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FOSTERING SUSTAINABLE FEEDSTOCK PRODUCTION FOR ADVANCED BIOFUELS ON UNDERUTILISED LAND IN EUROPE

D 2.1

FEASIBILITY STUDY ITALY

AGRONOMIC FEASIBILITY

CTXI - CREA

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

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Contents

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Fostering Sustainable Feedstock Production for Advanced Biofuels on underutilised land in Europe

The FORBIO project aims at developing a methodology to assess the sustainable bioenergy production potential on available "underutilized lands" in Europe (contaminated, abandoned, marginal, fallow land etc.) at local, site-specific level. Based on this methodology, the project will produce multiple feasibility studies in selected case study locations in three countries. The FORBIO project will also apply a series of innovative approaches in order to develop roadmaps for the removal of economic and non-economic barriers to sustainable bioenergy deployment and in order to promote and facilitate the formation of partnerships between farmers, bioenergy producers and local institutions. In addition, the project will carry out awareness raising and capacity building activities in order to share lessons learnt and good practices.

Objectives:

- Identification of social, economic, environmental and governance-related opportunities and challenges for advanced bioenergy deployment through a series of multi-stakeholder consultations
- Evaluation of the agronomic and techno-economic potential of the selected advanced bioenergy value chains in the case study sites of the target countries
- Assessment of the environmental, social and economic sustainability of the selected advanced bioenergy value chains in the target countries
- Analysis of the economic and non-economic barriers to the market uptake of the selected sustainable bioenergy technologies; and development of strategies to remove the aforementioned barriers, including identification of roles and responsibilities of relevant stakeholders
- Encourage European farmers to produce non-food bioenergy carriers and capacity building of economic actors and other relevant stakeholders for setting up sustainable bioenergy supply chains

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1. Introduction

The aim of this work is to carry out an agronomic feasibility of bioenergy feedstock production, in order to provide a rigorous and exhaustive knowledge base for the implementation of non-food cellulosic chains and biorefineries in the Sulcis area (Sardinia). Due to the pollution generated by human-dominated processes (i.e. former industrial sites and abandoned quarries), this area was converted into marginal land [1], thus representing an interesting opportunity to prove the feasibility of non-food crops for land restoration and alternative systems of bioenergy production [2].

This study is divided into three different parts:

1. the first part aims to develop of a comprehensive database of cellulosic biomass crops, based on literature data and field trial results;
2. the second part aims to compare the agronomic characteristics and biomass yield potential for transferable value chains;
3. the last part implements GIS-based evaluation on contaminated and marginal land considering different land use/cover and environmental constrains in order to define suitable areas for biomass production within existing land use patterns. The GIS-based methodology is based on a multy-criteria land suitability and land allocation process.

The outcome of this study strives to provide new insights into agronomic and methodological implementation of bioenergy crops at large scale, while also providing useful information for bioenergy developers, scholars and policy makers in the agriculture and in the energy sectors.

1.1. Site description

The study area is the Sulcis-Iglesiente catchment located in the south–western part of the Sardinia island, Italy (39°09′ North latitude, 8°29′ West longitude) (Figure 1). It is characterized by flat and undulating topography which extends from the coastline to inland rugged areas, with elevation ranging from 1 to 450 m a.s.l.

The **climate** of the area is between semi-arid and dry sub-humid, with the typical bimodal pattern of precipitation distribution (i.e. peaks in autumn and spring). Average annual rainfall is about 550-600 mm and annual mean temperature reaches 16° C. Detailed descriptions of climate data of Sardinia are available at the website of the Sardinia Environment Protection Agency (ARPAS http://www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/index.asp).

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The **soil types** of the agricultural land are mainly Xerofluvents (Petric Calcisols; Haplic Nitosols; Calcic Luvisols), Chromoxererts (Vertic ed Eutric Cambisols) and Xerochrepts (Eutric, Calcaric e Mollic Fluvisols).

The area is mainly covered by arable land over flat terrain (mainly cereal production), to a lesser extent vineyards, Mediterranean grasslands and eucalyptus plantations over slightly sloping and marginal land.

The coastal area is a sensitive and ecologically protected region and hosts endangered acquatic and terrestrial species [3].

The study area is located in the largest **Site of National Interest (SIN)** in Italy (about 22.000 ha), one of the most contaminated areas of the Country with heavy metals (mainly Pb, Cu, Zn) from industrial flumes derived from coal power generation, bauxite and aluminum production, as well as by the centuries-old previous mining activities. In the municipality of Portoscuso, contaminated by dust fallout of surrounding industrial area (see Figure 1), the topsoil heavy metals contents exceeds the legal limit values, and the cultivation and commercialization of agricultural goods and milk production is forbidden for the potential threat to human health (Ordinanza n.9 Comune di Porto Scuso dated 06/03/2014)

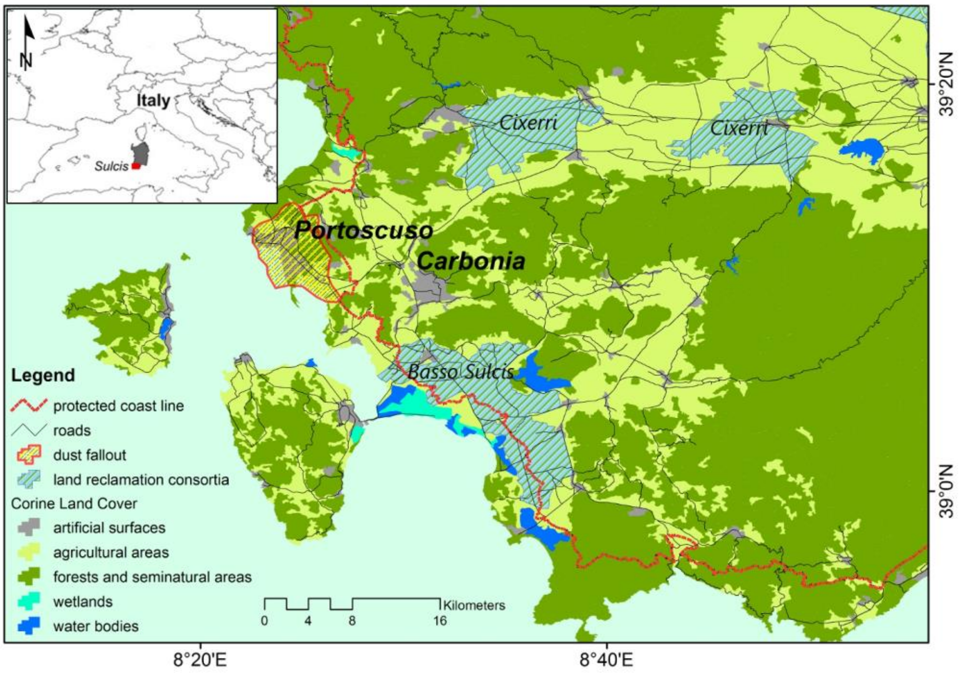

FIGURE 1. STUDY AREA.

1.1.1. The contaminated area

According to the information published by ARPAS in 2012, the areas affected by **heavy metals** contamination are found in a radius of 15 Km from the industrial area of Portovesme. The final mapping of the SIN, carried out in 2011, reports the following land use cathegories: 1) abandoned mining areas; 2) Industrial settlement areas; 3) scattered industrial sites; 4) abandoned landfills of municipal solid waste. Concentrations of pollutants are higher close to the emission sources, i.e. the metal factories of the industrial district. A recent study by Varrica et al., [4] on toxic metals in hair samples of children living near mining tailings of the Sulcis-Inglesiente district, reports a potential risk of adverse effects on the public health of the exposed population. In addition, heavy metal pollution is also evident in the shorefront of the industrial complex of Portovesme. In this sense, a study on the marine sediments showed high concentrations of Pb (up to 20 mg/kg), Zn (up to 70 mg/kg) and Cd (up to 120 mg/kg) in the first 2 cm of sediment [5]. In the past, emissions into the atmosphere have been estimated annually at 65,000 tons of SOx, 4,000 tons of dust, 10 tons of Pb and 100 tons of Fe [6]. ARPAS monitors water quality, air quality, soil quality and vegetation annually and all of analysis results are available at their website [7].

1.2. Feedstock identification and description

The implementation of a bioenergy cropping system as an integral part of a farming landscape is a difficult task, that requires an accurate agronomic evaluation in terms of environmental adaptability, productivity, logistics (i.e. establishment, harvesting, handling), as well as restricting factors and synergies with crop rotation schemes. Biomass species selected for bioenergy production must meet a number of standard requirements for the agronomic management such as productivity and yield stability, water use and nutrient use, pest resistance, suitability for available/common farm equipment, and feedstock quality. Essentially, the ideal crop would be easily and reliably established and well adapted to a range of environmental conditions.

Several types of biomass are expected to contribute to these objectives, including lignocellulosic energy crops. In order to establish the most suitable crops and understand differences in crop management, relevant results from scientific studies and field trials regarding bioenergy crops conducted in Sardinia were collected.

The species screening process consisted of a literature review with the use of the Institute of Scientific Information Web of Knowledge (ISI) databases and Google Scholar to search for published papers containing terms like ‘bioenergy’, ‘biomass’, ‘crop’, ‘feedstock’, ‘lignocellulosic’, ‘energy’ and Sardinia’ in titles, abstracts or keywords. The search was carried out selecting articles, papers, and reports published in English and in Italian in peer-reviewed journals, conference abstracts, technical reports, books and dissertations, prioritizing works that explicitly report field-based experiments, details on the cultivation techniques and yield data.

Furthermore, references reported in the identified papers were also checked. This study focused in particular on lignocellulosic energy crops, which entire above ground biomass is harvested for energy purposes.

The output of this analysis is a 'short list' of the most promising species highly suited to provide renewable feedstock that could be cultivated in the context of the study area. Table 1 summarizes the crops analysed, differentiated by typology of use on A) herbaceous (annual and perennial) and B) woody plants. Clearly, the list is not intended to be comprehensive, but it provides an overview of the most important candidate crops, especially for lignocellulosic crops. For a stable feedstock supply chain to be established, numerous criteria have to be considered for each biomass type, like, for example, efficient logistic for harvesting, transporting and storing a (i.e. cost-effective use tractors, harvesters, harvesting sites at large scale). In Table 1 the main characteristics of these crops such as general description, geographical origin, climatic and pedologic requirements are described.

TABLE 1. SUMMARY OF THE DIFFERENT TYPOLOGIES OF BIOMASS CROPS ANALYZED.

TYPOLOGY	HERBACEOUS PLANTS		WOODY PLANTS
	ANNUAL	**PERENNIAL**	
LIGNOCELLULOSIC CROPS	GLOBE-ARTICHOKE MILK THISTLE	GIANT REED MISCANTHUS SWICHGRASS SMILO GRASS TALL FESCUE RYEGRASS COCKSFOOT CARDOON	EUCALIPTUS
OLEAGINOUS CROPS	RAPESEED	ETHIOPIAN MUSTARD	
SUGAR CROPS	SWEET-SORGHUM		
STARCH CROPS	MAIZE DURUM-WHEAT TRITICALE		

1.2.1. *Arundo donax*

DESCRIPTION

Class	C3 perennial grass
Common Name	Giant reed, common reed, giant cane, wild cane, carrizo, canne de Provence
Distribution	Arundo donax is native of Eastern and Southern Asia. It has been widely naturalized in subtropical regions, and has also become naturalized and invasive in many regions, including the Mediterranean basin
Yield	10-40 dry matter Mg ha^{-1} year^{-1} (~ 590 GJ ha^{-1}) High variability across Europe and USA
Growing season	Perennial underground, above ground biomass (rhizomes & reed) Main growth season: April – October (7 months)
Temperature	7 – 29° C; Tolerates frost at -10°C. Optimum average temperature growing season: 19° C
Rainfall	> 450 mm/year Minimum vegetative rainfall: > 200 mm/growing season
Crop Coef. (Kc)	0.3 Apr–0.6 May–0.9 Jun–1.1 Jul –1.1 Aug–0.8 Sep–0.3 Oct
Soil Drainage	Impeded seasonally waterlogged
Soil type	Tolerance to salinity (up to 15 g L^{-1}) and lower quality soil, light and medium texture. Preferred soils with low sand content. It is reported to tolerate a soil pH of 5.0 to 8.7.
Harvest	Fully mechanized, from October to March; 45% moisture content
Agronomic features	Hydrophyte plant, tall cane with rapid growth. New shoots arise from rhizomes in nearly any season, but most commonly in spring. High resistance to drought; sterile seeds; low invasiveness when cultivated and managed
Description 	*Arundo donax* is a tall, erect, perennial cane and can grow to 2-10 m tall. Its root structure (rhizomes) forms compact bundles penetrating deep into the soil. The horizontal rhizomes give rise to many-stemmed, hollow, cane-like clumps allowing it to form large colonies many meters across. These tough, individual stems or culms are divided by partitions at the nodes like in bamboo, each node 12-30 cm in length and can reach diameters of 1-4 cm with walls 2-7 mm thick. The outer tissue of the stem is of a silicaceous nature, hard and brittle with a smooth glossy surface that turns pale yellow when the culm is fully mature. The pale, blue-green leaves clasp the stem broadly with a heart-shaped, hairy-tufted base, 2-6 cm wide at the base and tapering to a fine tip, up to 70 cm or more in length. The leaves are arranged alternately throughout the culm and very distinctly two-ranked, in a single plane. The culms can remain green throughout the year but often fade with semi-dormancy during the winter or in droughts. The flowers are borne in large plume-like panicles, 30-65 cm, at the upper tips of stems between March and September and are closely packed in a cream to brown-coloured cluster. The spikelets, flowering units comprised of one or more florets enclosed by two bracts or glumes, are several flowered, approximately 12 mm long with florets becoming successively smaller. The segmented central axis of the spikelet, the rachilla, is glabrous and dis-articulates above the glumes and between the florets. The more or less unequal glumes are 3-nerved membranous, narrow, slender, pointed and as long as the spikelets

1.2.2. *Miscanthus x giganteus*

	DESCRIPTION
Class	C4 rhizomatous grass
Common Name	Elephant grass, giant miscanthus, giant Chinese silver grass, miscanto
Distribution	Miscanthus is a genus native to Eastern Asia. Its range of distribution stretches from the equator to approximately 50° N. It is commonly found growing on roadsides, at field boundaries in the plains, abandoned milling sites, often favoring damp habitats, most species of the genus occur at altitudes below 2,400 m
Yield	15-30 dry Mg ha^{-1} year^{-1} (~ 296 GJ ha^{-1}) Biomass production depends on species and genotypes, soil type and water availability
Growing season	Perennial underground, above ground biomass (rhizomes & reed). Main growth season: April (emergence) – November (senescence)
Temperature	Begins to grow from dormant rhizomes when soil temperature reaches 10–12° C, while leaves begin to expand after air temperature average 5–10° C. Tolerates frost at -3.4°C
Rainfall	70-800 mm/year Minimum rainfall: > 400 mm/growing season
Crop Coef. (Kc)	0.3 Apr–0.6 May–0.9 Jun–1.1 Jul –1.1 Aug–0.8 Sep–0.3 Oct
Soil Drainage	Impeded seasonally waterlogged
Soil type	Tolerance to salinity (up to 5.8 g L^{-1}). Under water-limited conditions, it has performed best when planted on clay soils and worst when planted on sandy soils
Harvest	Fully mechanized as large round bales or large rectangular bales with commercially available haying equipment, from October to March; 45% moisture content
Agronomic features	Low requirement for N fertilizer, biomass rapidly accumulates through summer, peaking around September. High efficiency of water use, typically requiring between 100 and 300 l of water to produce 1 kg of biomass

Description 	Giant miscanthus is a natural triploid hybrid between diploid *Miscanthus sinensis* and tetraploid *Miscanthus sacchariflorus*. Miscanthus is a sterile plant and can be propagated only by rhizomes with little variation between clones. Miscanthus species have long been used for grazing and structural materials in China and Japan. Assimilates produced from photosynthesis accumulate in the new daughter rhizome, doubling its weight by the latter part of the season. By the winter, most N remains in the roots, rhizomes and litter. All Miscanthus species develop tuffs with high shoot density. They are generally 1.5 - 4 m high with 1 to 2 cm stem diameter, but some species such as M. *floridulus* and M. *lutarioriparius* can reach 6-7 m high. Their leaves have a prominent white midvein, with the size varying from 20 to 100 cm long and 1-3 cm wide depending on the species. Flowers are generally formed between July and September. Inflorescence consists of a fan-shaped plume made up of long branches attached to a central axis

1.2.3. *Panicum virgatum* L.

	DESCRIPTION
Class	C4 perennial rhizomatous warm-season grass
Common Name	Switchgrass, panic raide, Wild redtop, blackbent, tall prairie grass, le panic érigé, panico verga
Distribution	Switchgrass is native of North America where it occurs naturally from 55° N latitude to deep into Mexico, mostly as a prairie grass. In North America it has long been used for soil conservation and as a fodder crop
Yield	6-25 dry matter Mg ha^{-1} $year^{-1}$ (~ 590 GJ ha^{-1}) High variability across Europe and USA. European research indicates that lowland ecotypes yielded more than upland ecotypes
Growing season	Propagated by seed with a stand life of 10 to 20 years when used for biomass production in a delayed harvest system. Short day photoperiod <12 hours. Main growing season: April – October (7 months)
Temperature	Optimum average temperature growing season: min-max 17-32° C Absolute temperature growing season: min-max 6-36° C
Rainfall	> 450 mm/year. Minimum vegetative rainfall: > 200 mm/growing season
Crop Coef. (Kc)	n.a.
Soil Drainage	Somewhat dry to poorly drained
Soil type	Switchgrass does well on a wide variety of soil types, it is drought-tolerant and produces well on shallow, rocky soils. Soil pH should be 5.0 or above
Harvest	Fully mechanized as large round bales or large rectangular bales with commercially available haying equipment, from October to March. A cutting height of 10–15 cm maintains stands and keeps the windrows elevated to facilitate air movement and more rapid drying to less than 20% moisture content prior to baling
Agronomic features	Switchgrass has broad adaptability, high growth rates, and tolerates a wide variety of climatic and edaphic conditions. Switchgrass has good prospects as a biomass crop for energy and fibre production. The current research shows that between 50 to 100 kg N/ha/year is adequate for southern Europe

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Description 	Switchgrass exists as two ploidy levels (tetraploid and octaploid). Two ecotypes are generally defined based on morphological characteristics and habitat preferences. Lowland types are generally found in floodplains, they are taller, coarser, have a more bunch type growth habit, and may be more rapid growing than upland types. Upland types are found in drier upland sites, they are finer stemmed, broad based, and often semi-decumbent. The number of tillers per plant is lower in lowland cultivars with 30-75 while upland cultivars have 80-20 tillers, although the tillers of upland cultivars are thinner. It is suggest that lowland types may be better suited as biomass fuel plants. It is a perennial bunch grass averaging 0.9 to 1.55 m tall (it can grow up to 2.7 m), may spread from short, stout rhizomes. The stem (culm) is round and can have a red to straw colored tint. The seed head is an open, spreading panicle. A diffuse panicle produces 200-1000 kg ha^{-1} of seeds depending upon lodging level

1.2.4. *Piptatherum miliaceum* L.

