and Medium Rotation Coppice of Forestry (SRC/MRC – SRF/MRF) refers to dedicated plantations for the production of lignocellulosic biomass for bioenergy purposes [11]. SRC appeared for the first time in Sweden in early 1900 ans subsequently spreaded among all Europe, nowadays the most utilised species is poplar, even if also eucalyptus and black locust have an important share [12].

The difference between SRC and MRC consists of the different harvesting cycle and plantation scheme, indeed SRC shows harvesting cycle of 1-3 years with a planting density of 6000-7000 N/ha while MRC has harvesting cycle up to 5-6 years with planting density of 1000-1500 N/ha.

Obviously, longer higher cycle of MRC implies also higher dimension of plants to be harvested with average diameter at the cut point of 5-8 cm for SRC while up to 15-20 cm for MRC [13].

Previous researcher highlighted the suitability to such cultivation on marginal conditions, especially in contaminated soils [14,15].

The harvesting of an SRC includes felling, chipping and transport of the feedstock to the storage point. Such steps can be carried out at the same time or felling may be physically and temporally separated. In details, there are four main strategies: single pass cut-and-chip, double pass cut-and-store, single pass cut-and-bale, and single pass cut-and-billet [16]. The choice of the harvest system includes several variables (soil condition, length of harvest window, availability of auxiliary implements, type of storage facilities) that affect the final quality of thefeedstock but also the cost-effectiveness of the supply chain [13]. The single pass cut-and-chip is the most applied system for SRC. In this system stems are cut, instantly chipped and blown into an accompanying trailer. The major advantage is related to high work productivity, as a consequence of the fact that the collection of the biomass is carried out in a single passage operation [17]. Within the cut-and-chip it is possible to identify two different kind sof machineries: the modified forage harvester and the mower-chipper. Modified forage harvesters are always front harvester which offer high work productivity and consistent chip sizes; however, they show the disadvantage of being very heavy (up to 21 Mg) and of chipping the stems in a horizontal position [18]. Instead, mower-chippers can be either front or side harvesters, are much lighter and they chip the stems in an upright position, making these machineries most suitable for dense plantations and larger diameters [18].

The double pass cut-and-store technique implies two steps: first, stems are cut and deposited in windrows – or moved to a central location – for air drying; second, they are chipped at a later time. Generally, this technique implies machineries like feller-buncher or whip harvesters. Stems are subsequently chipped when they reach the ideal moisture content.

The main advantages of the cut-and-store system are: (a) no covered storage space is necessary for storage, considering that drying can take place outside; (b) microbial losses and emissions during storage are avoided; (c) transport costs of biomass are lower as a consequence of a lower moisture; and (iv) a dedicated forestry chipper can be used, as to achieve a high productivity and a proper particle-size distribution [19]. Main disadvantages are instead related to the lower overall productivity, which generally lead to high harvesting cost.

The single pass cut-and-bale and the single pass cut-and-billet techniques differ from the other harvesting techniques because they produce other formats, i.e. wood bales and billets respectively.

The single pass cut-and-bale is based on a machine defined Biobaler, which is fundamentally a round bale machinery modified to be able to manage woody material. The few documented trials of this system suggest suitable work productivity but high level of contaminants (ground and rocks) in the product, therefore the material is suitable only for industrial plants and not for small-scale ones [20].

The cut-and-billet system is instead an even less often applied solution documented in only one trial. This system consists of a self-propelled converted sugar cane harvester, with a converted head to cut woody material. The standard cutter box remains to leave the SRC fuel as billets.

An overview of the different machineries is given in Figure 10 [16].

Figure 10. (A-B) cut-and-chip with modified sel-propelled forage harvester; (C-E) cut-and-chip with mower-chipper; (D) cut-and-store with front whip harvester; (F) cut-and-bale system; (G) cut-and-store with side whip harvester [16].

Focusing on work productivity avegragely cut-and-chip harvester show higher productivity with values of about 30 Mg/h, while cut-and-store and cut-and-bale present productivity values of about 19 Mg/h and 13 Mg/h respecitively.

Harvesting costs are largely variable depending from the characteristic of the crop [16], with ranges of 6-70 €/Mg for cut-and-chip, 9-99 €/Mg for cut-and-bale and 13-26 €/Mg for cut-and-bale.

Regarding MRC the single passage harvesting option is rather difficult, the dimension of the stems is indeed a burden for the cutting elements of modified self-propelled forage harvester. Therefore, the possible harvesting sysyems are based on a double passage biomass collection. Obviously, some adjustments are needed in order to tackle the issue of larger dimension of the stems and lower field capacity (ha/h) is obviously expected although the higher biomass yield can lead however to satisfactory material capacity (Mg/h).

Regarding the presence of specific machineries for MRC it is possible to say that the market offers rather few possibilities. Indeed, only two prototypes, developed by CREA-IT and the Italian enterprise Spapperi (Umbria, Italy), represent the only machineries specifically developed for such kind of plants [21]. These prototypes are thought to be used together. The first machine is a cut-windrower which consists of a semi-trailed machine. The main components are the cutting system and the double pincer. The double pincer allows the machine to perform different functions such as gripping, transport and unload. The cut-windrower is able to cut and leave the plants along the inter-row parallel to the progress of the tractor. Once released on the ground, the trees have the crowns oriented in the opposite direction respect the advancement of the machine. The cutting system consists of a sawblade (1000 mm in diameter) that cuts at 2200 rpm. It is installed on a mobile support connected to a spring capable to absorb part of the stress occurred during cutting. The machine has moreover two wheels that allow to adjust the cutting height by the action of two jacks (the minimum cut height is 50 mm). The double pincer is made up of two series of mechanic arms (gripping elements) which can be partially overlapped and capable to spin around a master rotary column. When the pincer enters in contact with the cut stems it performs different operations consisting in griping, lifting, transport toward the inter-row, inclination, release of the plant, and return to the original position. The time scheduled for opening and tilt of the pincer can be modified with a specific command.

The second prototype is a self-propelled mobile chipper. This machine is driven by a 6 cylinders endothermic diesel engine with a maximum power of 260 kW. The prototype has a reversible drive, with a tipper for loading having the capacity of 15.7 m^3. To unload the product directly on the trailers of trucks, the tipper is hinged onto the outer frame of the

machine to a height of 3910 mm. Finally, the machine has frontally the PTO and two arms to connect respectively to the chipping device and to the pickup head.
The chipping system is able to comminute trees up to a maximum diameter of 380 mm. It consists of a disc with diameter and thickness of 1600 mm and 60 mm respectively working at a speed of 1000 rpm. The pick-up head consists of a rotary cylinder with diameter and length of 155 mm e 1750 mm respectively. This tool has both gripping and lifts functions; its rotational axis is 820 mm distant from the power supply system of the machine, presenting a space of 370 mm for unloading impurities.
The conveyor system is implemented by two groups of three counterrotating toothed drums, which help to direct the material toward the chipping apparatus. A vision of the two prototypes is given in Figure 11.

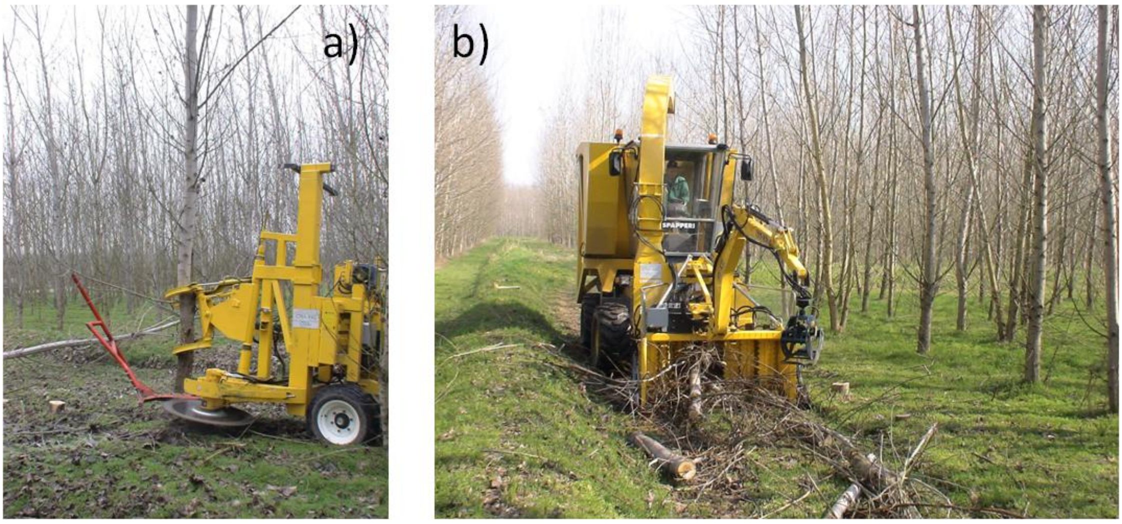

Figure 11: a) Cut-windrower. b) Self-propelled chipper.

Regarding the working performance the two prototypes reported average working speed of 0.86 km/h and 0.65 kn/h respectively for the cut-windrower and the self-propelled chipper, resulting in an effective capacity of 0.22 ha/h and 0.18 ha/h. The material capacity reached instead values of 44 Mg/h and 35 Mg/h respectively for cut-windrower and self-propelled chipper [21].
Notwithstanding the satisfactory working performance these machineries are still at the prototype step, and till now they did not get to become commercial machineries. This can be partially related to the stagnant oil prices have led to the generalized decline of energy plantations [22]. However, the scenario has completely changed in the last years. Indeed, the increasing demand of industrial roundwood and fiber wood from the industry of the sector has foster the establishment of extensive MRC poplar plantations [23]. In Europe, the major

part of the new poplar MRC plants have been established in countries such as Poland, Romania and Slovakia, where there is an ideal combination of fertile soil, moderate land prices and a rapidly developing economy [24]

The harvesting systems for these plants, which in the period closer to the establishment of the plantations were mainly based on motor-manual work, is changing into systems with a higher mechanization level, based on machineries usually applied in forest utilization [25].

All these systems are based on a simple concept that is: producing fiber wood from the main stem and biomass from tops and branches. Therefore, the system has to cut the stem and process it separating material up to 7 cm of diameter for fiber wood and leaving the remaining biomass for bio-energy.

Different working systems to perform the mentioned above tasks have been analyzed recently.

Felling and processing via an excavator-based grapple saw, motor-manual delimbing with chainsaw and extraction via 2nd hand forwarder reached a harvesting cost of 15-16 €/Mg_{fm} with a productivity of 14 Mg_{fm}/h, 26 14 Mg_{fm}/h, 20 Mg_{fm}/h and 10 Mg_{fm}/h respectively for felling, delimbing, processing and forwarding [25].

Harvesting costs in the range 9-17 €/Mg_{fm} are reported for a system based on an excavator-based feller-buncher for felling, a grapple skidder for extraction and excavator-based grapple saw for processing [26,27].

Finally, a system based on higher-investment equipment (fully mechanized harvesting via harvester and forwarder) reached instead a working productivity of about 18 Mg_{fm}/h for harvesting and 24 Mg_{fm}/h for forwarding with an overall cost ranging from 14.1 €/Mg_{fm} and 14.5 €/Mg_{fm} [28].

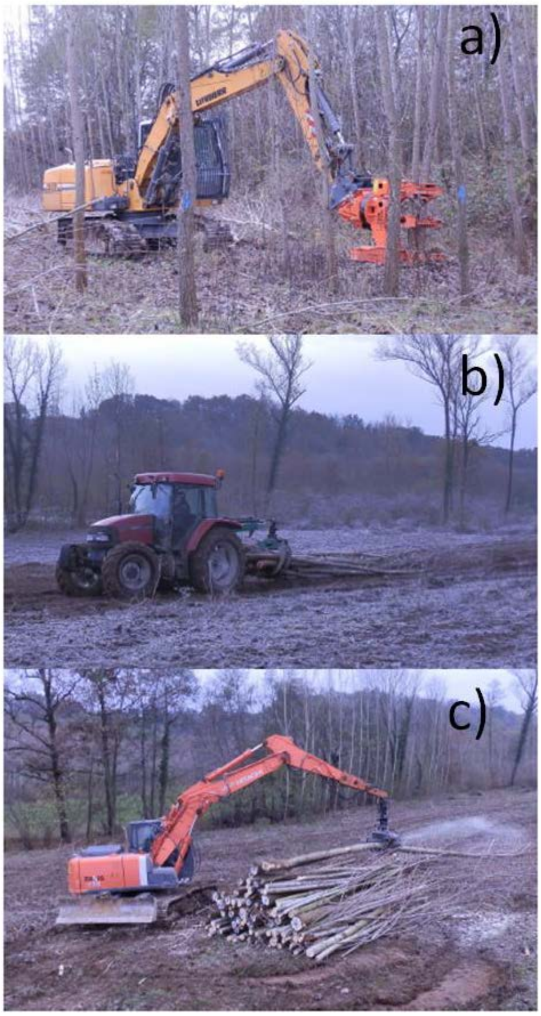

Figure 12: a) excavator-based feller-buncher. b) Grapple skidder (modified farm tractor). c) Excavator-based grapple saw [26].