	DESCRIPTION
Class	C3 perennial native to Mediterranean region
Common Name	Smilo grass, Millet mountain rice, Rice grass, Miglio multifloro
Distribution	Smilo grass is native to Mediterranean region, naturalized in California, South America, Australia and New Zealand. Is a hemicryptophyte and wind-pollinated
Yield	20-30 dry Mg ha^{-1} year^{-1} The biomass production depends on species and genotypes, soil types and water availability.
Growing season	Flowering time: april-september. Elevation up to ~ 1000 m
Temperature	n.a.
Rainfall	Rainfed in Mediterranean conditions
Crop Coef. (Kc)	n.a.
Soil Drainage	Drought tolerant
Soil type	Grows in harsh environments where nutrients availability is scarce (rocky soils, rocky slopes in direct sunlight, shallow soils, and roadsides)
Harvest	Fully mechanized, July-August
Agronomic features	Very common in pastures and open grassy places throughout Mediterranean regions, Smilo grass as a plant supplying amounts of palatable forage, grazed by livestock, component in natural pastures. its leaves dry up during summer, remaining in a semi-dormant state, and sprout again when sufficient rain has fallen
Description 	It is a perennial caespitose plant that produces robust grouping and erect stems of grass that can reach 1.5 meters high. Leaf sheath glabrous; ligules 1-3 mm, pubescent; limbo of up to 50 x 0.2-1.2 cm, flat or convolute with desiccation, with markedly striated and smooth beam and undersides. The inflorescence shaped panicles 20-50 cm, pyramidal, with top pendulous, lax; generally smooth shaft; whorls, erect-patent or patents, flexuous, hair. Spikelets of 2.5 to 3.6 mm, often violet. Glumes longer than the flower, lanceolate or ovate-lanceolate, acuminate, glabrous; 2.5 to 3.6 mm from the bottom; of 2.3 to 3.4 mm higher

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1.2.5. *Festuca arundinacea* S.

	DESCRIPTION
Class	C3 rhizomatus, cool season grass
Common Name	Tall fescue, reed fescue
Distribution	Native from northern Europe, introduced into the United States, South America, Australia, and New Zealand for turf, forage, soil stabilization, and wildlife food plots. It invades a variety of habitats including fields, forest margins, roadsides, ditches, railroad tracks, forest openings, savannas and moist, disturbed places
Yield	3-8 dry Mg ha^{-1} year^{-1}, High variability across Europe and USA
Growing season	Predominant cool-season bunchgrass
Temperature	Tall fescue grows best under relatively cool conditions. However, growth rate was found to decline as temperatures decreased from the optimal alternate 12-hour day/night temperatures of 24/19 °C to 15/10 °C
Rainfall	450 mm mean annual precipitation; optimal growth 700 mm
Crop Coef. (Kc)	n.a.
Soil Drainage	Tall fescue is mesic in its moisture requirements. It is tolerant of poor drainage, winter flooding, and fairly high water tables. It has fair drought tolerance
Soil type	Tall fescue is adapted to a wide range of conditions. It grows best on deep, fertile, silty to clayey loam (medium to heavy texture) soils with open sunlight and a balanced supply of moisture (mesic). Tall fescue is salt tolerant and does well on heavy alkaline soils. It grows at a wide range of pH
Harvest	Fully mechanized with commercially available haying equipment
Agronomic features	The herbage of mature tall fescue tends to be coarse, but it is taken by all livestock when it is young, green, and succulent. Tall fescue has good competitive ability against other species in mixtures; tall fescue stands are easily established and develop rapidly

Description 	Erect, tufted cool-season perennial grass 0.6 to 1.2 m in height, green in winter and spring, during which it is the most common green bunchgrass. Dark-green leaves appearing in late winter, usually flowering in spring (infrequently in late summer). It is semi-dormant during heat of summer, with whitish seed-stalks persisting. Growth resumes in fall and continuing into early winter. Stems are moderately stout, un-branched, hair-less with round cross section and one to three swollen light-green nodes widely spaced near the base. Flat and long lanceolate leaves are 10 to 45 cm long and 0.1 to 0.3 cm wide. In spring, greenish white flowers become purplish and form spindle-shaped clusters. Seeds are husked grain, spindle-shaped, and 3 to 5 mm long. It reproduces by seed and spreads vegetatively, forming dense, solid stands

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1.2.6. *Lolium perenne* L.

	DESCRIPTION
Class	C3 rhizomatus, cool season grass
Common Name	Ryegrass, winter ryegrass
Distribution	It is native to Europe, Asia and northern Africa, but is widely cultivated and naturalized around the world. As a bunchgrass, it produces only tillers and has limited ability to spread. In Italy, native perennial ryegrass is distributed between 0 and 2,000 m a.s.l.
Yield	0.9 – 5 dry Mg ha^{-1} year^{-}1; High variability across Europe and USA
Growing season	cool-season bunchgrass, the plant flowers from May to November
Temperature	Lolium perenne grows best under relatively cool conditions
Rainfall	Perennial ryegrass is recommended on better sites above 610 m elevation and receiving 711 mm) or more of annual precipitation
Crop Coef. (Kc)	n.a.
Soil Drainage	They will stand fairly wet soils with reasonably good surface drainage
Soil type	Soil pH for optimum ryegrass production is between 5.5 and 6.5. These grasses have a wide range of adaptability to soils, but thrive best on dark rich soils in regions having mild climates
Harvest	Fully mechanized with commercially available haying equipment
Agronomic features	Ryegrass responds well to good management, such as intensive rotational grazing and fertilizer applications. Perennial ryegrass is a palatable and nutritious forage for all classes of livestock and most wild ruminants. Perennial ryegrass grows rapidly and is easily established; it is often used for stabilization of soils
Description 	The plant is a low-growing, tufted, hairless grass, with a bunching growth habit. The leaves are dark green, smooth and glossy on the lower surface, with untoothed parallel sides and prominent parallel veins on the upper surface. The leaves are folded lengthwise in bud with a strong central keel, giving a flattened appearance. The ligule is very short and truncate, often difficult to see, and small white auricles grip the stem at the base of the leaf blade. Leaf sheaths at the base are usually tinged pink and hairless. Stems grow up to 90 cm. The inflorescence is unbranched, with spikelets on alternating sides edgeways-on to the stem. Each spikelet has a single glume, on the side away from the stem, and between 4 and 14 florets without awns. The anthers are pale yellow

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1.2.7. *Dactylis glomerata* L.

	DESCRIPTION
Class	C3 rhizomatus, tufted perennial grass
Common Name	Cocksfoot, cocksfoot grasses, orchard grass, erba mazzolina
Distribution	It is native to Eurasian and North African. It is widely used as a hay grass and for pastures. In dry areas Mediterranean subspecies such as subsp. *hispanica* are preferred for their greater drought tolerance
Yield	2 - 5 dry Mg ha^{-1} year^{-1}
Growing season	The plant flowers from June to September. Growth rates of 60–80 kg dry matter/ha/day are possible in autumn and spring under conditions of good moisture and temperature
Temperature	n.a.
Rainfall	Subsp. *hispanica* (Spanish cocksfoots) are suited to areas receiving low to moderate rainfall (450-650 mm), or where frequent, prolonged (5–6 months) moisture stress occurs over the summer–autumn period. Varieties of this subspecies become dormant at the end of spring, when temperatures rise
Crop Coef. (Kc)	n.a.
Soil Drainage	It does not perform well in soils that are prone to waterlogging
Soil type	Cocksfoot grows well in a variety of soils with pH greater than 4.0, performs best in a pH range of 5.8 – 7.0. it is the most acid-soil tolerant grass. It has a high tolerance of aluminium, and will also grow well in shallow soils
Harvest	Fully mechanized with commercially available haying equipment. Cocksfoot is capable of moderate to high levels of herbage production in well-managed, regularly fertilized pastures
Agronomic features	Paddocks in which cocksfoot will be sown should be managed in preceding years to minimize weed and insect burdens. Cocksfoot seedlings are very susceptible to competition from more vigorous annual grasses. To enhance establishment of cocksfoot-based pastures, the major elements – phosphorus, nitrogen and sulphur

Description

Cocksfoot grows in dense perennial tussocks to 20–140 centimeters tall, with grey-green leaves 20–50 cm long and up to 1.5 cm broad, and a distinctive tufted triangular flowerhead 10–15 cm long, which may be either green or red- to purple-tinged (usually green in shade, redder in full sun), turning pale grey-brown at seed maturity. The spikelets are 5–9 mm long, typically containing two to five flowers. It has a characteristic flattened stem base which distinguishes it from many other grasses

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1.2.8. *Cynara cardunculus* L. Var. Scolymus

	DESCRIPTION
Class	C3 perennial rosette plant
Common Name	Globe artichoke, alcachofa, artichaut, carciofo
Distribution	Globe artichoke is native to Southern Europe, Mediterranean basin and North-Western Africa. Southern Italy and Sicily have been considered as the origin of its domestication
Yield	3 - 30 Mg ha^{-1} year^{-1} for heads (fresh biomass); 25 – 140 Mg ha^{-1} year^{-1} for byproduct (wet biomass) High variability across varieties
Growing season	August - June
Temperature	The plant grows best under relatively moderate conditions. The optimal temperature is comprised between 15° and 20° C. At 0° C the flower heads have damage,
Rainfall	> 450 mm/year Forced cultivation cycle requires ~ 5000 m-3 h^{-1}
Crop Coef. (Kc)	0.6 Aug. – 0.8 Sept. – 1 October to December-February
Soil Drainage	It prefers medium texture soils, dry or moist soils, without waterlogging
Soil type	Globe artichoke grows well in a variety of soils with pH greater than 4.0., performs best in a pH range of 5.8 – 7.0.
Harvest	Manually harvesting of large fleshy head. Traditional varieties typically consist of heterogeneous populations. Early varieties mature tipically around autumn-winter until spring (October-April).
Agronomic features	Semi-dormant offshoots were hand-planted within the first ten days of August. Planting density of 1 plant m-2. It requires 150/200 kg N, 100/150 kg P2O5, 100 kg K

Description 	Globe artichoke is a perennial herbaceous plant, with main root, secondary fibrous roots, rhizome foam comprising gems. Very vigorous, can reach 1.5 m in height with arching, deeply lobed, silvery, glaucous-green leaves 50–82 cm long. It belongs to the Asteraceae family, and as such, it has an flower buds. The budding artichoke flower-head is a cluster of many budding small flowers (purple)together with many bracts, on an edible base. Once the buds bloom, the structure changes to a coarse, barely edible form. The flowers develop in a large head from an edible bud about 8–15 cm diameter with numerous triangular scales

1.2.9. *Cynara cardunculus* L. Var. Altilis

	DESCRIPTION
Class	C3 perennial rosette plant, grown as annual crop
Common Name	Cardoon, artichoke thistle, carde, cardo
Distribution	Cardoon is native to Southern Europe, Mediterranean basin and North-Western Africa.
Yield	10 – 25 dry Mg ha^{-1} year^{-1} High variability across varieties
Growing season	9 months, autumn to spring, blooms in late May
Temperature	As globe artichoke, quite sensitive to frost in the seedling state. Minimum -5° C, optimum 14-18° C
Rainfall	As globe artichoke, for good development of the plants, rainfall during autumn, winter and spring months should be about 400mm or more
Crop Coef. (Kc)	n.a.
Soil Drainage	As globe artichoke
Soil type	As globe artichoke. Tolerance to salinity
Harvest	Fully mechanized, collect separately the different biomass fractions (seeds and stalks)
Agronomic features	Drought-hardy plant, traditionally grown as vegetable plant for the production of side shoots edible. The plant shoot dries up in summertime while the underground plant organs remain quiescent. Planting density of 1-1.5 plant m-2. It requires 100 kg N, 60 kg P2O5, 100 kg K
Description 	Cardoon is a perennial herbaceous plant, with main root, secondary fibrous roots, rhizome foam comprising gems. Very vigorous, can reach 2 m in height, at aboveground it looks like a rosette plant, short stem (3-4 cm), high number of leaves, alternating, pennants, of longer than 1 m. The flowers are grouped in large globose capitula (up to 8cm in diameter). At flowering presents flower stems straight (1.5-3 m), tomentose and branched. Each branch in the terminal position brings a globular inflorescence surrounded by bracts. The intensity of the spiny character changes among the different varieties. Each plant has from 10 to 30 heads. Entomophilous pollination, cross-fertilization

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1.2.11. *Silybym marianum* L. Gaertn.

DESCRIPTION	
Class	C3 spiny herbaceous plant, seed propagated
Common Name	Milk thistle, Blessed thistle, holy thistle, cardo mariano
Distribution	Milk thistle is native to Mediterranean basin, Its current distribution includes most temperate areas of the world
Yield	10-20 dry Mg ha^{-1} $year^{-1}$
Growing season	Annual growth cycle , seed germination starts in October
Temperature	Warm average temp. > 10°C, Cold average temp. > 0°C, wet all year. Seeds germinated over a wide temperature range ($15^o/5^oC$ to $40^o/30^oC$)
Rainfall	As globe artichoke, for good development of the plants, rainfall during autumn, winter and spring months should be about 400mm or more
Crop Coef. (Kc)	n.a.
Soil Drainage	As globe artichoke
Soil type	It is adapted to poor quality soils and many different growing conditions. It grows best in areas of high fertility, such as alluvial flats, sheep camps, stock yards and other places with high soil nitrogen levels
Harvest	Fully mechanized, as cardoon
Agronomic features	It is common in the native flora of the Mediterranean basin; for its high competition ability (aggressive vegetative growth causing depression of adjacent plants) it is reputed as a dangerous weed in cropping areas and in particular in grass-legume mixtures. Milk thistle is a serious weed in many areas of North and South America, Africa, Australasia, and the Middle East. Milk thistle may be used for the phytoremediation of polluted soils

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Description 	It is a broad-leaved species belonging to Asteraceae, Annual or biennial. Stems branched above, ridged, with sparse mealy hairs at least above, 0.5-2 m tall, not winged. Leaves elliptic to lanceolate, lyrate-pinnatifid to pinnate, sinuate, coarsely dentate, green with conspicuous white markings along veins. with sparse short mealy hairs on lamina; base amplexicaul, auriculate, with very spinous margins; prickles marginal, yellowish, spreading, 5-12 mm long. Capitula ovoid, erect, 4-6 × 5-7 cm, solitary, terminal and pedunculate, and also sessile in axils of uppermost lvs; peduncles with appressed cobwebby tomentum. Involucral bracts sparsely covered with short mealy hairs; margins with sparse cobwebby hairs. Outer bracts leaflike, obovate with spinous apex and margins. Middle bracts oblong; appendage ovate, subulate, with spinous margins and a long spreading to recurved apical spine. Inner bracts lanceolate; appendage becoming linear-lanceolate, entire. Corolla normally reddish purple, 20-28 mm long; lobes unequal, 4-6 mm long. Is renowned as medicinal plant for the presence in its seed of the silymarin, a bioactive complex with antihepatotoxic action

1.2.12. Eucaliptus spp.

	DESCRIPTION
Class	C3 tree plant
Common Name	Eucalyptus, eucalitto
Distribution	Eucalyptus species are native to Australia, spread into many tropical and subtropical regions of the world. The genus Eucalyptus, with more than 550 species, belongs to the Myrtaceae. *Eucalyptus globulus* and *Eucalyptus camaldulenis* have proven to be excellent commercial crops in temperate climates
Yield	7-30 dry Mg ha^{-1} year^{-1}
Growing season	fast growth rates
Temperature	Optimal 12-18°C, minimum temperature above -6°C. Clones have proven to be superior characteristic
Rainfall	It is a drought-resistant species and grows in areas receiving 200mm rainfall per annum, though growth is better where the annual rainfall exceeds 400mm
Crop Coef. (Kc)	n.a.
Soil Drainage	Generally it requires good drainage
Soil type	It is adapted to poor quality soils and many different growing conditions
Harvest	Fully mechanized as short rotation coppice
Agronomic features	Generally managed as coppice crops, coppice shoots develop from dormant buds situated in the live bark or from lignotubers, buds found near the junction of root and stem in many eucalyptus species
Description 	*Eucalyptus globulus* Labill. The flower buds have a warty cap or operculum about 2.5 cm in diameter, which falls off, allowing the very numerous stamen filaments to extend in shaving-brush fashion above the cup-shaped base (hypanthium). The yellowish white flowers are pollinated by insects, hummingbirds, and other pollen and nectar feeders. As in almost all eucalyptus, pollen is usually viable before the stigma becomes receptive. The fruit, a distinctive top-shaped woody capsule 15 mm long and 2 cm in diameter, ripens in October to March, about 11 months after flowering

1.2.13. *Brassica carinata* A. Braun

	DESCRIPTION
Class	C3 herbaceous plant
Common Name	Ethiopian mustard, Abyssinian mustard, Ethiopian rape, Abyssinian Cabbage, Chou Éthiopien
Distribution	Ethiopian mustard is native to the central highlands of Ethiopia and North Africa
Yield	1-4 dry Mg ha^{-1} year^{-1}
Growing season	Annual growth cycle
Temperature	Optimal 15-20 °C
Rainfall	It is a drought-resistant species and grows in areas receiving 200-300 mm rainfall per annum
Crop Coef. (Kc)	n.a.
Soil Drainage	It prefers moist soil
Soil type	Suitable for: light (sandy), medium (loamy) and heavy (clay) soils and prefers well-drained soil. Suitable pH: acid, neutral and basic (alkaline) soils. It can grow in semi-shade (light woodland) or no shade
Harvest	Fully mechanized as Brassica napus
Agronomic features	Ethiopian mustard is highly heat and drought tolerant, has good resistance to blackleg disease, resistance to aphids and flea beetles. High erucic acid content of its seeds
Description 	*Brassica carinata* is an erect, annual herb growing from 30 to 200 cm tall formed through the interspecific hybridization of *Brassica nigra* L. and and *B. oleracea* L. It is usually branched with leaves arranged alternately on stems. It has a deep root system. The stems are reddish-green, often profusely branched with lateral buds. Leaves are alternate, non-heading with long petioles. The foliage is light green with purplish veins, often light brown glabrous or bearing a few hairs on the ribs. Flowers are usually light yellow about 1,5 cm across, on short pedicels on an extended raceme. Flowers are regular with four free sepals in one series and two sets of stamens. The flowers are hermaphrodite and are pollinated by bees. The fruit is a silique, usually less than 5 cm long, stout and broad with carinate angles, usually dehiscent. The seed is large and predominantly dark, small, often globular, 0,2 cm thick, filled with embryo

1.2.14. *Brassica napus* L.