4 Oil crops

4.1 Introduzione alle colture da olio erbacee

The new European Directives on Renewable Energy aim to increase the share of renewable energy and agriculture can contribute to achieve the goal not only via exploitation of agricultural residues but also through dedicated energy crops [29]. Herbaceous oil crops would contribute firmly to achieve the goal. This implies the need to increase the surface of cultivable land without competing with food production like, for instance, exploiting European marginal lands. Marginality factors are often limiting factors for industrial crops as well but, some of them seem performing quite well and it is worthy to further investigate them in order to develop a full and reliable value chain that is socially, economically and environmentally sustainable.
Additionally, to limiting factors present in marginal lands, another important hardle to go over to is represented by the degree of mechanization involved. Specifically, the possibility to carry out all the phases (soil preparation, sowing, harvesting and logistic activities) through machieneries is mendatory to reduce costs. In a developed country, it is practically impossible to set up a sustainable supply chain for a given crop without effective mechanical harvesting [30]. The labor costs would be too high to bear. Therefore, harvesting is the key stage of the supply chain that strongly affects both costs and biomass quality [31,32]. Mechanical harvesting can be performed either using a dedicated harvester or borrowing it from other crops and apply specific modifications, at different levels, in order to limit the loss and damage to kernels [30]. The availability of dedicated machines is not always guaranteed, since different challenges arise according to the phenology of the plant and the seeds.

Referring to the herbaceous oil crops, in Magic, three main crops have been studied: camelina (*Camelina sativa* (L.) Crantz), cardoon (*Cynara cardunculus* L.) and castor bean (*Ricinus communis* L.). Particularly, the harvesting operation has been investigated in each crop in order to assess performance, cost, loss and damages to the seeds. Before every test, the standing biomass was sampled in order to assess the growth parameters of the biomass, potential yield and residual moisture content of seeds, stems and leaves.

4.2 Material and methods

The characterists of each experimental field will be presented in the dedicated paragraph. In this section, the general methods applied for studying the performance of the machineries, pre-harvest conditions, post-harvest conditions, seed loss and cost.

4.2.1 Performance of the machineries: study of the working times and fuel consumption

Working times

In each experimental unit, the performance of the machines was evaluated through the study of the working times according to the standards ASAE S496.2 (2000). In addition to working times, the machinery test was used to obtain other data such as the field speed and the fuel consumption. All the gathered data was used to define the performance of the machine and the operative costs. Below are explained in detail how these data were collected in each experimental unit.

The field speed (FS) is the average rate of machine travel in the field during an uninterrupted period of functional activity (m/s or km/h). Average field speed can be measured by marking off a fixed distance (at least 100 m) in the field, placing a mark at each end, and counting the seconds it takes to drive between the marks. Average field speed can then be calculated from equation deriving from the formula of the velocity:

Velocity (v) = Space/Time

In this case the space is intended as the linear meters covered by the machine between a mark and the other. In case the combine is equipped with digital tachymeter, it is possible to obtain the field speed recording the value directly from the display.

Working times: the study of the working times and the evaluation of the field speed allowed determining parameters such as Theoretical field capacity (ha/h), Effective field capacity (ha/h), and the Field efficiency (%). By knowing the yield of the field (Mg/ha), it was possible to obtain the Material capacity (Mg/h).

Theoretical field capacity (TFC): depends only on the full operating width of the machine and the average travel speed in the field. It represents the maximum possible field capacity that

can be obtained at the given field speed when the full operating width of the machine is being used. It is calculated multiplying the field speed for the working width of the machine.
Effective field capacity (EFC): The Effective Field Capacity of a farm machine is the rate at which it performs its primary function, i.e., the number of hectares that can be harvested per hour.
Measurements or estimates of machine capacities are used to schedule field operations, power units, labor and to estimate machine operating costs. The effective field capacity (EFC) of a machine in the field can be easily calculated by dividing the hectares completed by the hours of Operative Time (OT).

EFC = worked area (ha) / OT (h)

The operative time is the real time necessary to complete the harvest of the surface object of the test, including also turnings, stops, regulations, etc.

The formula used for the estimation of the operative time is the following:

Operative Time (OT) = ET + AT

ET = is the effective time, i.e. the time in which the machine is actually harvesting the product.

AT = are the accessory times which includes accessory time for maintenance (ATM), that includes the pauses required for filling or unloading the hoppers (seeds, fertilizers, grains, etc.); accessory time for turning (ATT), corresponding to the time needed to reverse the direction; accessory time for regulations (ATR), corresponding to the times for adjustments in relation to the conditions of the field or the work.

Field efficiency (FE): expressed as percentage, the field efficiency is the ratio of actual or effective field capacity (EFC) to theoretical field capacity (TFC)

FE (%) = EFC (ha/h) / TFC (ha/h)

Material Capacity (MC): The working capacity of harvesting machines can be measured also by the quantity of material harvested per hour. This capacity is called the machine's material capacity (MC), expressed as tons per hour (Mg/h). It is the product of the machine's EFC and the average yield of crop per hectare and can be calculated from equation (5).

MC (Mg/h) = EFC (ha/h) x crop yield (Mg/ha)

Fuel consumption

Fuel consumption can be determined through machine tank refilling until full level at the end of each experimental unit (plot) using a graduated large cylinder to define the volume of fuel consumed (l/ha or l/t of biomass harvested). Another way could be to weight the amount of fuel consumed (kg of diesel/ha or kg/t of biomass harvested) considering that 1 liter of diesel is 0.835 kg.