DESCRIPTION	
Class	C3 herbaceous plant
Common Name	Rapeseed, rape, canola, oilseed rape, fodder rape, olraps, winter oil seed, colza
Distribution	Rapeseed is native of Europe. It is a temperate crop but it can be grown in the tropics at elevations between 1500-2200 m
Yield	Yields of 2-4 dry Mg ha^{-1} year^{-1} are considered good, yields of 0.5-2 dry Mg ha^{-1} year^{-1}are more usual
Growing season	Annual or biennial herb. Spring cultivars growing 85-160 days, and winter cultivars 160-340 days
Temperature	Widely adapted, rape is resistant to frost at all stages of growth. Unhardened plants can survive -4°C, while fully-hardened spring type rapeseed can survive -10 to -12°C, and hardened winter rapeseed can survive short periods of exposure to -15 to -20°C
Rainfall	Optimall 500-1000 mm
Crop Coef. (Kc)	0.35 initial; 1 midseason; 0.35 end season
Soil Drainage	It prefers well drained soils
Soil type	Soil depth 50-150 cm, medium texture, pH optimal 6.5-7.6
Harvest	Fully mechanized
Agronomic features	Rape can be sown in either the fall or the spring depending on the type of variety. Rape responds well to nitrogen fertilizer and soil fertility, similar to those for small grains. The emerging crop is very susceptible to soil crusting; seedbed preparation is important. Canola is susceptible to blackleg and Sclerotinia stem rot. If not rotated with resistant crops, seed treatment may be necessary
Description 	A herb, 0.5-2 m tall with a strongly branched stem. Basal leaves of flowering plant stalked, highest leaves sessile and clasping stem. Flowers with 11-15 mm long, pale to bright yellow petals. The seeds are extracted for an oil used especially in margarine and for cooking. Newly bred cultivars with a high content of erucic acid are used for extraction of industrial oil. It is also used as a fodder crop

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1.2.15. *Zea mais* L.

	DESCRIPTION
Class	C4
Common Name	Corn, maize, mais, mielie
Distribution	Maize is native to Mexico
Yield	20-30 dry Mg ha^{-1} year^{-1}
Growing season	Annual growth cycle
Temperature	Maize is grown in temperatures between 18°C and 27°C during the day and around 14°C during the night, optimum range from 30-34°C
Rainfall	Grows in areas receiving 700-800 mm rainfall
Crop Coef. (Kc)	0.3 initial; 1.15 midseason; 0.85 late
Soil Drainage	It prefers well-drained moist soil
Soil type	Maize grows in a wide range of soils, best suitable deep clay-loam soils, pH between 6.5 and 7.5
Harvest	Fully mechanized
Agronomic features	Annual cereal grain, is widely cultivated throughout the world, is increasingly being used as a biomass fuel. It requires high energy input like fertilizers and water
Description 	The maize plant is often 3 m in height. The stem is commonly composed of 20 internodes of 18 cm length. A leaf, which grows from each node, is generally 9 cm in width and 120 cm in length. Ears develop above a few of the leaves in the midsection of the plant, between the stem and leaf sheath, elongating by 3 mm/day, to a length of 18 cm with 60 cm being the maximum alleged in the subspecies. There are female inflorescences, tightly enveloped by several layers of ear leaves commonly called husks. Elongated stigmas, called silks, emerge from the whorl of husk leaves at the end of the ear. There are often pale yellow and 18 cm in length, like tufts of hair in appearance. At the end of each is a carpel, which may develop into a "kernel" if fertilized by a pollen grain. The pericarp of the fruit is fused with the seed coat referred to as "caryopsis", typical of the grasses, and the entire kernel is often referred to as the "seed"

1.2.16. *Sorghum bicolor* L. (Moench)

	DESCRIPTION
Class	C4 plant
Common Name	Sorghum, black amber, chicken corn, sudangrass, durra, sorgo forrajero, sorgo
Distribution	Sorghum originated in northern Africa, and is now cultivated widely in tropical and subtropical regions
Yield	10-20 dry Mg ha^{-1} year^{-1}
Growing season	Annual growth cycle
Temperature	Is a warm season crop that requires soil temperatures of at least 16°C to initiate the germination process. Optimum temperature for growth is 30°C. Sorghum is not tolerant to frost, shade, or sustained flooding
Rainfall	Drought tolerance, high water use efficiency
Crop Coef. (Kc)	0.3 initial; 1 midseason; 0.55 late
Soil Drainage	It prefers well-drained soils
Soil type	Sorghum grows in a wide variety of soils and is drought resistant, best suitable soils are deep clay-loam soils, pH between 6.5 and 7.5 is optimum
Harvest	Fully mechanized
Agronomic features	Sorghum is a seed-propagated annual crop that can be grown as either a self-pollinated variety or a hybrid. It is an "opportunity crop" for resource-poor farmers. The plant looks much like grain sorghum, except that it is often taller (sometimes much taller, reaching up to 4 meters) and it accumulates a great deal of sugary juice in the stalk
Description 	It is a typical grass with a deep and fibrous root system, primary culm and the capacity for both basal and axillary tillering. Grows in clumps that may reach over 4 m high. The grass blades are flat, stems are rigid, and there are no creeping rhizomes. Sorghum has a loose, open panicle of short, few flowered racemes. As seed matures, the panicle may droop. Glumes vary in color from red or reddish brown to yellowish and are at least three quarters as long as the elliptical grain. The grain is predominately red or reddish brown

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1.2.17. Triticale

	DESCRIPTION
Class	C3 plant
Common Name	Triticale
Distribution	Triticale is a hybrid of wheat (Triticum) and rye (Secale) first bred in laboratories during the late 19th century in Scotland and Sweden. Actually the major producers are in Europe
Yield	10-20 dry Mg ha^{-1} $year^{-1}$
Growing season	Annual growth cycle
Temperature	Triticale closely overlaps the areas of adaptation common to the extremes of its wheat and rye parents
Rainfall	Triticale performs well under rainfed conditions throughout the world
Crop Coef. (Kc)	0.15 initial; 1.1 midseason; 0.15 late
Soil Drainage	It prefers well-drained soils
Soil type	Excellent tolerance to low pH levels, Although triticale responds very similarly to wheat grown under a wide range of environments, it is in general superior under stress conditions
Harvest	Fully mechanized as durum wheat
Agronomic features	Triticale combines the yield potential and grain quality of wheat with the disease and environmental tolerance (including soil conditions) of rye. It is grown mostly for forage or fodder
Description 	The great majority of today’s triticales are descendants of primaries involving either common wheat or durum wheat as the seed parent and cultivated diploid rye as the pollen parent

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1.2.18. *Triticum durum* Desf.

DESCRIPTION

Class	C3 plant
Common Name	Durum wheat, grano duro
Distribution	Durum wheat, is an annual grass native to the Mediterranean region and southwest Asia, which is one of several species of cultivated wheat, now grown in temperate climates worldwide for its cereal grain, which is one of the top two cereal crops grown in the world for human consumption
Yield	5-10 dry Mg ha^{-1} $year^{-1}$
Growing season	Annual growth cycle
Temperature	Germination 2-3°C minimum, 37°C maximum; optimal development 20-25°C
Rainfall	500-800 mm for the entire production cycle
Crop Coef. (Kc)	0.15 initial; 1.1 midseason; 0.15 late
Soil Drainage	It prefers well-drained soils
Soil type	Durum wheat is well adapted to well drained, medium texture and clay soils, while it is give low productions in sandy soils, poor and acidic; pH 6.5-7.8 optimal
Harvest	Fully mechanized
Agronomic features	Durum wheat provides the best results when it is preceded by corn, beet, potato or meadow. It is sown from October to November, nitrogen fertilization (75-170 kg/ha), chemical weed control is performed in pre-sowing and post-emergency, susceptible to fungal attack, rainfed
Description 	The plant is made up of a root and shoot system, the plant height 0.7-1.2 m. The shoot is made up of a series of repeating units or phytomers, each potentially having a node, a leaf, an elongated internode and a bud in the axil of the leaf. There are from 6 to 16 or more of these units forming the vegetative part of each shoot. A leaf is inserted at each node although at maturity the basal leaves are usually dead and may have disappeared. The shoot is terminated by an ear or spike bearing about 20 spikelet's. In the ear, the phytomer is made up of the spikelet (the axillary bud) and the rachis (node and internode). Each leaf comprises the sheath, wrapping around the subtending leaf, and a lamina (blade). The flowers are hermaphrodite and are pollinated by wind. The fruit is a caryopsis rich in starch

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2. Data collection on bioenergy feedstock

This project section aims at collecting all available information regarding the cultivation of cellulosic feedstock, in particular for the study area and more generally in Sardinia. More specifically, the action intends to collect and further analyze the information available regarding a list of dedicated crops, including annual and perennial.

Following the data obtained above in Chapter 1, the results from scientific studies and field trials regarding bioenergy crops conducted in Sardinia were analyzed. In addition, the results from field trials conducted by Biochemtex spa in collaboration with the Department of Agriculture of the University of Sassari were combined with relevant information from the literature. All these findings were analyzed considering cultivation protocols, crop requirements and site-specific conditions that influence biomass yields and composition during the growing season (i.e. yield, dry matter, cultivar, fermentable sugars, irrigation, fertilisation, soil texture and pH, elevation, growing seasons). Reporting precise geo-referenced field trial data will allow in the future to test plant-growth models and empirical estimates. The output of this analysis is a short list of bioenergy crops that could be cultivated under the study area conditions. All relevant data extracted and examined were implemented in a relational database implemented in MySQL (Figure 2), following the structure recently reported by Laurent et al., [8]. The full database is attached to this deliverabble as .CSV file in order to allow an easy use with any database or spreadsheet program.

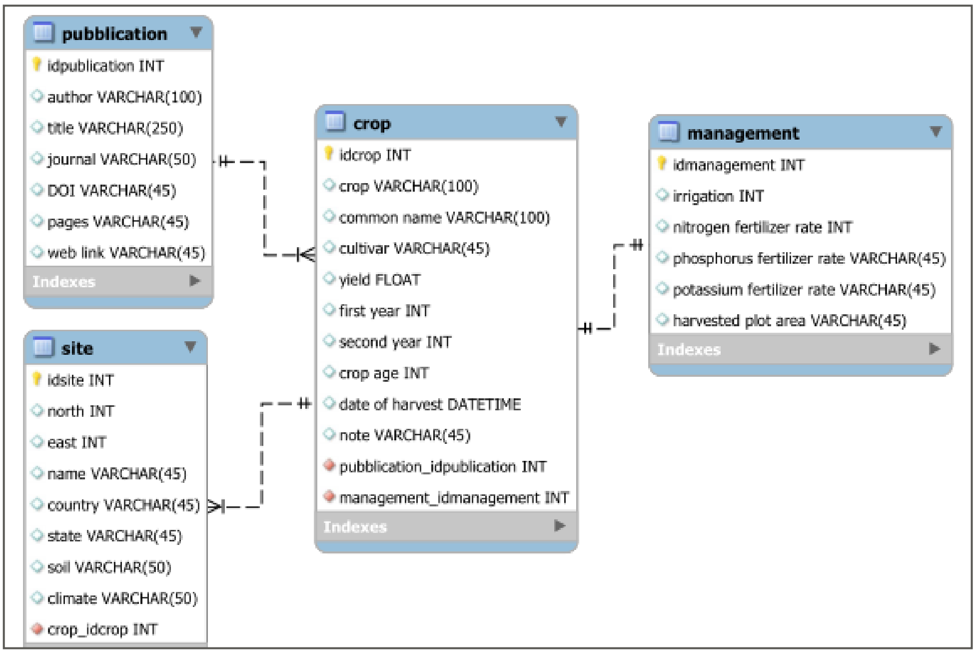

FIGURE 2. RELATIONAL DATABASE OF CROPS OBSERVATIONS.

This database contains detailed information regarding the publication or experimentation (i.e. author, title, journal, DOI, pages, web link), the site of experimentation (i.e. geographic coordinates, name, soil, climate), crop information (i.e. type of crop, name and common name, yield, crop age, date of harvest), and crop management (i.e. irrigation, fertilizer rate, harvested plot area).

2.1. *Arundo donax* Field Trials

The field trials of *Arundo donax* in Sardinia started in 2013 by Biochemtex and are ongoing. The coexistence in the region of large portions of land that are unused or underused, together with the actual availability of water thanks to existing irrigation facilities, makes the context interesting to build a sustainable value chain.

Arundo donax was chosen by Biochemtex in a reasonable expectation, thanks to the previous experiences of the company, of good potential biomass yield at low levels of inputs, advantages in supply chain management and good conversion rates to cellulosic sugars. *A. donax* is also known to be at least partially adapted to local conditions, since the plant is naturally present in the landscape.The field trials were conducted in three different locations, in Masainas and Tratalias in the Sulcis Iglesiente region, and in Serramanna, in the Medio Campidano district. These three locations fall outside the contaminated area where food crop production is forbidden.

The fields used for experimental trials all belong to local farmers.

- Masainas

The experimental field is located in the municipality of Masainas, approx. 20 Km from Portovesme. The area has interesting agricultural activities, as well as land with marginal production. Surrounding the trial site, farmers cultivate artichokes, grapes, olives, melons, cereals; there is also fallow land, grassland and areas occasionally used as pastures. This specific location has been chosen to evaluate the agronomic performances of Arundo donax in comparison with other productions, and to study the potential integration of energy crops into existing farming models with minimal risk of food production displacement.

The field area is 0,5 ha. The soil type is a sandy loam.

The experimental design is composed of 18 blocks 6 m x 36,6 m.

Three propagation methods were used: micropropagation, rhizomes, stem cuttings, evenly distributed in the experimental blocks.

Plant density of 2,2 plant/m^2 (H - High density) and 1,2 plant/m^2 (L - Low density).Time of plantation were also recorded: blocks 1 to 6 were planted in autumn 2013, the remaining (6 to 18) in spring 2014.

Yield in the 2nd year of trial was 25,56 t/ha (wet), with an irrigation dose of 500 mm (unpublished result). Drip irrigation was used from the 2nd year.

- Serramanna

The agricultural context around the experimental field in Serramanna sees cereal cultivation, silviculture and forage production in addition to horticulture.

The experimental field area is 0,5 ha. The soil type is a sandy-clay loam.

The available irrigation system is normally used by farmers in selected cases.

The experimental design used is identical to Masainas.

Water availability allowed to differentiate and obtain data on yields in function of irrigation quantities.

Yield in the 2nd year of trial was 17.45 t/ha (wet), with an irrigation dose of 600 mm (unpublished results). Drip irrigation was used from the 2nd year.

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- Tratalias

The field trial in Tratalias started in June 2014, in a region where irrigation is less common: cereals and grassland for feed are the most frequent agricultural activities.

The experimental field area is 1 ha, and it was divided in 2 sectors and 18 blocks, where only rhizomes were planted, with a plant density of 1,2 plant/m^2.

Two types of data were gathered: yields in function of fertilization doses and plant carbon sequestration.

Yield in the 1st year was 5,6 t/ha (wet). Irrigation dose the first year was xxx. (unpublished results). Sprinkler system was used both years.

2.2. Comparison of agronomic characteristics

The compiled database includes 451 observations of agronomic traits for a total of 19 sites, including the *Arundo donax* field trials described at paragraph 2.1, for 17 different crops The diversity of studies included in our dataset was intended to facilitate regional assessment as a result of multiple studies from a wide range of locations and conditions. Among these characteristics, yields and productive capacity are the most important to assess the suitability of different lignocellulosic crops. Intraspecific biomass yield comparison provide the effectiveness of the crops and cultivars in terms of crop management practices, while productive capacity compared with first-generation[1] bioenergy feedstock types (interspecific assessment) returns a detailed understanding useful to identifying the most promising bioenergy crops [9]. An overview of the main agronomic traits is reported in Tables S1 and S2 (Annex 1) for annual and perennial crops, respectively. In addition, Tables S3 and S4 show an overview of some agronomic results of experiments conducted in Italy. Table S5 is a matrix that provides a comprehensive and intuitive overview as a basis for a qualitative assessment of all results of studies on the agronomic characteristics of all crops evaluated. Figure 3 shows the box and whisker plot diagram of above-ground biomass yield for the crops evaluated.

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1. [1] This definition includes those feedstocks widely used for first generation biofuels, including food and feed crops and residues.

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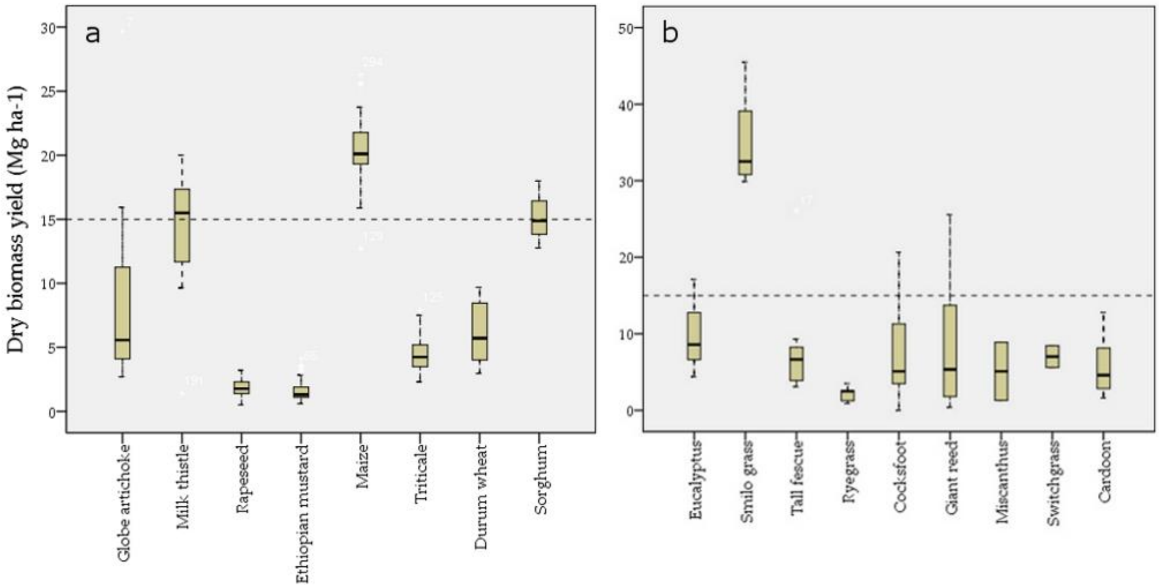

FIGURE 3. (A) BOX-PLOT OF BIOMASS YIELD FOR ANNUAL CROPS. (B) BOX-PLOT OF BIOMASS YIELD FOR PERENNIAL CROPS.