It is important to start each experimental unit with the tank completely full. The fuel consumed must be proportioned to the exact surface of the experimental unit tested in order to define the fuel consumed per hectare in that experimental unit. In case of onboard computer availability, the fuel consumption can be derived directly from the dashboard of the tractor or the combine harvester.

4.2.2 Pre-harvest test: aerial biomass, expected seed yield and dehiscence

To estimate the main crop features 10 sample plots (2-3 m^2 of area) were randomly selected within the experimental field. In each plot the plants were counted, and measured in height. In case of cardoon and castor, the respective capitula and recemes were counted and sampled for potential yield (PSY) estimation and moisture content assessment. Stems and leaves were also sampled for moisture, fresh and dry weight estimation. At thelaboratory, samples from each plot were weighted through a precision scale. Subsequently, a representative subsample was weighted and put into the oven at 105 °C until constant weight in order to estimate residual moisture. Eventually, h-index was also calculated.

During the pre-harvest, seed loss due to dehiscence (DSL) was also assessed. In cardoon and castor, the capitula and the capsules found on the ground were collected and processed at the laboratory for the fresh and dry weight of DSL. Samples were processed in laboratory as already described. In camelina, dehiscence was not evaluated.

4.2.3 Post-harvest test, seed loss and seed quality

Regarding camelina, the total seed loss (TSL) was calculated as the mere difference between the theoretical biomass assessed during the pre-harvest and the effective quantity of seeds collected and weighted at the farm scale. This includes the seed loss due to the impact of the combine header (ISL) and the ineffectiveness of the cleaning shoe of the machine (CSL).

Subsequently, a tarpaulin was installed at the end of two sample plots to collect the seeds lost by the combine harvester from the sieves and straw walkers. The entire amount of biomass expelled by the machine was thus collected by the tarpaulin laying on the ground. The biomass was shipped to the laboratory, weighted and sieved to estimate CSL. The weight of the seeds found was referred to a surface of 13.4 m^2 given by the width of the combine header (6.4 m) multiplied by the length of the tarpaulin (2 m). Furthermore, the 1000-seed weight was recorded in order to compare it with the 1000 seed-weight of the harvested camelina seeds. The loss of seeds due to the impact (ISL) of the combine harvester with the siliques is calculated as TSL-CSL. In camelina, an evaluation of Material Other than Grain (MOG) was carried out sampling the material collected from the combine harvester and discharged into the trailer.

In cardoon a slightly different approach was used. The total harvesting seed loss (HASL) is given by the sum of the seed loss due to the inefficiency of the header to correctly collect the capitula (ISL), and the ineffectiveness of the cleaning shoe of the combine harvester to discriminate the seeds from the other portions of the processed biomass (CSL). To summarize, ISL is given by not-threshed capitula laying on the ground or standing on plants not correctly cut by the header, and CSL corresponds to seeds discharged from the rear of the combine instead than being collected in its container.

To estimate CSL a tarpaulin was manually held rear the combine harvester in five sample plots of 96 m^2 each (4.8 x 20 m) to collect the seeds lost from the sieves and straw walkers. The overall amount of material expelled by the machine was therefore collected in the tarpaulin. Such material was carried to the laboratory, then weighted and sieved to assess the amount of CSL.

To estimate ISL ten sample plots of 30 m^2 each (5 x 6 m) were randomly established in the field. All the not-threshed capitula present both on the ground and on not-cut plants were collected and put in sealed bags to be brought in CREA-IT laboratory. Here the stationary thresher PLOT 2375 was used to thresh them and collect the seeds of the capitula. Seeds were subsequently weighted to estimate ISL.

In castor, after setting the cleaning shoe of the combine harvester, the harvesting phase started. The machinery was positioned at the beginning of each plot assuring that the cutting bar could work at full capacity; then the harvesting started. Once the cleaning system started working at full capacity (approximately 50-80 meters after the start) a sample of about 20 kg of seeds were collected from the tank and brought to the laboratory for qualitative analysis. During the last 15 m of the plot, the threshed biomass was harvested behind the combine harvester (Figure 13a) and carried to laboratory, then sieved to permit the quantitative assessment of loss seeds due to the cleaning shoe (CSL). In correspondence to the sampled area for CSL assessment, all capsules laying on the ground were manually collected and weighted (Figure 13b). The weight was reduced by dehiscence value for the impact seeds loss assessment (ISL).

Figure 13. Collection of threshed biomasses (a) and lost capsule (B) for CSL and ISL assessment respectively.

Seeds collected from the combine harvester's hopper were further processed for the determination of the ratio between damaged seeds, undamaged seeds and unopened seeds (Figure 14). In particular, from the 20kg bags collected from each plot, three subsamples approximately 500g each were randomly taken and dispersed on a flat disk. The foreign material was removed manually and the remaining part was classified either as damaged seeds, undamaged seeds or unopened seeds (stuck in a valve of the capsule) then dried and weighted. Unopened seeds were manually opened to allow the weighting.

Figure 14. Sample of seeds collected within the tank of the combine harvester showing: a) damaged seeds; b) undamaged seeds; c) unopened seeds.

4.2.4 Estimation of harvesting costs

An interview with the contractors allowed to identify purchase and operating costs of the applied machineries, whilst the performance of the harvesting system was gained from the results of the field tests and used as input data. Finally, standard values for calculation were taken from CRPA (Research Centre on Animal productions) methodology [33]. Hourly costs of combine harvester were estimated taking into account the market value of the agricultural machinery. The price of the machine was discounted through the application of a lending rate of 3%.

4.3 Camelina

Camelina is a member of *Brassicaceae* family [34]. This species originated from South-East Europe and South-West Asia [35]. Plant height usually ranges from 65 to 110 cm [36]. Seeds are contained within siliques, usually called seed capsules or pods, which measure from 5 to 14 mm in length, pear-shaped, slightly flattened, and contain eight to 15 seeds [37]. Seeds are very small (0.7 mm × 1.5 mm), with a 1000-seed weight ranging between 0.8 and 1.8 g, depending on cultivar and growing conditions [38,39]. Seed oil content has been reported to range from 30% to 49% [38–41].

Camelina, similarly to canola, can be directly combined with cereal header or swathed and then combined. Both of the methods result in similar seed yields [42]. The setting of the combine harvester has to be adapted to the species' characteristics, mostly to the tiny dimension of seeds; e.g., speed, wind flow (fan speed), small opening screens, leak sealing, distance between the threshing cylinder, and the concave in order to prevent seed loss [43].