In the overview of studies, reported biomass yields are quite variable (Figure 3), as a function of species and cultivar, fertilizer and irrigation application rates, soil type and more generally management regime. Generally, first-generation annual feedstock show higher peak yields values compared to second-generation ones. Indeed, the highest performance of conventional annual crops depends on high energetic and agronomic inputs like fertilizers, pesticides, irrigation and tillage operations. Conversely, second-generation crops combine low agronomic requirements with stable productions*.* Detailed examination of energy comparison for crops in European agricultural systems by Venturi and Venturi [10] showed that row crops (e.g. wheat, maize, sugar beet) have a low energy balance ratio (range 1 - 4) compared with lignocellulosic crops such as giant reed and cardoon (range 10 - 75).

These results seem to be consistent with other research indicating that perennial lignocellulosic species on marginal and semi-arid Mediterranean land have the potential to effectively support biomass energy value chains [11–15]. Interestingly, in a meta-analysis on yield data for 36 different crop species, Laurent et al. [8] found that second-generation crops such as giant reed and miscanthus were more productive than first-generation feedstocks and woody crops. However, this information should be interpreted with caution because a broad amount of data found in literature come from small plot experiments, while yields are reduced when produced at large scale [16].

Specifically, sorting out yield response of first generation annual crops, median yield was highest for maize (~20 Mg ha^{-1} - dry matter), followed by sweet sorghum (~15 Mg ha^{-1} - dry matter). The most striking result is the high harvestable yield of byproduct for the cultivar 'Mardigal' of globe artichoke, reaching a peak of 29.7 Mg ha^{-1} of dry matter, followed by 'Tema' cultivar (15.9 Mg ha^{-1}), 'C3' cultivar (11.2 Mg ha^{-1}), while the cultivars 'Spinoso sardo' and 'Violetto' showed a lower byproduct yield (6.4 and 5.7 Mg ha^{-1} of dry matter, respectively) [17]. Obviously, these observations come from experimental plots and therefore need to be interpreted with caution.

Among annual species, it is interesting to note that milk thistle emerges as promising bioenergy crop, reaching a peak of 20 Mg ha^{-1} of fresh weight under rainfed conditions and low nitrogen input [18,19]. Conversely, grain crops such as cereals and oilseeds have more stable but lower harvestable yields (~7 Mg ha^{-1} durum wheat; ~6 Mg ha^{-1} triticale; ~2 Mg ha^{-1} rapeseed and ethiopian mustard).

With regard to fertilizers input, maize, sorghum and globe artichoke had the highest requirements, always associated with high irrigation rates. These results provide further support for the hypothesis that biomass feedstock production is highly dependent on water availability in these crops [20]. Likewise, in Mediterranean cropping systems the highest yields of row crops are associated with high tillage intensity and have the potential to induce soil erosion, nitrogen leaching and reduce soil organic carbon [21]. Ultimately, strategies to enhance the productivity of large-scale dedicated biomass crops in Mediterranean areas should be undertaken with caution and considering the impacts on water resources [22]. On the contrary, cardoon and milk thistle had the lowest fertilizer needs associated with rainfed conditions. Unfortunately, studies of biomass crops have not dealt with byproduct yields of oilseed crops, and thus it is difficult to make a direct comparison with other bioenergy crops. Similarly, data on fermentation of sugars such as cellulose and hemicellulose are very scarce, and it is not possible to come to any reliable conclusion regarding all selected crops. Nevertheless, as recently observed by Ledda et al. [19] in Sardinia and also seen in other recent studies investigating the chemical composition of lignocellulosic contents [23,24], cardoon genotypes and milk thistle may be considered as a good source of biomass for energy purposes.

This combination of findings provides some support for the conceptual premise that among annual field species, Cardueae crops would seem the more suitable bioenergy crops for long-term cropping systems thanks to the attributable stable productions under minimal energy input (especially nitrogen application and reduced tillage) and high water use efficiency [15,25,26]. Further experimental investigations are needed to estimate the more suitable genotypes and agronomic practices, as well as decreasing production rate over time reported by scholars [15,27]. Certainly, one criticism of much of the literature on annual crops is that they have a higher environmental impact, especially for soil compaction, erosion and run-off, that should be evaluated with an in-depth life cycle assessment.

Overall, the analysis of yield response of perennial crops revealed that median yield was highest for two smilo grass cultivar (~45 Mg ha^{-1} - dry matter; ~40% cellulose content), while eight cultivar have reached a notable peak yield of biomass (over 30 Mg ha^{-1} - dry matter) [28]. Furthermore, in this study tall fescue cultivar 'Flecha', identified as a benchmark, returns high yields (~26 Mg ha^{-1}) associated with drought tolerance and low input requirements. These interesting results are likely to be related to a good rainfall distribution over the growing seasons. It is interesting to note that in these trials all of smilo grass cultivars are derived from seeds collected from native populations all over Sardinia [28]. In a previous observations on tall fescue cultivars carried out in Sardinia, Lelièvre et al. [29] highlighted good productivity (~9.3 Mg ha^{-1} - cultivar 'Flecha') and resistance to summer drought stress as a consequence of high winter production and vigorous growth during the cool season.

Similarly, cocksfoots cultivar 'Jana' selected in Sardinia from north-African and Sardinian germoplasm showed a good productivity (~16 Mg ha^{-1}) in rainfed conditions with low-input fertilization, and was among the best yielding cultivars under irrigation (up to ~20 Mg ha^{-1}) [30]. On the contrary, native perennial ryegrass accessions show low yield potential and high variability of morphological and productive traits (~3.5 Mg ha^{-1}) [31]. These results suggest that native germoplasm of perennial grasses could represent a valuable low-input,x rainfed alternative for bioenergy production in Mediterranean environment. Further research should be undertaken in breeding programs to better study their long-term agronomic potential.

In addition to information from the literature, for specific perennial grasses information from experimental fields has been collected and included in this report. Two experimental fields with giant reed were carried out starting from 2013, in Masainas (39°02'N 8°37'E, 57 m a.s.l.) and in Serramanna (39°24'N 8°52'E, 38 m a.s.l.). A third field trial was carried out starting from 2014 in Tratalias (39°06'N 8°33'E, 17 m a.s.l.). During the first year the above-ground dry matter yield of giant reed was of 7.26 Mg ha^{-1}, 4.18 Mg ha^{-1} and 5.6 Mg ha^{-1} in Masainas, Serramanna and Tratalias, respectively. In the second year, the dry matter yield was of 25.56 Mg ha^{-1} in Masainas and 17.45 Mg ha^{-1} in Serramanna.

The results showed a remarkable increase of above-ground biomass production from establishment year to second year. In particular, biomass dry yield increased +72% and +76% from first year to second year in Masainas and Serramanna, respectively. The low biomass yield in the establishment year is a characteristic of *Arundo donax*, which reaches maximum biomass production at the third year. Several authors reported similar trend of crop productivity in Mediterranean environment. Similarly, Porqueddu et al. [79] observed considerable yield peak at the second year in North Sardinia (24.6 Mg ha^{-1} - dry matter) in a field-trial carried out without irrigation but in a plot with good soil conditions very near to a stream channel. In studies carried out in Southern Italy, Copani et al. [32] observed a rapid increase (+92%) of biomass dry yield from establishment year to third year (from 2.6 Mg ha^{-1} to 31.3 Mg ha^{-1}, respectively), while Cosentino et al. [33] observed an increase from 11 Mg ha^{-1} to 22 Mg ha^{-1} between first and second year (+50%). In studies carried out in Central and Northern Italy, others authors observed similar trend of crop productivity, even if greater yields were recorded. Angelini et al. [12] in an experimental study located near Pisa, reported a yield of 29 Mg ha^{-1} and 51 Mg ha^{-1} in the first and second years (increase of +43%), while Di Candilo et al. [34] in field study located in Emilia Romagna observed an increase of +52% (from 20 Mg ha^{-1} to 42 Mg ha^{-1}).

In summary, the results of the field trials managed by Biochemtex in Sardinia support previous research into the trend of giant reed productivity from first to second year reported by others authors in Mediterranean environment. Yields recorded in our experimental fields are more similar to those reported by trials carried out in Southern Italy rather than those conducted in the North of the Country. This is likely due to similarities in climate conditions of the experimental trials in Sardinia and in the trials carried out in Southern Italy.

Little information is available for miscanthus in Sardinia, where reported harvestable yields reached at the second year (~9 Mg ha^{-1} - dry matter) are comparable with those values reported by Monti et al. [35] in a field trial carried out in Sicily. In contrast to earlier findings, yield reported by Angelini et al. [12] (29 Mg ha^{-1} - dry matter) in a long-term field experiment carried out in central Italy suggests that higher yields can be obtained under rainfall conditions.

Contrary to expectations, low median yield was detected for cardoon (~6,7 Mg ha^{-1} - dry matter) [19], except to the values reported by Porqueddu et al. [36] (up to 23 Mg ha^{-1} - dry matter), that are in line with some published studies in Italy that reported highest aboveground dry biomass yield [37–39]. These differences can be explained in part by differences on agronomic techniques and genotypes (i.e. cultivated and wild cardoon) [40], although the pedo-climatic context were the same for milk thistle, and Cardueae crop. However, data on harvestable biomass need to be interpreted with caution due to the limited amount of yield data available for some species and differences in reporting the amount of biomass as dry or fresh weight at harvest.

Regarding woody crops, *Eucalyptus globulus* shows good productivity managed as short-rotation forestry biomass and harvested at the end of a four-year rotation (~68 Mg ha^{-1} - dry matter, or 17 Mg ha^{-1} y^{-1} DM) [41]. Conversely, eucalyptus clones show lower productivity in a field trial managed as short-rotation coppice harvested at the end of a three year rotation (~34 Mg ha^{-1} - dry matter for the most productive clone, or 11 Mg ha^{-1} y^{-1} DM) [42]. However, it should be noted that in the latter case there were significant pest attacks that compromised biomass yields. In summary, these results showed that eucalyptus species grown in rainfed conditions could yield interesting quantities of biomass also without the application of fertilizers.

Yield performance of lignocellulosic crops in these environments are similar to values recorded by other authors in Italy. For example, Cosentino et al. [33] reported for giant reed a mean yields of 11 Mg ha^{-1} of dry matter in the first year and 22 Mg ha^{-1} in the second year for 39 clones studied. Similarly, in a study conducted by Fagnano et al. [43] in a low-input cropping system, it was reported for giant reed a mean yields of 14 Mg ha^{-1} and 16.2 Mg ha^{-1} of dry matter for nitrogen fertilization doses of 50 kg ha^{-1} and 100 50 kg ha^{-1}, respectively.

With regard to fertilizers and irrigation demand, perennial crops generally require low energy input and agronomic practices. For instance, miscanthus and giant reed are recognized for efficiently recycling nitrogen from the above-ground biomass to the rhizomes [44], and generally biomass production is not significantly affected by nitrogen fertilization [45,46]. Actually, they are less flexible than the annual crops in terms of propagation, processing and utilization, but they seem particularly attractive for farmers looking to set up alternatives to food crops. Ultimately, strategies to enhance large-scale of dedicated biomass crops in Mediterranean areas should be undertaken with caution and considering the impacts of climate change on sustainability of water resources [22].

Overall, lignocellulosic perennial crops are recognized for providing environmental services such as soil erosion control, carbon storage and support for biodiversity [47,48]. In addition, they can significantly contribute to increase soil quality and fertility, water cycle dynamics and microbial activities [49].

3. GIS data collection and land suitability modelling

In Chapter 3 a GIS-based evaluation of contaminated and marginal land potentially suitable for biomass production within existing land use patterns was conducted. In order to accurately spatialise the suitable land for the cultivation of feedstock crops, a series of georeferenced data were identified, collected and organized with a relational geodatabase. The following typologies were collected: Digital Elevation Model (DEM), soil type map, land use map, climate data and administrative boundaries. Table 2 describes the whole input dataset used for spatial modeling, spatial resolution, constraints and data supplier.

The land suitability modelling follows a multicriteria decision-making approach by considering diagnostic criteria based on the literature reviewed and results of field trials. A large and growing body of literature has investigated the use of GIS for multi-criteria land feasibility analysis of bioenergy crop systems [50–56]. See for instance Lewis and Kelly [57] for a comprehensive analyses on definitions, data and models used for mapping bioenergy crop potential on marginal lands.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

TABLE 2. DATA SOURCES USED IN THE GIS-BASED ANALYSIS.

INPUT DATA	RESOLUTION	CONSTRAINTS	DATA SOURCE
Land use/cover	~ 1:10.000	orchards, forestry	CREA
Corine land cover	1:25.000	orchards, forestry	EEA
Natural and protected areas	1:10.000	whole areas	RAS
Restricted areas	1:10.000	whole areas	RAS
Soil data	1:250.000	1st - 2nd capability class >5th capability class	RAS
DEM (slope)	10 m	>10%	RAS
Meteorological data (precipitation, temperature)	~ 1km	<300 mm $year^{-1}$ <15° C $year^{-1}$	WorldClim
Hydrography, lakes	1:10.000	150 m	RAS
Roads	1:10.000	150 m	RAS
Coast line	1:10.000	~ 2500 m	RAS
Built-up areas	1:10.000	150 m	RAS
Administrative borders	1:10.000	-	RAS
Irrigation and Land reclamation borders	1:10.000	-	CREA

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3.1. Land suitability evaluation

This step is structured in **two phases**. The first phase aims to identify the **availability map**, consisting of an exclusion approach derived from environmental, topographic and climatic constraints, as a result of specific potentials and limitations of the bioenergy crops evaluated. The second phase aims to derivate the **suitability map**, as a result of agronomic and economic choices made to avoid the competition and conflict with food crops. Although the Renewable Energy Directive [58] and the Italian legislation actually limit the cultivation for producing biofuels only for land with high biodiversity value (i.e. primary forest and other wooded land, designated areas, highly biodiverse grassland, etc.), in this study we applied very restrictive and precautionary constraints in terms of environmental factors (i.e. soil, water, flora and fauna, biodiversity and landscape). In fact, the conversion of marginal land to bioenergy crop production is a decision driven by the interaction of a multitude of natural and human driving forces [59] with inevitable trade-offs between natural resources and their use [60].

In this regard, the conversion of traditional cropping system to large scale bioenergy plantations may affect soil properties, hydrologic processes and nutrient cycling with unknown consequences to the current ecological status. Furthermore, marginal and degraded lands can be rich in biodiversity and hotspot for vulnerable and endangered species [47,61], thus a conservative landscape management approach could contribute to mitigating the impacts of land use change. The diagram in Figure 3 shows the GIS-based methodology developed to estimate land suitability for biomass crops, according to the aforementioned environmental and agronomic constraints.

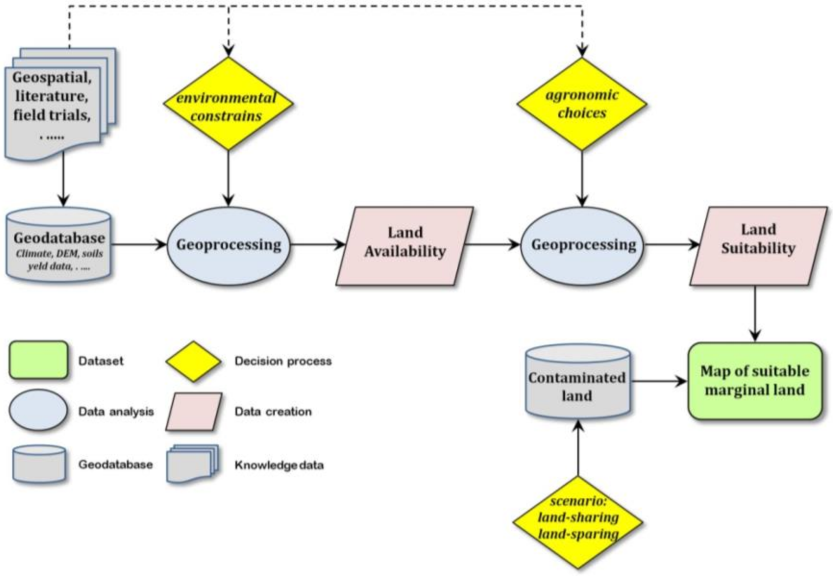

FIGURE 4. DIAGRAM ILLUSTRATING THE METHODOLOGY DEVELOPED TO ESTIMATE THE MAP OF SUITABLE MARGINAL LAND.

Following these rules, a buffer distance was defined for those areas in order to protect the natural features from dissemination of seeds, pollen and sprouts, boost biodiversity, as well as to ameliorate the visual impact and the aesthetic appeal of the landscape. Similarly, Miyake et al. [62] identifies a buffer zone of 200 m from water and natural areas to avoid the possibility of seed dispersal on the conversion of underutilized marginal land in a case study region in subtropical Queensland, Australia. Combining research findings with scholars observations [55,63,64], soil slope >10% was deemedunsuitable considering problems for machinery operations and soil erosion risk. Furthermore, this study followed the outcomes of Angelini et al. [12] that for perennial rhizomatous grasses cultivation (i.e. giant reed and miscanthus) in Mediterranean agricultural areas suggest minimum precipitation at 300 mm and at least 1800 growing degree days (GDD[2]).

The meteorological data were acquired from WorldClim [65], regional data were provided by Sardinia Region (RAS) [66], while Corine Land Cover was provided by European Environment Agency (EEA) [67]. All data are available for download free of charge. Data on Irrigation and Land Reclamation Consortia (ILRC) were supplied by Council for Agricultural Research and Economics (CREA).

In order to ensure the profitability of a biomass commodity chain, we hypothesize a maximum cultivation distance of about 70 km from a potential biorefinery located in the most contaminated area in Portoscuso. Logistics management involved in the supply system included collection, baling, field hauling, loading, transportation and stacking [68]. Recent field study by Garofalo et al. [69] on energy performance for the biofuel supply chain in southern Italy also support this maximum distance.

Firstly, slope, precipitation and temperature maps were calculated, reclassified and converted in vector format applying the constrains listed in Table 2. As a result areas not overcoming all constrains get a value score of 0 on the attribute table, otherwise the score is 1 if all constraints are overcome, and therefore are included in the following analysis. Secondly, buffer zones were defined and calculated around residential areas, major roads, rivers and lakes, restricted areas, restricted coast line, natural and protected areas, orchards and forest plantations derived from Corine Land Cover were also excluded from the analisys. All these areas were geometrically merged and dissolved, getting a value score of 0 on attribute table and excluded in the analysis. Thirdly, buffer zones were erased from the areas with value score 1 in the first step, subsequently a geometric merging with the soil map was performed. Furthermore, in this output land capability classes higher than the fifth level (soils with severe limitations suitable only for pastures, afforestation and restoration) get a

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2. [2] The Growing Degree Day, or GDD, is a heat index that can be used to predict when a crop will reach maturity. Each day's GDD is calculated by subtracting a reference temperature, which varies with plant species, from the daily mean temperature. Because many developmental events of plants and insects depend on the accumulation of specific quantities of heat, it is possible to predict when these events should occur during a growing season regardless of differences in temperatures from year to year.

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value score of 0 in the attribute table, while the remaining classes from the first to fifth get a value score equal to 1. This constitutes the final availability map.

Finally, the land suitability map is the result of agronomic choices that restrict bioenergy crops to marginal and less productive soils (class III, IV and V – soils with severe limitations that restrict their use or require careful management) (Table 3), thus excluding the best and highly productive soils (class I and II - soils with slight or moderate limitations that restrict their use) (Figure 3). Similarly, Tenerelli and Carver [51] tended to avoid the use of the best land capability classes on a GIS-based multi-criteria land allocation modelling of biomass crops.

TABLE 3. CHARACTERISTICS OF LAND CAPABILITY CLASSES.

TYPOLOGY	DESCRIPTION
Class I	Soils in this class are suited to a wide range of plants and may be used safely for cultivated crops, pasture, range, woodland, and wildlife. The soils are nearly level and erosion hazard (wind or water) is low. The soils in class I are not subject to damaging overflow. They are productive and suited to intensive cropping. The local climate must be favourable for growing many of the common field crops. Soils in class I that are used for crops need ordinary management practices to maintain productivity, both soil fertility and soil structure
Class II	Soils in class II require careful soil management, including conservation practices, to prevent deterioration or to improve air and water relations when the soils are cultivated. The limitations are few and the practices are easy to apply. The soils may be used for cultivated crops, pasture, range, woodland, or wildlife food and cover. The soils in this class provide the farm operator less latitude in the choice of either crops or management practices than soils in class I
Class III	Soils in class III have more restrictions than those in class II and when used for cultivated crops the conservation practices are usually more difficult to apply and to maintain. They may be used for cultivated crops, pasture, woodland, range, or wildlife food and cover. Limitations of soils in class III restrict the amount of clean cultivation; timing of planting, tillage, and harvesting; choice of crops; or some combination of these limitations
Class IV	The restrictions in use for soils in class IV are greater than those in class III and the choice of plants is more limited. When these soils are cultivated, more careful management is required and conservation practices are more difficult to apply and maintain. Soils in class IV may be used for crops, pasture, woodland, range, or wildlife food and cover. Soils in class IV may be well suited to only two or three of the common crops or the harvest produced may be low in relation to inputs over a long period of time
Class V	Soils in class V have limitations that restrict the kind of plants that can be grown and that prevent normal tillage of cultivated crops. They are nearly level but some are wet, are frequently overflowed by streams, are stony, have climatic limitations, or have some combination of these limitations. Examples of class V are (1) soils of the bottom lands subject to frequent overflow that prevents the normal production of cultivated crops, (2) nearly level soils with a growing season that prevents the normal production of cultivated crops, (3) level or nearly level stony or rocky soils, and (4) ponded areas where drainage for cultivated crops is not feasible but where soils are suitable for grasses or trees

Class VI	Physical conditions of soils placed in class VI are such that it is practical to apply range or pasture improvements, if needed, such as seeding, liming, fertilizing, and water control with contour furrows, drainage ditches, diversions, or water spreaders. Some soils in class VI can be safely used for the common crops provided unusually intensive management is used. Some of the soils in this class are also adapted to special crops such as sodded orchards, blueberries, or the like, requiring soil conditions unlike those demanded by the common crops. Depending upon soil features and local climate the soils may be well or poorly suited to woodlands
Class VII	Physical conditions of soils in class VII are such that it is impractical to apply such pasture or range improvements as seeding, liming, fertilizing, and water control with contour furrows, ditches, diversions, or water spreaders. Soil restrictions are more severe than those in class VI because of one or more continuing limitations that cannot be corrected. Depending upon the soil characteristics and local climate, soils in this class may be well or poorly suited to woodland. They are not suited to any of the common cultivated crops
Class VIII	Soils and landforms in class VIII cannot be expected to return significant on-site benefits from management for crops, grasses, or trees, although benefits from wildlife use, watershed protection, or recreation may be possible. Badlands, rock outcrop, sandy beaches, river wash, mine tailings, and other nearly barren lands are included in class VIII. It may be necessary to give protection and management for plant growth to soils and landforms in class VIII in order to protect other more valuable soils, to control water, or for wildlife or esthetic reasons.

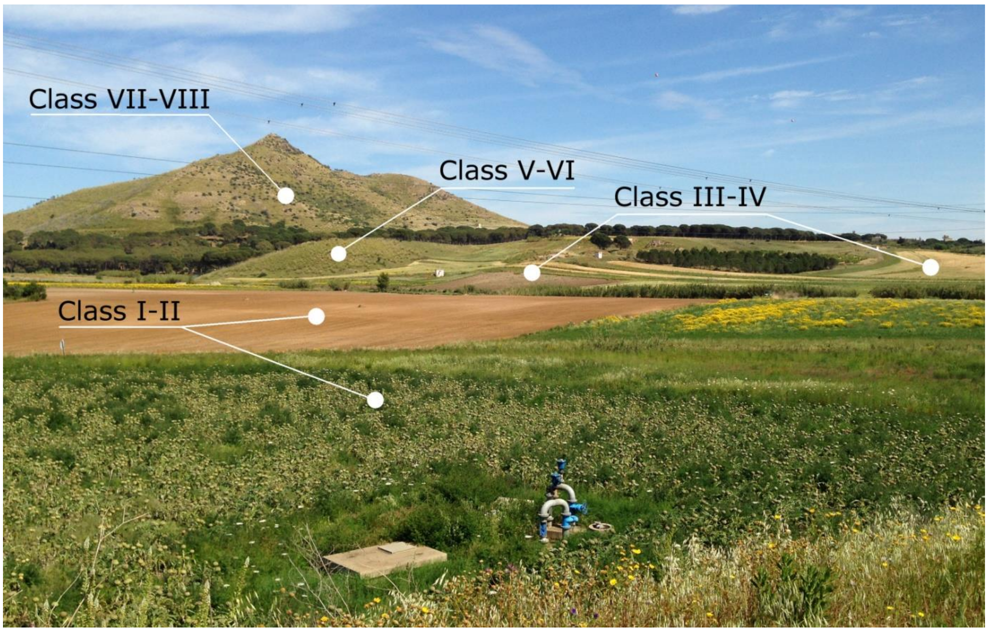


FIGURE 4. EXAMPLE OF THE AGRICULTURAL LANDSCAPE IN THE STUDY AREA AND DIFFERENT SOIL CAPABILITY CLASSES.

3.2. Actual land use/cover

The identification of actual land use/cover is an important aspect for the best allocation of energy crops. The investigations have been carried out within the Land Reclamation and Irrigation Consortium "Cixerri", an important agricultural irrigation district in the Sulcis-Iglesiente area. This area is not inside the contaminated perimeter where food crops cultivation is restricted by local laws. The detection of the actual cultivation pattern (especially irrigated areas and orchards) is accomplished through a "multi-temporal analysis" based on a time series of the Normalized Vegetation Index (NDVI), derived from satellite images (i.e. Landsat OLI 8) as depicted in Figure 5. NDVI time series provide the temporal evolution of the crops and vegetation during its growing season. The methodology is based on the assumption that in arid and semi-arid environment like the study area, high rates of vegetation growth are compatible only with irrigation (excluding natural vegetation along rivers).

The analysis process based on temporal pattern recognition exploits the differences from the canopy cover and development to assign each pixel to a vegetation class. Overall, the following 8 classes were identified: 1) irrigated arable land; 2) non irrigated arable land; 3) orchards; 4) olive trees; 5) vineyards; 6) urban area; 7) woodland; 8) water. The procedure requires a precise knowledge of crops and their phenology, and needs further corroboration by an experienced operator of the study area. Moreover, some irrigated crops such as fruit trees, vineyards, or olive trees which exhibit low canopy growth could require additional information to that of satellite imagery, like orthophotos and existing land use/cover database. For this reason, in compiling the actual land use/cover map, orthophotos have been used as geometric reference, while the infrared images and NDVI time series supported the thematic photo-interpretation and parcel delimitation. The final land use/cover map is shown in figure 6.

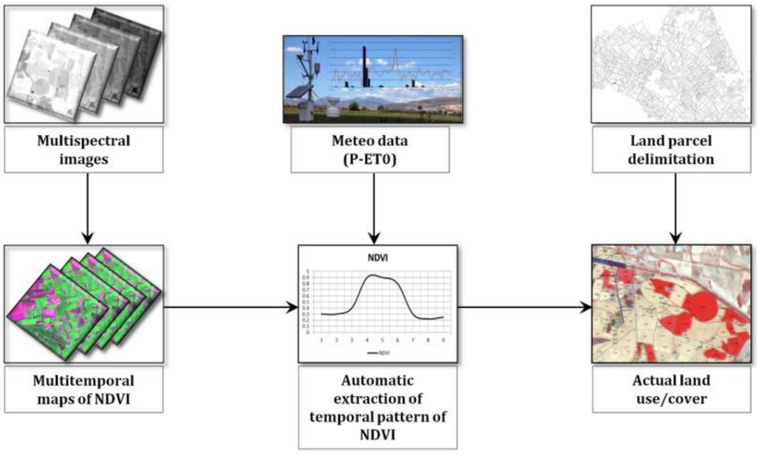


FIGURE 5. FLOWCHART ILLUSTRATING THE METHODOLOGY DEVELOPED TO IDENTIFY THE ACTUAL LAND USE/COVER

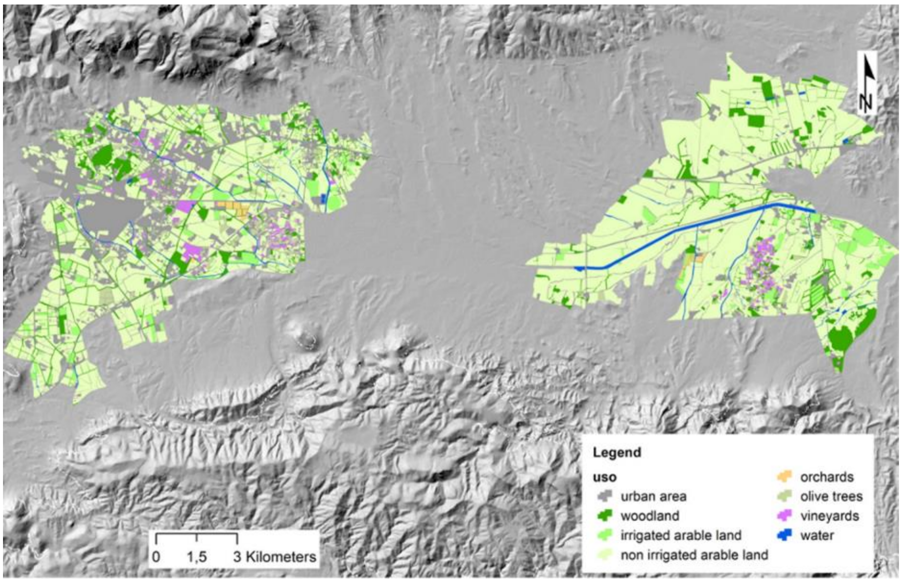


FIGURE 6. LAND USE/COVER FOR ILRC CIXERRI.

3.3. Land use/cover scenario

We used the land suitability map and the actual land use/cover map to assess a local scenario for biomass supply chains based on the actual land framework with a comparison of a land-sharing versus land-sparing cultivation strategy [70]. Land-sparing options promote intensification and specialization of agriculture activities with a separation of protected habitats to foster biodiversity conservation, while land-sharing promotes an integration of these strategies coupled with a more heterogeneous and evenly distributed type of landscape, e.g. alternance of cultivated, natural, pasture etc. as opposed to homogeneous use landscape (e.g. vast monoculture) [71]. The integrated landscape management with the optimal allocation of land resources among food production, feedstock production and ecosystem protection should minimize the competition and increase the farming sustainability over the long run. According to our GIS-based multi-criteria approach and constraints, the total area suitable for biomass cultivation, hypothesizing a supply radius of 70 km to the biorefinery, amounted to 51.000 ha. Interestingly, these available surfaces are comparable with the finding provided by RAS [72], that estimates about 37.000 ha potentially available for conversion to dedicated bioenergy crops.

Generally, the identified suitable areas are almost entirely overlapping agricultural flat zones within ILRC, while natural and sensitive protected areas were excluded from our model. Regarding the study area, the suitable marginal land meeting all constraints posed by this research, which could be used for biomass cultivation and their spatial distribution across ILRC, are shown in Table 4 and Fig. 7, respectively.

Considering a land-sparing scenario, all available rainfed arable land can be converted from traditional uses for biomass feedstock production. The results indicate that the available surface area for biomass cultivation is 5.679 ha, accounting for 86% of the total available area equipped with irrigation infrastructures. On the other hand, considering a land-sharing scenario, only suitable arable land as a result of our GIS-based model can be used for biomass production. In this case, the cultivable area is 2.883 ha, accounting for 44% of the area equipped with irrigation systems. Land-sharing design mitigated negative impacts of bioenergy crops by promoting large patches of buffer riparian corridors and natural habitats interspersed with areas of traditional crops.

With regard to the most contaminated area (Figure 7), the available surface for biomass cultivation resulting from our suitability model is approximately 1.000 ha. Taking into account that the area is outside the equipped ILRC, the most suitable crops should be rainfed species.

TABLE 4. AVAILABLE AREAS FOR BIOMASS PRODUCTION ACROSS THE LAND RECLAMATION AND IRRIGATION CONSORTIA 'CIXERRI'.

AVAILABLE AREAS	ILRC CIXERRI (HA)
TOTAL AREA	9180
EQUIPPED AREA	6580
ARABLE LAND	6104
ARABLE LAND - SOIL CLASS I-II	1186
ARABLE LAND - SOIL CLASS III-V	4813
RAINFED ARABLE LAND 2015	5679
IRRIGATED ARABLE LAND 2015	425
VINEYARDS, ORCHARDS 2015	477
WOODS, NATURAL AREAS 2015	803
LAND SUITABILITY AREA[1]	2883

[1] DATA OBTAINED BY SUBSTRACTING LAND USE/COVER LAYER CONSTRAINTS FROM LAND SUITABILITY MAP.

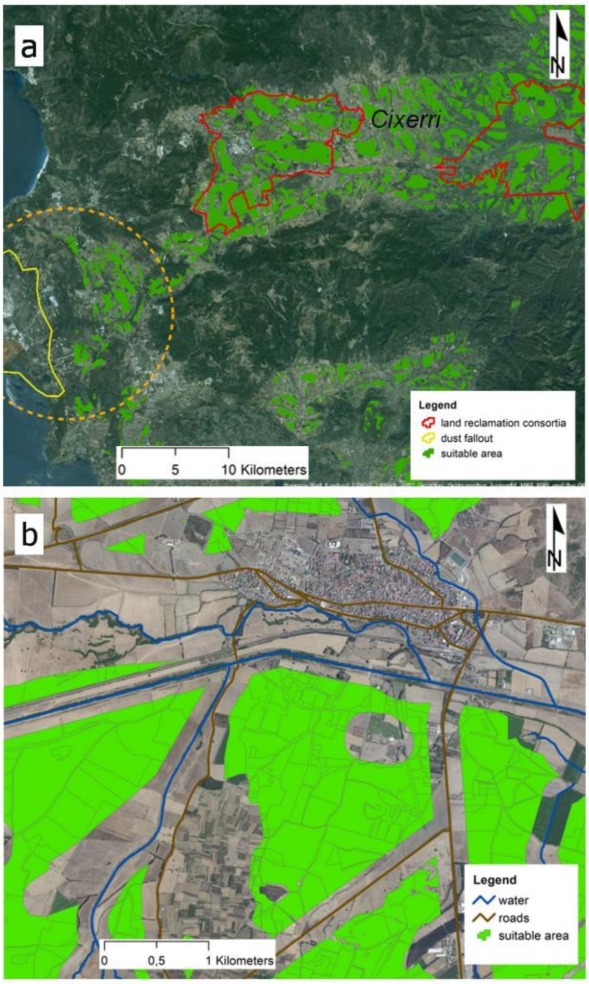


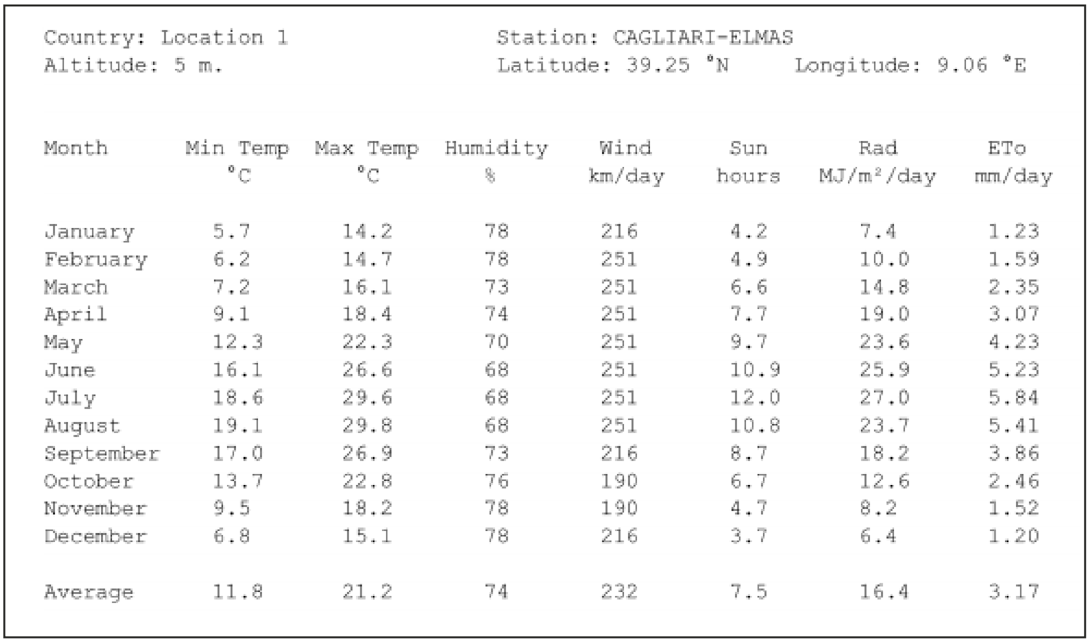
FIGURE 7. (A) SUITABLE LAND FOR LAND RECLAMATION AND IRRIGATION CONSORTIA 'CIXERRI'. DASHED LINE INDICATES THE MOST CONTAMINATED AREA; (B) PARTICULAR OF SUITABLE AREAS NEAR BUILT-UP AREAS, RIVERS AND ROADS.