4.3.1 Field test conducted in Spain to investigate performance, seed loss and cost of camelina direct mechanical harvesting

The test was carried out in the Municipality of Palencia (Castilla y Leon, Spain) during summer 2020 (Figure 15). The field area was 3.82 ha, the altitude 912 m a.s.l. with a negligible slope value.

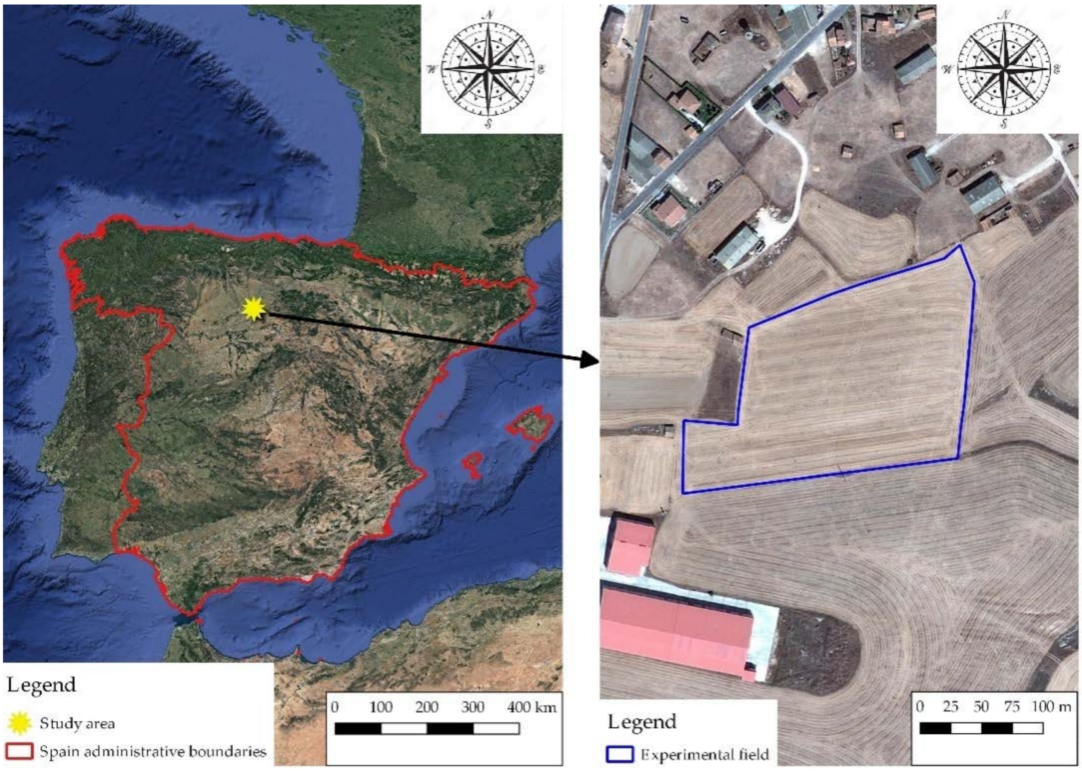

Figure 15. Map of the experimental field in Castilla y Leon region of Spain.

The cultivar Alba was sown in early December 2019 at the rate of 8 kg/ha and grown under conventional farming regime. Fertilizer was provided twice at the rate of 250 kg/ha of NPK 8-15-15 and 250 kg/ha of liquid Nitrogen fertilizer (32 %) in winter and April, respectively. Successively, herbicide was applied for weed control.

The contractor provided the combine harvester, a John Deere W650 equipped with a conventional cleaning shoe and a 6.7 m wide cereal header. The machine was driven by 240 kW diesel engine and the setting applied (Table 2) was kept constant throughout the test.

Table 2. Combine harvester settings used during harvesting of camelina.

Rotor speed (rpm)	800
Cleaning Fan Speed (rpm)	700
Openings of Upper Sieve (mm)	closed
Openings of Lower Sieve (mm)	5
Straw treatment	threshed

4.3.1.1 Work performance and cost analysis

The recorded working speed was very high, i.e. 5.05 km/h, with a corresponding TFC of 3.38 ha/h and a EFC of 3.17 ha/h. Therefore, the harvesting system showed a very high Field efficiency (FE) of 93.70 %. However, it is important to underline that such high working performance was related to the dimensions and to the particular shape of the experimental field, which allowed to minimize the turnings, thus decreasing the accessory time and increasing the EFC and FE.

Resulting harvesting costs were 65.97 €/ha and 69.42 €/Mg, so even lower that the cost reported for combine harvesters working other crops [44,45].

4.3.1.2 Seed loss evaluation

Total seed loss (TSL), given by the sum of the seed loss as a consequence of the impact of the combine harvester's header on the plants (ISL) and the seed loss related to inefficiency of the cleaning shoe of the machinery (CSL), resulted equal to 80 kg/ha, corresponding to 7.82 % of the potential seed yield. Analyzing more in details the source of seed loss it is possible to notice that the major part of the loss is related to the cleaning shoe of the combine harvester (60 kg/ha) while only 20 kg/ha are related to ISL. Therefore, the major source of loss in camelina harvesting was the cleaning shoe of the machinery, and this was rather expected consifering the tiny dimension of the seeds. Interestingly, the mean 1000 seed-weight measured for harvested seeds and lost seeds were not statistically different. Indeed, this highlights that there was not enough physical difference among seeds to trigger loss. In fact, the idea behind to such investigation was that those seeds lost by the combine harvester could differ from the others because some physical properties, such as weight, shape or volume that, in turn, could have been linked to different content of oil, proteins or carbohydrates [46]. This was not the case; therefore, the seed loss is to be related only to either the machine setting or the working speed.

The obtained results are however rather satisfactory, indeed about 8 % of seed loss, even if higher than what reported for several other oil crops [47], is an acceptable value, considering that the tiny dimension of camelina seeds will never allow for a 100 % harvesting efficiency.

No particular modifications were needed to harvest camelina seeds via a combine harvester equipped with a cereal header, therefore it si possible to assert that this harvesting system is valid for this crop, highlighting however the importance of a proper setting of the combine harvester.