4. CROPWAT model

CROPWAT is a decision support model developed by the Food and Agriculture Organization (FAO) of the United Nations. With this tool it is possible to estimate evapotranspiration, crop water requirements and irrigation requirements and irrigation schedules by means of a model based on the method described on FAO N. 56 paper "Crop Evapotranspiration - Guidelines for computing crop water requirements" and FAO N. 33 paper "Yield response to water" [73]. CROPWAT can also be used to evaluate farmers' irrigation practices and to estimate crop performance under both rainfed and irrigated conditions. This model is based on climate, soil and crop data. Climate data could be retrieved using the climate database CLIMWAT 2.0 on the basis of 30-year averages, or, if available, using data from meteorological stations located within the study area.

4.1. Modelling evapotranspiration and water requirements

The aim of this investigation is to quantify and assess the response of giant reed in the study area in terms of evapotranspiration and water requirements. *Arundo donax* was selected for this simulation to predict water requirements for field trials described at paragraph 2.1. In this simulation, the calculation have been done using climate data from the CLIMWAT meteorological station located in Cagliari-Elmas (Figure 8). The database for this station reports monthly data on temperature (min and max), humidity, wind speed, sunlight hours, radiation and evapotranspiration.



```
Country: Location 1                 Station: CAGLIARI-ELMAS
Altitude: 5 m.                      Latitude: 39.25 °N     Longitude: 9.06 °E

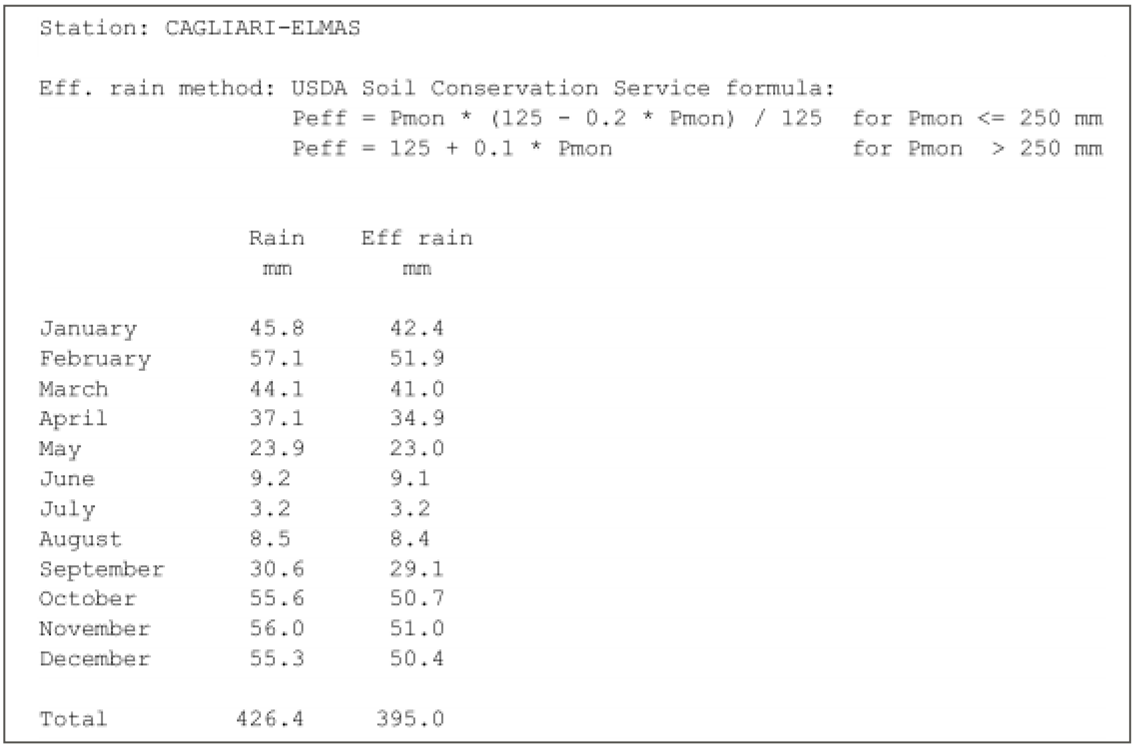

Month        Min Temp  Max Temp  Humidity    Wind      Sun       Rad       ETo
                °C        °C        %       km/day    hours   MJ/m²/day  mm/day

January        5.7      14.2       78        216       4.2       7.4      1.23
February       6.2      14.7       78        251       4.9      10.0      1.59
March          7.2      16.1       73        251       6.6      14.8      2.35
April          9.1      18.4       74        251       7.7      19.0      3.07
May           12.3      22.3       70        251       9.7      23.6      4.23
June          16.1      26.6       68        251      10.9      25.9      5.23
July          18.6      29.6       68        251      12.0      27.0      5.84
August        19.1      29.8       68        251      10.8      23.7      5.41
September     17.0      26.9       73        216       8.7      18.2      3.86
October       13.7      22.8       76        190       6.7      12.6      2.46
November       9.5      18.2       78        190       4.7       8.2      1.52
December       6.8      15.1       78        216       3.7       6.4      1.20

Average       11.8      21.2       74        232       7.5      16.4      3.17
```

FIGURE 8. CLIMATE DATA FOR THE METEOROLOGICAL STATION CAGLIARI-ELMAS.

For this meteorological station the average daily ET0 is 3.17 mm, with a minimum of 1.23 mm in January and a maximum of 5.84 in July. The transpiration values reported in this simulation are consistent with those reported by Cosentino et al. [46] and Triana et al. [74] for giant reed in Sicily and Tuscany, respectively. As shown in Figure 9, 30-year rainfall average for this station (very close to the sea) was 426 mm, lower than the Sulcis area, about 550 mm.



```
Station: CAGLIARI-ELMAS

Eff. rain method: USDA Soil Conservation Service formula:
                  Peff = Pmon * (125 - 0.2 * Pmon) / 125  for Pmon <= 250 mm
                  Peff = 125 + 0.1 * Pmon                 for Pmon  > 250 mm

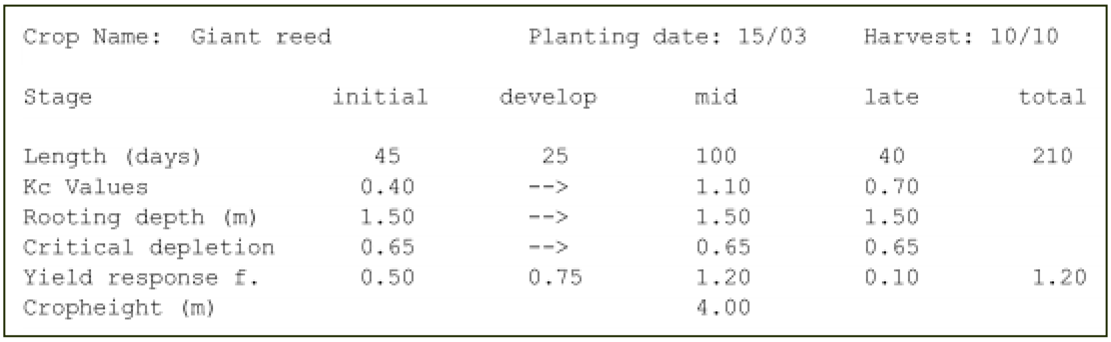

               Rain    Eff rain
                mm        mm

January        45.8      42.4
February       57.1      51.9
March          44.1      41.0
April          37.1      34.9
May            23.9      23.0
June           9.2       9.1
July           3.2       3.2
August         8.5       8.4
September      30.6      29.1
October        55.6      50.7
November       56.0      51.0
December       55.3      50.4

Total         426.4     395.0
```

FIGURE 9. RAIN DATA FOR THE METEOROLOGICAL STATION CAGLIARI-ELMAS.

Crop data (rooting depth, critical depletion, etc.) and crop coefficients (kc) were obtained from bibliography, considering a crop length differentiated on four stages (initial, development, mid-season, late season). In the case of giant reed the growing period was 210 days (Figure 10). Clearly, our Kc are standard values from bibliography that, however, in different crop management systems and agro-climatic locations can vary widely. Thus, Kc values should be accurately estimated for better irrigation scheduling instead of using the fixed values reported in the literature.



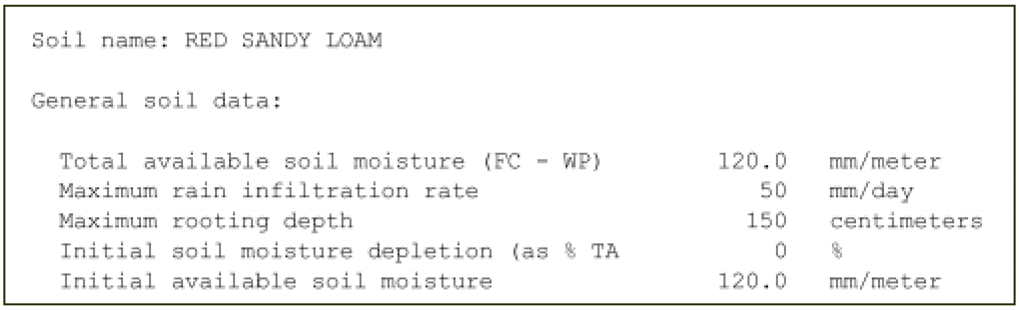
```
Crop Name:  Giant reed                 Planting date: 15/03     Harvest: 10/10

Stage                  initial     develop       mid         late        total

Length (days)            45          25          100          40          210
Kc Values               0.40        -->         1.10         0.70
Rooting depth (m)       1.50        -->         1.50         1.50
Critical depletion      0.65        -->         0.65         0.65
Yield response f.       0.50        0.75        1.20         0.10         1.20
Cropheight (m)                                  4.00
```

FIGURE 10. CROP DATA FOR GIANT REED.

Specific soil properties for the study area was obtained from the project MARSALA [75], in particular for total available soil moisture for a red sandy loam soil (Figure 11).



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Soil name: RED SANDY LOAM

General soil data:

  Total available soil moisture (FC - WP)          120.0    mm/meter
  Maximum rain infiltration rate                      50    mm/day
  Maximum rooting depth                              150    centimeters
  Initial soil moisture depletion (as % TA             0    %
  Initial available soil moisture                  120.0    mm/meter
```

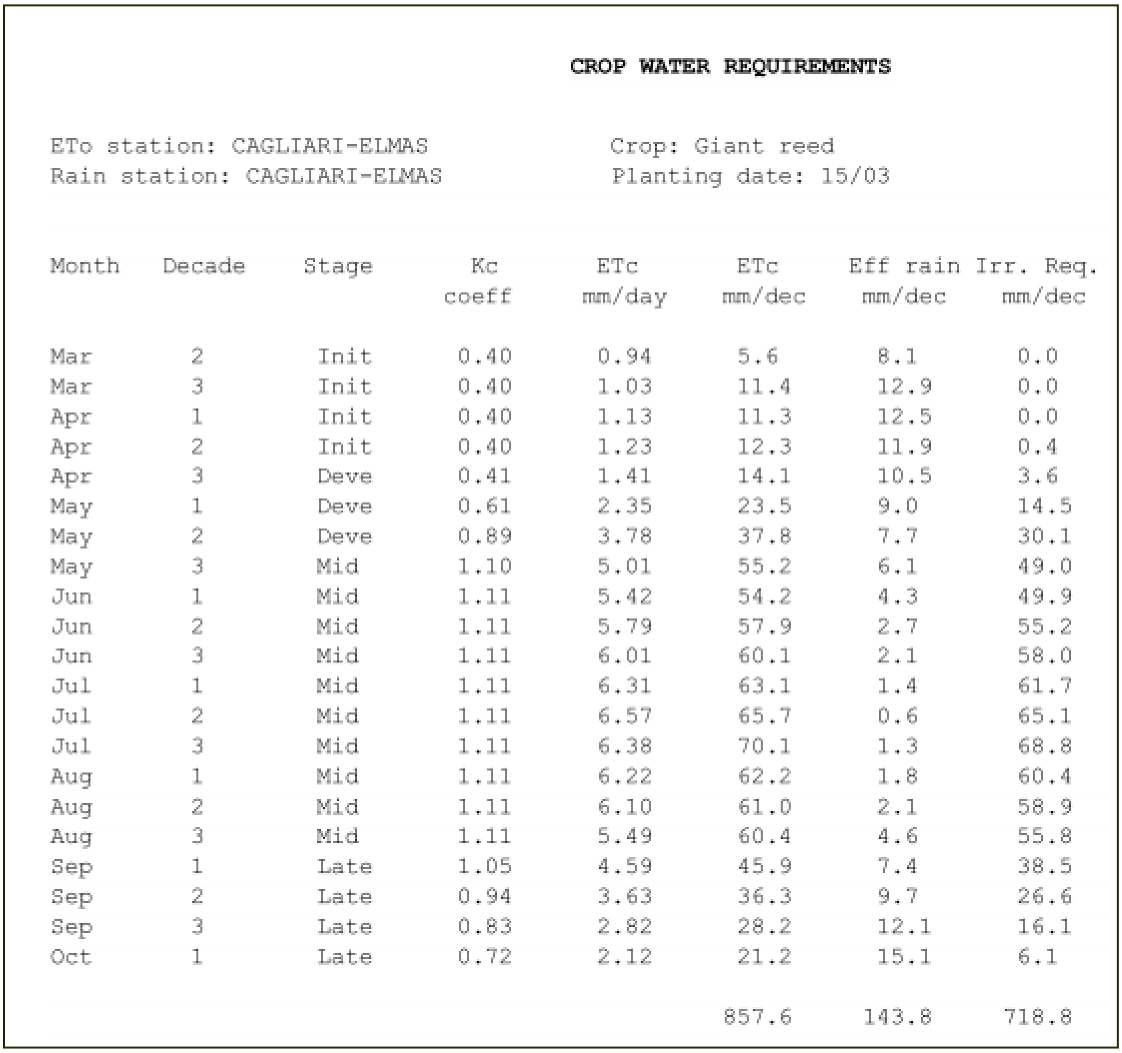
FIGURE 11. TYPICAL SOIL DATA FOR THE STUDY AREA.

CROPWAT simulates evapotranspiration on the basis of the Penman-Monteith approach. Crop water requirements estimates evapotranspiration under optimal conditions, which means that crop evapotranspiration (ETc) equals the crop water requirement (CWR). Optimal means disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions and achieving full production under the given climatic conditions [76]. ETc is estimated with a ten day time step and over the total growing season using the effective rainfall. To calculate the effective rainfall, the method of the Soil Conservation Service of the United States Department of Agriculture (USDA SCS) was chosen.

$ETc = ET0 \times Kc$ (mm)

where Kc refers to the crop coefficient, which incorporates crop characteristics and crop type, plant health and averaged effects of evaporation from the soil. ET0 represents the reference evapotranspiration, which expresses the evapotranspiration from a hypothetical grass reference crop not short of water. Crop evapotranspiration can be calculated under both optimal and non-optimal conditions over the total growing season using the soil water balance approach. The irrigation schedule option requires climate, crop and soil data. Irrigated conditions can be simulated by specifying how the crop is irrigated, and different irrigation timing and application options can be selected depending on the irrigation strategy. In our experiment the irrigation timing " irrigate at critical depletion" and irrigation application "refill soil to field capacity" has been set, and assumes optimal irrigation where the irrigation intervals are at a maximum while avoiding any crop stress. In addition, irrigation efficiency has been set as 95%. The average irrigation application depth per irrigation period is related to the irrigation method practiced. Generally, in the case of high frequency irrigation systems, such as micro-irrigation and centre pivot, about 10 mm or less per wetting event are applied. In the case of sprinkler irrigation, irrigation depth is 40 mm. The module Crop Water Requirement (CWR) in CROPWAT calculates the irrigation water requirement of the crop on a decadal basis and over the total growing season. Irrigation requirements are defined as the water volume needed to equilibrate the water deficit between evapotranspiration and rainfall during the growing period. For a given growing period the water balance is calculated as follows:

IWR=ETc-P



```
                                  CROP WATER REQUIREMENTS


 ETo station: CAGLIARI-ELMAS             Crop: Giant reed
 Rain station: CAGLIARI-ELMAS            Planting date: 15/03


 Month    Decade    Stage       Kc       ETc       ETc      Eff rain Irr. Req.
                               coeff    mm/day    mm/dec     mm/dec    mm/dec

 Mar        2        Init       0.40     0.94      5.6       8.1       0.0
 Mar        3        Init       0.40     1.03     11.4      12.9       0.0
 Apr        1        Init       0.40     1.13     11.3      12.5       0.0
 Apr        2        Init       0.40     1.23     12.3      11.9       0.4
 Apr        3        Deve       0.41     1.41     14.1      10.5       3.6
 May        1        Deve       0.61     2.35     23.5       9.0      14.5
 May        2        Deve       0.89     3.78     37.8       7.7      30.1
 May        3        Mid        1.10     5.01     55.2       6.1      49.0
 Jun        1        Mid        1.11     5.42     54.2       4.3      49.9
 Jun        2        Mid        1.11     5.79     57.9       2.7      55.2
 Jun        3        Mid        1.11     6.01     60.1       2.1      58.0
 Jul        1        Mid        1.11     6.31     63.1       1.4      61.7
 Jul        2        Mid        1.11     6.57     65.7       0.6      65.1
 Jul        3        Mid        1.11     6.38     70.1       1.3      68.8
 Aug        1        Mid        1.11     6.22     62.2       1.8      60.4
 Aug        2        Mid        1.11     6.10     61.0       2.1      58.9
 Aug        3        Mid        1.11     5.49     60.4       4.6      55.8
 Sep        1        Late       1.05     4.59     45.9       7.4      38.5
 Sep        2        Late       0.94     3.63     36.3       9.7      26.6
 Sep        3        Late       0.83     2.82     28.2      12.1      16.1
 Oct        1        Late       0.72     2.12     21.2      15.1       6.1