On the other hand, the quantity of seeds lost is not the only variable which should be taken into account, but there is another noteworthy parameter to consider that is the high percentage of MOG (weed seeds and fine camelina residues) found in the harvested seeds.

MOG percentage is related to the capability of the combine harvester to discriminate efficiently seeds form impurities because they can affect negatively the quality of the seeds in different ways: by lowering the market value and, in the worst-case scenario, jeopardizing the proper conservation of the seeds.

The obtained results clearly showed that the residuals from camelina plants blended with the harvested seeds increased their moisture content up to 15.71% which is above the threshold value of 8% for avoiding spoiling processes. In particular, the high amount of poppy seeds implied the need to further clean the camelina seeds before delivering either to the industries for oil extraction or to farmers for sowing. Additionally, the lower bulk density of the collected material caused by the presence of MOG, could increase the cost for transportation.

4.4 Cardoon

Cardoon belongs to the Compositae family, which bears flowers in inflorescences, called capitula or heads. The name of the fruit is cypsela (an achene from an inferior ovary) crowned by plumose filaments, called pappi [48]. Cardoon is cultivated as a multiannual crop and it can reach 2 m in height. In the Mediterranean area, the establishment of cardoon crops is performed either during autumn or spring [49]. Ploughing and harrowing are recommended in order to allow for the proper development of the root system [50], even if Fernando et al. (2018) highlighted the possibility of cultivating cardoon in no tillage system also demonstrating a reduction in the environmental impact [51]. The most interesting aspect of cardoon is the possibility to exploit its biomass in several ways.

In the energy sector, the oil seed is suitable for the production of biodiesel [52]. The lignocellulosic biomass of the stems can be used as solid biofuel [53] or as substrate for gasification [54], pyrolysis [55], bioethanol production [56], and biomethane [57]. The pappi are particularly suitable for the production of paper pulp [58,59]. Finally, cardoon exhibits interesting features as a medicinal plant [60] or source of food for both humans and animals [61].

4.4.1 Field test conducted in Central Italy to investigate performance, seed loss and cost of cardoon seed mechanical harvesting on marginal land

Tests of mechanical harvesting of cardoon were performed in Maccarese (Fiumicino, Lazio, Italy) (WGS84-UTM33T coordinate 271167 E, 4633933 N; 0 m a.s.l.) in August 2020. The overall surface of the field was 18.32 ha but the effectively sown area corresponded to 17.67 ha, considering the presence within the field of ditches not affected by the sowing (Figure 15). Soil texture of the field, which shows a high percentage of clay, along with the frequent water stagnation in some zones, make practically impossible to cultivate this field with the typical crops of the area (carrots and potatoes). Additionally, frequent stagnation of water is experienced in this field. This also compromised some cardoon plants as shown in Figure 16.

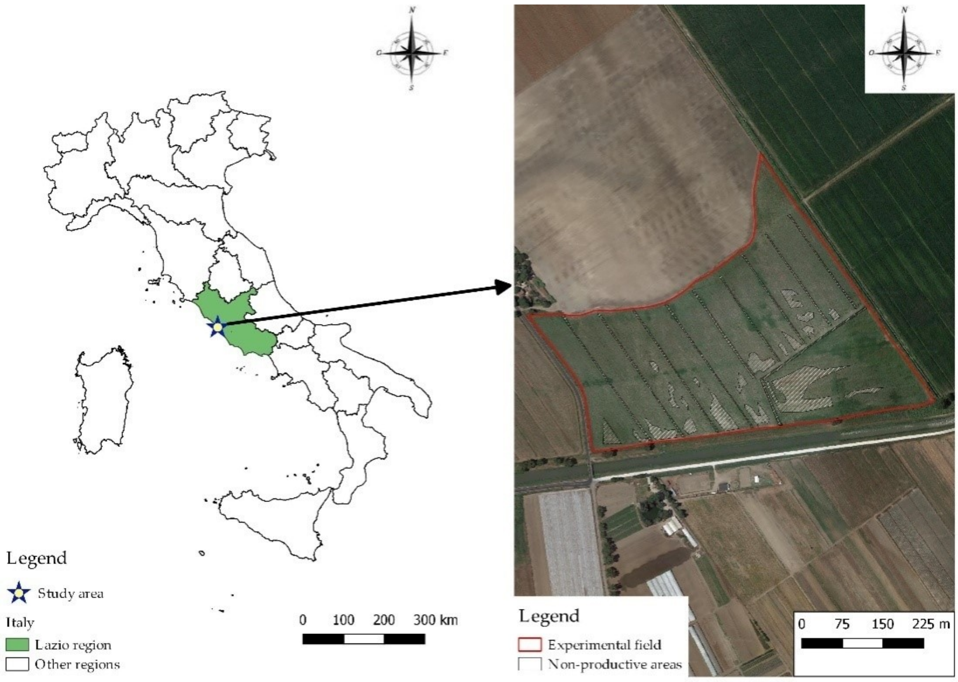

Figure 16. Experimental field location.

The local contractor enterprise provided the combine harvester which was in details a FiatAgri L624 (Figure 17) equipped with a conventional cleaning shoe and a 4.8 m wide sunflower header. The machine was driven by 176 kW diesel engine. The applied setting, which was kept constant throughout the test, was as follow: concave clearance 23.7 mm, thresher speed 800 rpm, fan speed 420 rpm, upper sieve clearance 5 mm, lower sieve clearance 4 mm.

Figure 17. FiatAgri L624 combine harvester at work.

4.4.1.1 Work performance and cost analysis

Combine harvester's performance is given in Table 3. The effective seed yield (ESY) resulted in 0.89 Mg/ha, whilst the working speed of 4.92 km/h which led to a TFC of 2.36 ha/h. The EFC was 2.05 ha/h and the subsequent FE was 87.24 %. MC reached instead 1.82 Mg/h.

Table 3. Performance of combine harvester equipped with sunflower header to harvest cardoon seeds.

Parameter	Measure unit	Average	St.Dev.
Working speed	km/h	4.92	0.87
Theoretical Field Capacity (TFC)	ha/h	2.36	0.42
Effective Field Capacity (EFC)	ha/h	2.05	0.33
Field Efficiency (FE)	%	87.24%	4.13%
Material Capacity (MC)	Mg/h	1.82	0.30

The reported above values for working performance led to a cost per surface unit of 69.52 €/ha, which consists in a cost per biomass unit of 86.15 €/ha (Table 4).