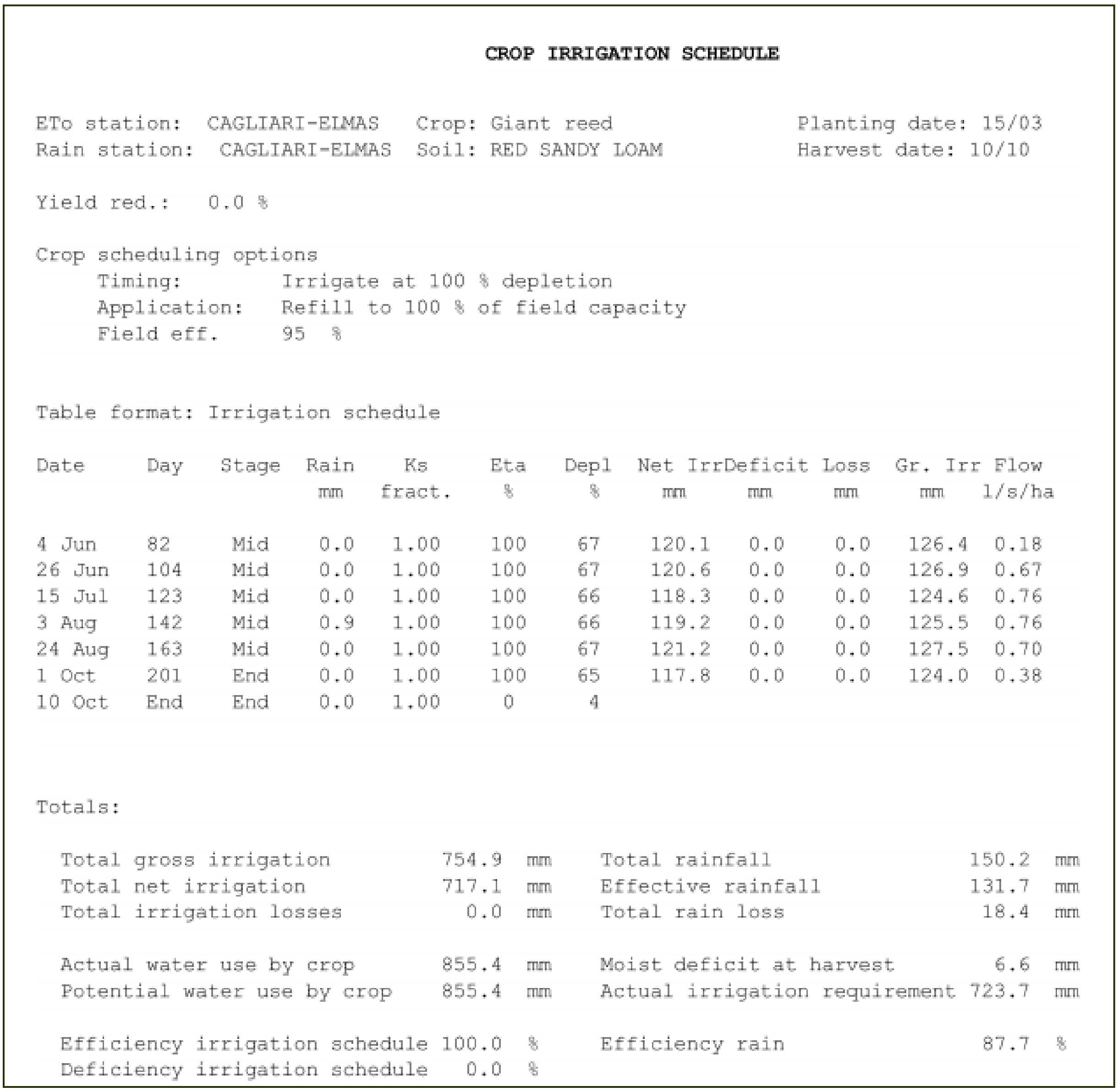
                                                 857.6     143.8     718.8
```

FIGURE 12. CROP WATER REQUIREMENTS FOR GIANT REED.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

Where IWR is the net water requirement and P refers to precipitation. In the following we give the outputs of the CWR calculations and irrigation schedule for giant reed.

The total amount of ETc is 857 mm. Effective rainfall is the part of the total amount of precipitation that is retained by the soil so that it is potentially available for meeting the water need of the crop. For the growing period the effective rain available was about 143 mm. CROPWAT calculates the irrigation requirement as the difference between crop water requirement and effective precipitation. Decadal irrigation requirements started from 14.5 mm for the first decade of May (development) to a peak of 68.8 mm for the third decade of July (midseason).



```
                              CROP IRRIGATION SCHEDULE

ETo station:  CAGLIARI-ELMAS   Crop: Giant reed              Planting date: 15/03
Rain station:  CAGLIARI-ELMAS  Soil: RED SANDY LOAM          Harvest date: 10/10

Yield red.:   0.0 %

Crop scheduling options
     Timing:        Irrigate at 100 % depletion
     Application:   Refill to 100 % of field capacity
     Field eff.     95  %


Table format: Irrigation schedule

Date     Day   Stage  Rain   Ks     Eta   Depl  Net IrrDeficit Loss  Gr. Irr Flow
                      mm    fract.   %     %     mm      mm     mm     mm   l/s/ha

4 Jun    82     Mid    0.0   1.00   100    67    120.1   0.0    0.0   126.4  0.18
26 Jun   104    Mid    0.0   1.00   100    67    120.6   0.0    0.0   126.9  0.67
15 Jul   123    Mid    0.0   1.00   100    66    118.3   0.0    0.0   124.6  0.76
3 Aug    142    Mid    0.9   1.00   100    66    119.2   0.0    0.0   125.5  0.76
24 Aug   163    Mid    0.0   1.00   100    67    121.2   0.0    0.0   127.5  0.70
1 Oct    201    End    0.0   1.00   100    65    117.8   0.0    0.0   124.0  0.38
10 Oct   End    End    0.0   1.00    0      4



Totals:

  Total gross irrigation         754.9  mm    Total rainfall                  150.2  mm
  Total net irrigation           717.1  mm    Effective rainfall              131.7  mm
  Total irrigation losses          0.0  mm    Total rain loss                  18.4  mm

  Actual water use by crop       855.4  mm    Moist deficit at harvest          6.6  mm
  Potential water use by crop    855.4  mm    Actual irrigation requirement 723.7  mm