Table 4. Evaluation of the harvesting unitary costs.

Parameter	Measure unit	Value
Costs per unit of time	€/h	142.74
Cost per unit of surface	€/ha	69.52
Costs per unit of seed yield	€/Mg FM	86.15

The obtained results regarding both working performance and harvesting costs are in line with previous studies on cardoon seeds mechanical harvesting [62,63]. Confirming the suitability of this harvesting system for this crop.

4.4.1.2 Seed loss

Concerning the evaluation of seed loss, reported in Table 5, the major part of lost seed was due to impact of the header on the plants (ISL), with a value of 28.72 kg/ha accounting for 2.58 % of the PSY, whilst the combine harvester cleaning shoe (CSL) led to only 6.44 kg/ha of lost seed, corresponding to 0.58 %. Overall harvesting loss (HASL) resulted therefore 35.16 kg/ha, corresponding to the 3.16 % of PSY.

Table 5. Evaluation of seed loss due to the header and the threshing system.

Parameter	Measure unit	Average	St.Dev.
Header seed loss (ISL)	kg/ha	28.72	17.13
Header seed loss (ISL)	%	2.58%	1.54%
Threshing system seed loss (CSL)	kg/ha	6.44	3.20
Threshing system seed loss (CSL)	%	0.58%	0.29%
Harvesting seed loss (HASL)	kg/ha	35.16	-
Harvesting seed loss (HASL)	%	3.16%	-

Interestingly, this trial carried out with a non-specific device for cardoon showed similar performance of previous trials performed with a prototype header specifically developed for cardoon seeds in order to collect both seeds and biomass [63]. The obtained value of about 3 % seed loss is indeed acceptable, and in line with the harvesting performance of the major oil seeds [47].

Therefore, a combine harvester equipped with sunflower header is a suitable harvesting system to collect cardoon seeds. However, if the aim is also the collection of the biomass for bio-energy purposes, the specific prototype remains the best solution.

4.5 Castor

The world production of castor oil seeds (*Ricinus communis* L.) increased from 1.19 Mt in 1998 to 1.4 Mt in 2018, with a pick of 2.74 Mt in 2011 [64], highlighting a constant growing interest on this crop. India is currently the top producer of castor oil (more than 80% of the worldwide production) along with Mozambique, China, Brazil, Myanmar, Ethiopia, Paraguay and Vietnam [65]. Castor is of particular interest because it can grow well on marginal lands; furthermore it is resistant to drought and pests. The seeds oil content ranges from 35% to 55% w/w for high yield breed type (more than 1,000 l/ha can be obtained when cultivated), has one of the highest viscosities among vegetable oils, and a molecular weight of 298 [66]. Globally, it only accounts for 0.15% of the total vegetable oil production [67] but it offers a wide spate of possible applications that stretch from pharmaceutical and cosmetic sectors to lubricants and oil-derived products [68].

4.5.1 Field test conducted in Greece to compare performance, seed loss and cost associated with direct combining castor seeds using a combine harvester equipped with cerel header and sunflower header

Tests of mechanical harvesting of castor bean seeds were performed on an experimental field located in Koutso (Xanthi, Greece) (WGS84-UTM35T coordinate 334961 E, 4546505 N) on 8th September 2021.
The overall surface of the field was 0.46 ha. Pre-seeding operations consisted of ploughing (20th April 2021) and harrowing (29th April 2021).
Sowing was carried out on 29th April 2021 applying 21 kg/ha of seed of hybrid C1012 with sowing distance 95 cm X 22 cm through a cotton seed sowing machine.
The same day a first fertilization with 270 kg/ha of fertilizer NPK 21-17-3 was performed. To contrast weeds a chemical control with 4000 g/ha of Stomp (BASF, Lud-wigshafen, Germany) was performed, as well as a mechanical control via ripper on 8th June 2021, further refined with a manual weeds' removal on 14th June 2021. Irrigation was carried out on 30th April, 9th May, 14th July, 22th July, 28th July 6th August and 20th August, it was not needed on June because there was sufficient natural rainfall.
On 29th July 2021 a foliar fertilizer Nutri-Gemma B-Zn (Biolchim, Bologna, Italy) was applied at a rate of 10 l/ha. The same day also 500 cm^3/ha of Score 25C fungicide (Syn-genta, Basel, Switzerland) were applied.

On 28th August 2021 crop was terminated via the application of 6000 cm^3/ha of Reglone 20 SL (Syngenta, Basel, Switzerland).

A vision of the experimental field prior to harvesting is given in Figure 18.

Figure 18: Castor field before harvesting.

A combine harvester New Holland CX8060 (New Holland, Pennsylvania, USA) was provided by a local contractor and utilized for the harvesting trial (Figure 19). Half of the experimental field was harvested with a New Holland cereal header with 5.5 m working width, while the remaining half with a Fantini (Mantova, Italy) sunflower header with 4 m working width. A vision of the combine harvester equipped with the two different headers is given in Figure 18. The applied settings of the combine harvester were: Threshing speed 400 rpm, Fan speed 800 rpm, Concave clearance 10 mm, Upper sieve clearance 17 mm, Lower siece clearance 10 mm.

Figure 19. a) Combine harvester New Holland CX8060 with cereal header. b) Combine harvester New Holland CX8060 with sunflower header.

4.5.1.1 Work performance and cost analysis

No statistically significant difference was found between the work productivity of direct combining operation with the two different headers. The average working speed was 2.3 km/h, corresponding to an average EFC of 1.03 ha/h. Detected fuel consumption was 21.27 l/h. It is important to highlight that the low EFC is related mostly to the small dimension of the experimental field, factor which negatively influenced the turning time of the combine harvester with subsequent decreased work productivity.

4.5.1.2 Seed loss

ISL for cereal header was 282.02±60.22 kg/ha DM (14% ww of potential seed yield) while 158.16±18.8 kg/ha DM (8% ww of potential seed yield) was found for sunflower header. The conducted analysis revealed the presence of statistically significant differences between such values (Figure 20a). On the other hand, no significant differences between the two headers were revealed regarding CSL (162. 41 kg kg/ha DM for cereal header and 145.56 kg/ha DM for sunflower one corresponding to 8% and 7% ww of potential seed yield respectively respectively), as shown in Figure 20b. The sum of ISL and CSL resulted in a harvested seed yield of 1558.57 kg kg/ha DM and 1699.28 kg/ha DM respectively for cereal header and sunflower one.