  Efficiency irrigation schedule 100.0  %     Efficiency rain                  87.7  %
  Deficiency irrigation schedule   0.0  %
```

FIGURE 13. CROP IRRIGATION SCHEDULE FOR GIANT REED.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

It can be seen from the data in Figure 13 that for our simulated irrigation timing and application the actual irrigation requirement is 723 mm, in line with others experiments in Mediterranean conditions for giant reed [46].

As stressed by Cosentino et al. [46] giant reed was able to uptake water at 160-180 cm soil depth when irrigation was applied. In addition, results of field trial experiment showed that root system of giant reed exhibits a proportional root depth and constant water capture [77], tolerating drought periods, thanks to its ability to improve water use efficiency and to maintain a high level of biomass production. Water use efficiency is defined as the ratio between above-ground dry yield (or marketable crop yield) and the cumulated seasonal evapotranspiration [78]. Giant reed can proficiently regulate stomatal conductance and closure in relation to the available soil water content. This induces a reduced water vapor loss with unchanged CO_2 assimilation (i.e. carbohydrates). Hence, these results further support the idea that deficit irrigation (e.g. 50% or 80% ETc restitution) can support relevant biomass yield saving up more than 50% of water supply. In this sense, in a recent case study of physiological responses of giant reed ecotypes to drought, Haworth et al., [79] reported that "[giant reed] is adaptable to grow in semi-arid hot Mediterranean climates, making it a viable crop species for biomass production in drought-prone marginal lands".

However, more research on this topic needs to be undertaken to investigate water-use dynamics and the response of giant reed and perennial crops to different stresses such as water stress, salinity and cold temperature or limiting factors such as pests, diseases and weeds.

5. Conclusion

In this project a GIS-based methodology was undertaken to design a land suitability model for mapping marginal areas and evaluate the amount of land available for biomass crops cultivation in the study area. The methodology uses a multicriteria approach by considering a set of environmental and techno-economic constraints described at paragraph 3, in order to ensure a long-term sustainable crop system. Based on the findings gathered in this study, the following conclusions can be drawn:

- The results obtained indicate that about **51.000 ha** could be available for feedstock cultivation, hypothesizing a supply radius of 70 km from a hypothetical biorefinery and considering a land-sparing scenario where all available **rainfed** arable land are convertedto biomass production;
- A pilot investigation within the Land Reclamation and Irrigation Consortium "Cixerri" and carried out considering the actual land use/cover revealed that about **5.700** ha can be exploited for feedstock cultivation, accounting for 86% of the total available area equipped with **irrigation** infrastructures;

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

- Lastly, focusing on the most **contaminated** area, in a radius of 15 km from Portovesme, the available surface is approximately **1.000 ha**, falling within an unequipped area for irrigation, thus most suitable for rainfed crops. It should be noted that these crops should demonstrate tolerance to the contaminants levels in the area to be cultivated.

When it comes to the choice of which dedicated crop to cultivate in suitable marginal land for bioenergy purposes, the decision-maker should take into consideration different aspects and impacts: if productivity and cost-effectiveness is the primary objective of the end-user, ecological services have an important role, especially in long-term scenarios, together with scarcity or temporary unavailability of agronomical inputs (e.g. water).

From the reviews of field trials performed on the species considered in this study, in the case of Sardinia, the most promising candidates for a large-scale deployment appear to be **giant reed** *Arundo donax L.* among perennials and **milk thistle** *Silybum marianum L. Gaertn.* among annuals.

As shown in Table S2 of Annex I, *Arundo donax* shows good comparative performances in terms of yield, modest irrigation needs, water efficiency and nutrient requirements. The perennial nature of the plant, that requires tillage only at planting stage and during the first year, is a potential contribution to increasing soil carbon stocks [43]. The invasiveness risk posed by giant reed is quite important but, since it reproduces asexually through rhizomes, setting up buffer strips around fields is an efficient way of managing this risk.

Milk thistle, among annuals, shows good yield even under non-irrigated conditions on alcaline soils, and it has an interesting content of fermentable sugars.

The mean score of the impact on the ecological system that the agronomic characteristics of milk thistle can offer, shown in Table S4 of Annex I, makes it more suitable for a large deployment than other annuals.

ANNEX 1: TABLES OF AGRONOMIC CHARACTERISTICS OF BIOMASS CROPS INVENTORIED

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

TABLE S1. OVERVIEW OF AGRONOMIC CHARACTERISTICS OF ANNUAL BIOMASS CROPS INVENTORIED IN SARDINIA.

Crop	Biomass yield Mg ha^{-1}	Humidity	Ferment. Sugar	Fertilizers kg ha^{-1}	Mean irrigation	Soil detail	Growing season	Location	References
Globe artichoke[1]	5.6 – 29.9* (residual biomass)	~ 20% (~ 88% dry organic matter)	n.a.	as conventional practice	as conventional practice	sandy-clay-loam pH 8.3	2014 – 2015 2 years	Ottava, SS 80 m a.s.l.	[17]
Globe artichoke[2]	4.1 (residual heads and biomass)	n.a.	C 39.6 % (stalks)	150 N, 80 P_2O_5, 100 K_2O	until first rainfall	sandy-clay-loam pH 8.3	2007 to 2010 3 years	Ottava, SS 80 m a.s.l.	[19]
Milk thistle	16.4	n.a.	C 39.3 % (stalks)	35 N (only first year)	non-irrigated	sandy-clay-loam pH 8.3	2007 to 2010 3 years	Ottava, SS 80 m a.s.l.	[19]
Milk thistle	~ 20	~ 80%	n.a.	35 N, 100 P_2O_5	non-irrigated	clay-loam calcareous pH 7.5	2006 – 2007 2 years	North-Sardinia	[18]
Milk thistle	9 - 16	n.a.	~ 450 g kg^{-1} (dry matter neutral detergent fiber)	36 N, 90 P_2O_5	non-irrigated	sandy-clay-loam pH 7.5	2011 – 2011 2 years	North-Sardinia	[80]
Rapeseed[3]	1.6**(seed) ~ 6 (residues)	n.a.	n.a.	132 N, 92 P_2O_5	non-irrigated	alluvial, deep clay soil layers pH 6.48	2008 – 2010 2 years	Ottana, NU 187 m a.s.l.	[81]
Ethiopian mustard[4]	1.1** (seed) ~ 10 (residues)	n.a.	n.a.	132 N, 92 P_2O_5	non-irrigated	alluvial, deep clay soil layers pH 6.48	2008 – 2010 2 years	Ottana, NU 187 m a.s.l.	[82]

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Ethiopian mustard[5]	0.7 – 4.14 (seed)	n.a.	n.a.	n.a.	non-irrigated	sandy-clay-loam pH 7.9	2008 – 2010 2 year	Ussana, CA 97 m a.s.l.	[82]
Rapeseed[6]	~ 2.03 (seed)	n.a.	n.a.	n.a.	non-irrigated	sandy-clay-loam pH 7.9	2009 – 2010 1 year	Ussana, CA 97 m a.s.l.	[82]
Maize[7]	~ 24 (above-ground biomass - silage)	n.a.	n.a.	~ 290 N (slurry + urea)	4140 m^3 ha^{-1} - 1st year 5740 m^3 ha^{-1} - 2nd year	sandy pH 7.4	2010 – 2011 2 years	Arborea, OR 7 m a.s.l.	[83]
Triticale[8]	~ 7.91 (above-ground biomass - silage)	n.a.	n.a.	251 N (slurry + urea)	300 m^3 ha^{-1}	sandy pH 7.4	2010 – 2011 1 years	Arborea, OR 7 m a.s.l.	[83]
Triticale[9]	~ 6.2 (grain yield)	n.a.	n.a.	n.a.	non-irrigated	n.a.	between 1995/96 and 2012/13 18 years	Sardinia (20 field experiments)	[84]
Durum wheat[10]	~ 5.7 (grain yield)	n.a.	n.a.	n.a.	non-irrigated	n.a.	between 1995/96 and 2012/13 18 years	Sardinia (20 field experiments)	[84]
Durum wheat[11]	8.48 (no-tillage) 6.74 (conventional)	13% humidity	n.a.	80 N, 72 P_2O_5	non-irrigated	clay-loam pH 8.5	2013 – 2014 1 years	Benatzu, CA 80 m a.s.l.	[85]

Durum wheat[11]	4 (no-tillage) 4.81 (conventional)	13% humidity	n.a.	80 N, 72 P_2O_5	non-irrigated	sandy-clay-loam pH 7.9	2013 – 2014 1 years	Ussana, CA 80 m a.s.l.	[85]
Sweet sorghum	16 – 20 (dry matter) 60 (fresh weight)	n.a.	n.a.	n.a.	n.a.	alfisols, petrocalcic palexeralfs pH 7.8	n.a.	Ussana, CA 97 m a.s.l.	[72]
Globe artichoke	2,7 (dry matter) 4,4 (fresh weight)	n.a.	n.a.	n.a.	n.a.	alfisols, petrocalcic palexeralfs pH 7.8	n.a.	Ussana, CA 97 m a.s.l.	[72]
Milk thistle	1,4	n.a.	n.a.	n.a.	n.a.	alfisols, petrocalcic palexeralfs pH 7.8	n.a.	Ussana, CA 97 m a.s.l.	[72]
Sweet sorghum	36 -42 (silage)	n.a.	n.a.	n.a.	n.a.	n.a.	2012	S. Nicolò d’Arcidano (OR) 13 m a.s.l.	[86]
Maize[12]	62 (silage)	n.a.	n.a.	n.a.	n.a.	n.a.	2012	S. Nicolò d’Arcidano (OR) 13 m a.s.l.	[86]
Triticale[13]	4,7	n.a.	n.a.	105 N, 90 P_2O_5	non-irrigated	sandy-clay-loam pH 8.3	2012-2013	Ottava, SS 80 m a.s.l.	[87]
Triticale[13]	3,8	n.a.	n.a.	100 N, 92 P_2O_5	non-irrigated	alfisols, petrocalcic palexeralfs pH 7.8	2012-2013	Ussana, CA 97 m a.s.l.	[87]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

Maize[14]	19,62 (dry matter) 56,06 (fresh weight)	~ 63%	n.a.	200 N, 110 P_2O_5	as conventional practice	clay	2003	Arborea, OR 7 m a.s.l.	[88]

1. Field trial of 5 varieties: ‘Madrigal’, ‘Spinoso sardo’, ‘C3’, ‘Tema’, ‘Violetto’.
2. Field trial of ‘Spinoso sardo’ variety.
3. Field trial of 4 varieties.
4. Field trial of 2 varieties.
5. Field trial of 5 varieties.
6. Field trial of 34 varieties.
7. Field trial of ‘FAO class 700’ in 2010, and ‘FAO class 600’ in 2011.
8. Field trial of ‘Agrano’ variety.
9. Field trial (long term) of 85 varieties.
10. Field trial (long term) of 131 varieties.
11. Field trial of 26 varieties.
12. Field trial of ‘FAO class 600’.
13. Field trial of 28 varieties.
14. Field trial of 16 ‘FAO class 700, 600 and 500’.

*Results for the best performing cultivar ‘Madrigal’.
**Results affected by adverse weather conditions.

TABLE S2. OVERVIEW OF AGRONOMIC CHARACTERISTICS OF PERENNIAL BIOMASS CROPS INVENTORIED IN SARDINIA.

Crop	Biomass yield Mg ha^{-1}	Humidity	Ferment. sugar	Fertilizers kg ha^{-1}	Mean irrigation	Soil detail	Growing season	Location	References
Eucalyptus clones[1]	20 - 34 (aboveground biomass)	n.a.	n.a.	n.a.	non-irrigated	sandy-clay, pH 7.88	2004 – 2005 2 years	Massama, OR 9 m a.s.l.	[42]
Smilo grass[2]	29.9 – 45.5 (aboveground biomass)	n.a.	~ 39 % cellulose ~ 26 % hemicel. 8 % lignin (leaves)	no fertilizers	non-irrigated (50 mm after transplanting)	sandy-clay-loam, pH alkaline	2013 – 2014 2 years	Leccari, SS 27 m a.s.l.	[28]
Tall fescue[3]	26.1 (aboveground biomass)	n.a.	44.1 % cellulose 21.9 % hemicel. 5.8 % lignin (leaves)	no fertilizers	1st year (50 mm after transplanting)	sandy-clay-loam, pH alkaline	2013 – 2014 2 years	Leccari, SS 27 m a.s.l.	[28]
Ryegrass[4]	0.9 – 3.5 (cutted once on July 2008)	n.a.	n.a.	36 N, 92 P_2O_5 (1st year)	non-irrigated	calacareous	2006 – 2009 3 years	Ottava, SS 80 m a.s.l.	[31]
Tall fescue[5]	~ 3.6 (1st year) ~ 8.6 (2 nd year) ~ 6.7 (3 rd year)	~ 54 % (summer leaf bases water content)	n.a.	44 N, 46 P_2O_5 (before sowing) 75 N (every year)	non-irrigated	calacareous sandy-loam soil pH 7.7	2004 – 2007 3 years	Ottava, SS 80 m a.s.l.	[29]
Cocksfoot[6]	~ 2.1 (1st year) ~ 4.6 (2 nd year) ~ 4.8 (3 rd year)	~ 48 % (summer leaf bases water content)	n.a.	44 N, 46 P_2O_5 (before sowing) 75 N (every year)	non-irrigated	calacareous sandy-loam soil pH 7.7	2004 – 2007 3 years	Ottava, SS 80 m a.s.l.	[29]

Cocksfoot[7]	~ 20 (irrigated) ~16 (rainfed)	n.a.	n.a.	50 N, 150 P_2O_5, 100 K_2O	360 mm	clay-loam pH 8	1996 – 1998 3 years	Sanluri, Ca 68 m a.s.l.	[30]
Cardoon[8]	10.4	n.a.	C 41 % (stalks)	80 N, 100 P_2O_5	non-irrigated	sandy-clay-loam pH 8.3	2007 to 2010 3 years	Ottava, SS 80 m a.s.l.	[19]
Cardoon	4,6	n.a.	n.a.	n.a.	n.a.	alfisols, petrocalcic palexeralfs pH 7.8	n.a.	Ussana, CA 97 m a.s.l.	[72]
Cardoon	20 - 23	8 – 32%	n.a.	36 N, 90 P_2O_5	non-irrigated	sandy-clay-loam, pH alkaline	2013 – 2014 2 years	Leccari, SS 27 m a.s.l.	[36]
Cardoon	10 - 12	85% dry matter	n.a.	50 N 100 N	non-irrigated	fertile soil	1993 – 1996 2 years	Uras, OR 10 m a.s.l.	[89]
Giant reed	7 – 10 (dry matter)	15 (fresh weight)	n.a.	n.a.	n.a.	alfisols, petrocalcic palexeralfs pH 7.8	n.a.	Ussana, CA 97 m a.s.l.	[72]
Miscanthus	1.3 (1st year) 8.9 (2 nd year)	~ 47 %	n.a.	36 N, 90 P_2O_5	non-irrigated	sandy-clay-loam, pH alkaline	2013 – 2014 2 years	Leccari, SS 27 m a.s.l.	[36]
Giant reed	5.1 (1st year) 24.6 (2 nd year)	~ 50 %	n.a.	36 N, 90 P_2O_5	non-irrigated	sandy-clay-loam, pH alkaline	2013 – 2014 2 years	Leccari, SS 27 m a.s.l.	[36]
Giant reed	~ 2	~ 50 %	C 47.3%	50 N, 130 P_2O_5, 130 K_2O (only first year)	350 mm only first year	sandy marginal land	1994 – 1998 4 years	Palmas Arborea, OR 5 m a.s.l.	[41]
Giant reed	~ 1.6	~ 47 %	C 47.3%	96 P_2O_5	40 mm	fertile soil	1997 – 1998	Solarussa, OR	[41]

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				(only first year)	only first year		1 years	5 m a.s.l.	
Giant reed[9]	25.56 (2nd year)	~ 47 %	n.a.	100 N, 175 P_2O_5	~ 500 mm	sandy loam	2013 – 2016 2 years	Masainas, CA 5 m a.s.l.	[90]
Giant reed[9]	17.45 (2nd year)	~ 42 %	n.a.	100 N, 175 P_2O_5	600 mm	sandy-clay-loam	2013 – 2016 2 years	Serramanna, Ca 38 m a.s.l.	[90]
Giant reed[9]	5.6	~ 52 %	n.a.	100 N, 175 P_2O_5	n.a.	clay	2014 – 2016 1 year	Tratalias, Ca 17 m a.s.l.	[90]
Switchgrass	8.44 (fresh biomass)	~ 50 %	n.a.	100 N, 175 P_2O_5	600 mm	sandy-clay-loam	2013 – 2016 2 years	Serramanna, Ca 38 m a.s.l.	[90]
Eucalyptus globulus	52.8 (3x2 plot) 68.4 (3x1 plot)	10%	C 47.1%	50 N, 130 P_2O_5, 130 K_2O (only first year)	26 mm only first year	sandy marginal land	1994 – 1998 4 years	Palmas Arborea, OR 5 m a.s.l.	[41]
Eucalyptus globulus	268 (wood) 92 (residual)	11%	n.a.	n.a.	non-irrigated	sandy marginal land	1977 – 1998 21 years	Marrubiu, OR 20 m a.s.l.	[41]

1. Field trial of 5 clones of eucalypt compared with Eucaliptus camaldulensis. Detected the presence of the invaders eucalyptus gall wasps
2. Field trial of 10 autochthonous populations.
3. Field trial of cultivar Flecha.
4. Field trial of 11 native populations.
5. Field trial of 5 cultivars from Mediterranean semi-arid areas.
6. Field trial of 6 cultivars and 1 ecotype from Mediterranean semi-arid areas.
7. Field trial of 8 cultivars.
8. Field trial of ‘Bianco Avorio’ variety.

TABLE S3. OVERVIEW OF AGRONOMIC CHARACTERISTICS OF ANNUAL BIOMASS CROPS INVENTORIED IN ITALY.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

Crop	Biomass yield $Mg\ ha^{-1}$	Humidity	Ferment. sugar	Fertilizers $kg\ ha^{-1}$	Mean irrigation	Soil detail	Growing season	Location	References
Sweet sorghum[1]	24.7 (3-year mean)	75%	9.1 °Brix; 8.4 TSS* ($Mg\ ha^{-1}$)	0 N - 1st trial 75 N - 2nd trial 150 N - 3rd trial 100 P_2O_5	120 mm - 1st year 176 mm - 2nd year 300 mm - 3rd year	silty-clay pH 8.3	2009 – 2012 3 years	Foggia, FG 90 m a.s.l.	[69]
Rapeseed[2]	2.8 - seed 7.11 - residues (3-year mean)	seed 9% moisture	n.a.	150 N	non-irrigated	loam pH 8	2010 – 2013 3 years	Palazzolo dello Stella, UD 5 m a.s.l.	[91]
Rapeseed[2]	4.0 - seed 8.06 - residues (3-year mean)	seed 9% moisture	n.a.	150 N	non-irrigated	loam pH 7.8	2010 – 2013 3 years	Osimo, AN 43 m a.s.l	[91]
Rapeseed[2]	1.52 - seed 2.81 - residues (3-year mean)	seed 9% moisture	n.a.	150 N	non-irrigated	clay pH 8	2010 – 2013 3 years	Cassibile, SR 15 m a.s.l	[91]
Ethiopian mustard[3]	1.92 - seed (3-year mean)	seed 9% moisture	n.a.	80 N	non-irrigated	loam pH 8	2010 – 2013 3 years	Palazzolo dello Stella, UD	[91]
Ethiopian mustard[3]	3.10 - seed (3-year mean)	seed 9% moisture	n.a.	80 N	non-irrigated	loam pH 7.8	2010 – 2013 3 years	Osimo, AN 43 m a.s.l	[91]
Ethiopian mustard[3]	0.91 - seed (3-year mean)	seed 9% moisture	n.a.	80 N	non-irrigated	clay pH 8	2010 – 2013 3 years	Cassibile, SR 15 m a.s.l	[91]
Sweet sorghum[4]	~ 20 (dry matter)	65%	n.a.	100 N	n.a.	clay	2012 1 years	Bagnacavallo, (Ra) 800 m a.s.l.	[92]
Durum wheat	6.17	13%	n.a.	n.a.	non-irrigated	n.a.	2012 1 year	Sicily	[93]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691846.

Maize[5]	~20 (dry matter)	70%	n.a.	245 N, 92 P_2O_5, 160 K_2O	irrigated	n.a.	2007-2008 1 year	Po valley	[94]
Triticale[6]	16.5 (dry matter)	82%	n.a.	110 N, 60 P_2O_5, 500 K_2O	non-irrigated	n.a.	2008 1 year	Po valley	[94]
Sweet sorghum[7]	19.3 (dry matter)	85%	n.a.	44 N, 75 K_2O	non-irrigated	n.a.	2007 1 year	Po valley	[94]

1. Field trial of cultivar 'Sucro 506'.
2. Field trial of 43 varieties.
3. Field trial of 4 varieties.
4. Field trial of 11 varieties.
5. Field trial of 20 varieties FAO 500, 600, 700.
6. Field trial of varieties "Bienvenù" and "Talentro".
7. Field trial of variety Grazer N (2 harvests).
8. *TSS: total soluble solid.

TABLE S4. OVERVIEW OF AGRONOMIC CHARACTERISTICS OF PERENNIAL BIOMASS CROPS INVENTORIED ITALY.

Crop	Biomass yield $Mg\ ha^{-1}$	Humidity	Ferment. sugar	Fertilizers $kg\ ha^{-1}$	Mean irrigation	Soil detail	Growing season	Location	References
Giant reed	13.9 (50 N) 16.2 (100 N)	48.4 % (50 N) 47.7 % (100 N)	n.a.	two trials: 50 N 100 N	non-irrigated	clay, pH 8.1	9 years	Sant ’ Angelo dei Lombardi, AV 700 m a.s.l.	[43]
Giant reed	37.7	42.9 %	n.a.	100 N, 100 P_2O_5, 100 K_2O	non-irrigated	loam, pH 8.3	12 years	Rottaia, PI 2 m a.s.l.	[12]
Miscanthus	28.7	46 %	n.a.	100 N, 100 P_2O_5, 100 K_2O	non-irrigated	loam, pH 7.9	12 years	Rottaia, PI 2 m a.s.l.	[12]
Miscanthus	14.5* (25 % ETm) 27.0* (100 % ETm)	n.a.	n.a.	tree trials: 0 N 60 N 120N	25 % ETm 50 % ETm 100 % ETm	medium-loam, pH 8.6	1993 – 1996 4 years	Catania, CT 10 m a.s.l.	[95]
Giant reed[1]	10.6 (1st year) 22.1 (2nd year)	n.a.	n.a.	80 N, 100 P_2O_5, 100 K_2O	30 mm after transplant; 300 mm (1st year) 150 mm ~2st year)	tipic Xerofluvent	1997 – 1998 2 years	Primosole, CT 10 m a.s.l.	[33]
Giant reed[2]	36.5 (1st year) 27.3 (2nd year)	47 % (1st year) 41 % (2nd year)	n.a.	100 N, 100 P_2O_5, 100 K_2O	non-irrigated	loam, pH 7.9	2011 – 2012 2 years	San Piero a Grado, PI 1 m a.s.l.	[96]
Giant reed[3]	62	n.a.	n.a.	247 N	1102 mm (irrigation + rainfall)	sandy-loam	3 years	Reggio Calabria, RG	[97]

Crop	Biomass yield $Mg\ ha^{-1}$	Humidity	Ferment. sugar	Fertilizers $kg\ ha^{-1}$	Mean irrigation	Soil detail	Growing season	Location	References
Giant reed[3]	51	n.a.	n.a.	279 N	736 mm (irrigation + rainfall)	clay	3 years	Catania, CT 10 m a.s.l.	[97]
Giant reed[4]	20.4 – 51.5	52 % (1st year) 42 % (2nd year)	43.4 % (cellulose)	40 $Mg\ ha^{-1}$ solid digestate	non-irrigated	sandy-loam	2011 – 2013 2 years	Cremona, CR 57 m a.s.l.	[98]
Switchgrass	5.7 - 8	47 % - 62 %	n.a.	n.a.	n.a.	n.a.	n.a.	Bologna, BO	[99]
Switchgrass	13.6 - autumn 16.7 - winter	57 % - autumn 37 % - winter (moisture)	n.a.	43 P_2O_5	irrigated	loam, pH 7.6	2008 – 2013 6 years	Cadriano, BO 32 m a.s.l.	[35]
Miscanthus	~ 16	n.a.	n.a.	43 P_2O_5	irrigated	loam, pH 7.6	2008 – 2013 6 years	Cadriano, BO 32 m a.s.l.	[35]
Giant reed	~ 7 - autumn ~ 19 - winter	~54% (moisture)	> 30 % (winter)	nitrogen fertilization	constantly irrigated	medium-loam, pH 8.6	2011 – 2013 3 years	Catania, CT 10 m a.s.l.	[35]
Miscanthus	~ 3 - autumn ~ 10 - winter	52 % - autumn 13 % - winter (moisture)	>35 % (winter)	nitrogen fertilization	constantly irrigated	medium-loam, pH 8.6	2001 – 2013 3 years	Catania, CT 10 m a.s.l.	[35]
Giant reed	39.6	n.a.	n.a.	120 N, 120 P_2O_5 (every year)	only first year	loam-silty, pH 8.2	2002 – 2019 7 years	Anzola dell'Emilia, (BO) 38 m a.s.l.	[100]
Miscanthus	25.2	n.a.	n.a.	120 N, 120 P_2O_5 (every year)	only first year	loam-silty, pH 8.2	2002 – 2019 7 years	Anzola dell'Emilia, (BO) 38 m a.s.l.	[100]

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Crop	Biomass yield Mg ha^{-1}	Humidity	Ferment. sugar	Fertilizers kg ha^{-1}	Mean irrigation	Soil detail	Growing season	Location	References
Switchgrass[5]	~ 32 (Alamo) ~16 (Blackwell)	n.a.	n.a.	three trials: 0 N 50 N 100 N	0 % ET$_0$ 75 % ET$_{75}$	silty-clay-loam; sandy-loam pH 8.1 – 7.7	2010 – 2013 4 years	San Piero a Grado, PI 1 m a.s.l.	[101]
Cardoon[6]	19.22 - 27.57 (3-year mean)	14.35 – 17.73 (Mg ha^{-1})	51.8 % (stems cellulose)	0 N - 1st trial 50 N - 2nd trial	non-irrigated (only after transplanting)	silty-clay loam pH 6.7	2011 – 2013 3 years	Tor Mancina, RM 43 m a.s.l.	[24]
Wild cardoon[7]	9.28 – 13.22 (3-year mean)	8.11 – 11.24 (Mg ha^{-1})	51.1 % (stems cellulose)	0 N - 1st trial 50 N - 2nd trial	non-irrigated (only after transplanting)	silty-clay loam pH 6.7	2011 – 2013 3 years	Tor Mancina, RM 43 m a.s.l.	[24]
Wild cardoon[8]	7.4	92.9%	n.a.	120N, 100 P$_2$O$_5$, 80 K$_2$O	30m^3 ha^{-1} (only after transplanting)	sandy-loam pH 7.7	2005 – 2012 7 years	Ispica, RG 42 m a.s.l.	[40]
Cardoon[9]	14.6	89.4%	n.a.	120N, 100 P$_2$O$_5$, 80 K$_2$O	30m^3 ha^{-1} (only after transplanting)	sandy-loam pH 7.7	2005 – 2012 7 years	Ispica, RG 42 m a.s.l.	[40]

1. Field trial of 39 clones collected in Sicily and Calabria.
2. Field trial on mature crops (6 – 7 years old) and evaluate the effect of three single harvest and six double harvest.
3. Field trial under non-limiting conditions of water and N availability.
4. Field trial of 24 clones (23 from Europe, 1 from China).
5. Field trial of 2 cultivars: 'Alamo' (lowland ecotype) and 'Blackwell' (upland ecotype).
6. Field trial of 2 varieties: 'CDL07' and 'Gigante'.
7. Field trial of 2 varieties: 'RCT10' and 'Tolfa Mountains'.
8. Field trial of wild cardoon landrace.
9. Field trial of cultivar 'Bianco Avorio'.

*Aboveground dry biomass were dried at 60° C in a thermo-ventilated oven until constant weight was achieved.

TABLE S5. QUALITATIVE MATRIX OF AGRONOMIC CHARACTERISTICS AND THEIR IMPACT ON ECOSYSTEM SERVICES/DISSERVICES OF BIOMASS CROPS INVENTORIED.

Crop	Yield	Water efficiency	Fertilizers application	Pest resistance	Propagation and plantation	Tillage intensity	Carbon storage	Biodiversity	Non invasivity
Giant reed	+ + +	+ + +	+ + +	+ + +	+	+ +	+ + +	+ +	+
Switchgrass	+ + +	+ + +	+ + +	+ + +	+ +	+ +	+ +	+ +	+ +
Miscanthus	+ +	+ + +	+ + +	+ + +	+ +	+ +	+ + +	+ +	+ +
Eucalyptus	+ +	+	+ +	+	+ +	+ + +	+ +	+ +	+
Smilo grass	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+ + +	+ +
Tall fescue	+	+ +	+ +	+ +	+ +	+ +	+ +	+ + +	+ +
Ryegrass	+	+ +	+ +	+ +	+	+ +	+ +	+ + +	+ +
Cocksfoot	+	+ +	+ +	+ +	+ +	+ +	+ +	+ + +	+ +
Globe artichoke	+ +	+	+	+	+ +	+	+	0	+ +
Cardoon	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+	+
Milk thistle	+ +	+ +	+ +	+ +	+ +	+ +	+ +	+	+
Rapeseed	+	+ +	0	0	+ + +	+	+	0	+ +
Ethiopian mustard	+	+ + +	+ +	+ +	+ +	+	+	0	+ +
Maize	++	+	+	0	+ + +	0	0	0	+ + +
Triticale	+	+ +	+	+	+ + +	0	0	0	+ + +
Durum wheat	+	+ +	+	+	+ + +	0	0	0	+ + +
Sweet sorghum	++	+	+	0	+ + +	0	0	0	+ + +

Note: + + + = highly suitable; + + = suitable; + = less suitable; 0 = not suitable/hindering; ? = no information. Based and modified from Zagada-Lizarazu et al. 2010 [102] .

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