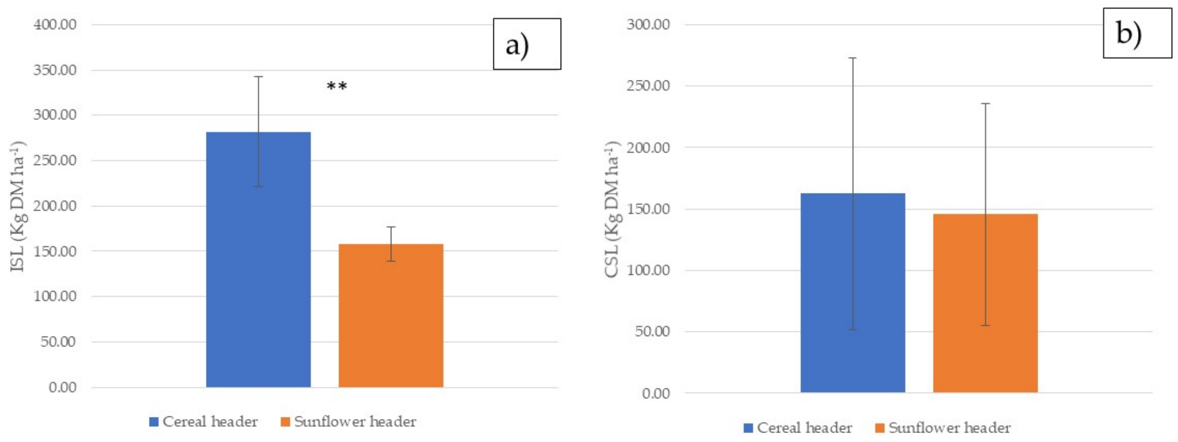

Figure 20. a) Comparison of ISL between the two headers. b) Comparison of CSL between the two headers. "**" indicates statistically significant differences at 0.01% according T-test.

Sunflower header showed significantly lower ISL than cereal header, highlighting its higher suitability for castor bean mechanical harvesting. On the other hand, as expected, no differences were found regarding CSL, considering that this variable is influenced mostly by the setting of the cleaning shoe, which in this trial was the same for both treatments.

However, the main finding of this trial is that there is still much work to do before reaching a satisfactory harvesting system for castor bean seeds. Indeed, a sunflower header represents just a good starting point, but the performance in terms of ISL is still far from the values of the other oilseeds [47]. The way to follow seems to be the development of dedicated headers for castor bean, as well as further advances in both genetic and agronomy in relation to this crop.

Another very importan aspect which was investigated within this trial is the quality of the collected seeds. The obtained results were not satisfactory at all, indeed, for both treatments, the percentage of properly opened seeds (not damaged and without capsules) was about 20 %. The major part of the seeds was either damaged (broken or without envelop) or not properly opened (still inside the capsule). This is probably related to the high quantity of fresh biomass which entered into the threshing system along with seeds, thus decreasing the performance of the cleaning shoe. The development of a specific header able to allow only seeds and a lower amount of biomass into the combine, as well as improving crop drying before harvesting could be the solutions to this issue. Another possibility consists of setting the combine with higher concave clearance and lower threshing speed in order to collect castor bean seeds without opening them but avoiding damages, and then carried out the dehulling as a second passage operation with stationary machineries.

5 Summary results

The present deliverable investigated and described the possible harvesting solutions for several industrial crops suitable fro cultivation on marginal lands. The main outputs for the different crops are:

- **Hemp for fiber production**: several oprions are available on the market both for simple fiber harvesting and for simultaneous harvesting of seeds and fiber. The cultivation aim, the dimension of the farm and the magnitude of marginality in which the crop is established are the parameters to be taken into account for the selection of the harvesting system.
- **Miscanthus**: many different options are available and all these are based on the concept of harvesting the biomass and increasing its density through chopping or baling. Several systems also allowed for both chopping and baling of miscanthus biomass.
- **SRC and MRC**: the recent trend for the harvesting of these crops, mostly for poplar, is gradually shifting from dedicated systems for biomass harvesting and densification to semi or fully mechanized systems, typical of forestry sector, to produce two different assortments, i.e. fiber wood from the main stem (up to 7 cm of diameter) and fuelwood from branches and tops. This aspect is particularly interesting in the framework of cultivation on marginal lands, considering that steep slope is a major factor of marginality and that the mentioned above harvesting systems are able to work on steeper slopes than the specific SRC-MRC ones, based for instance on self-propelled forage harvesters.
- **Camelina**: camelina seeds harvesting is possible to be carried out with a conventional combine harvester equipped with cereal header. Particular attention has to be put in the cultivation phase in order to avoid excessive presence of weeds, which can be particularly detrimental during harvesting as a consequence of the tiny dimensions of camelina seeds.
- **Cardoon**: a conventional combine harvester equipped with a sunflower header is a suitable harvesting system for cardoon seeds. In the case the farmer would like to collect also the biomass for bio-energy purposes specific headers (at the phase of prototype) are still the best solutions.
- **Castor bean**: there is still much work to do before reaching a satisfactory harvesting system for castor bean seeds. Indeed, a sunflower header represents just a good starting point, but the performance in terms of seed loss is still far from the values of

the other oilseeds. The way to follow seems to be the development of dedicated headers for castor bean, as well as further advances in both genetic and agronomy in relation to this crop. Another very importan aspect which was investigated within the activity of Magic Project was the quality of the collected seeds. The obtained results were not satisfactory at all, indeed the percentage of properly opened seeds (not damaged and without capsules) was about 20 %. The major part of the seeds was either damaged (broken or without envelop) or not properly opened (still inside the capsule). This is probably related to the high quantity of fresh biomass which entered into the threshing system along with seeds. The development of a specific header able to allow only seeds and a lower amount of biomass into the combine, as well as improving crop drying before harvesting could be the solutions to this issue. Another possibility consists of setting the combine with higher concave clearance and lower threshing speed in order to collect castor bean seeds without opening them but avoiding damages, and then carried out the dehulling as a second passage operation with stationary machineries.

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