Effects of compost and defatted oilseed meals as sustainable organic fertilisers on cardoon (Cynara cardunculus L.) production in the Mediterranean basin

Domenico Ronga a, Domenica Villecco b and Massimo Zaccardelli b

aInterdepartmental Research Centre, Valorisation of Biological Resources and Food Safety (BIOGEST-SITEIA), University of Modena and Reggio Emilia, Reggio Emilia, Italy; bCouncil for Agricultural Research and Economics, Research Centre for Vegetable and Ornamental Crops, Pontecagnano, Italy

ABSTRACT
Cardoon (Cynara cardunculus L.) is considered as one of the most suitable energy crops for Southern Europe. The aim of this work was to outline the effects of organic fertilisers on the productivity and the global warming potential (GWP) on cardoon production. Six fertilisers (N 100 kg ha−1, N 50 kg ha−1, Compost 30 t ha−1, Compost 15 t ha−1 + N 25 kg ha−1, 3 t ha−1 of defatted oilseed meals of sunflower, 3 t ha−1 of defatted oilseed meals of Brassica carinata), and unfertilised control, were evaluated on two cultivars (‘Gobbo di Nizza’ and ‘Altilis 41’) in a split-plot experiment. Defatted oilseed meal of sunflower recorded higher total dry weight (+10%), seed yield (+17%), nitrogen use efficiency (+14%) and better GWP (−66%) compared to the other organic fertilisers and performing as well as N 100 kg ha−1. Altilis 41 cultivar showed the highest aboveground total dry weight (10 t ha−1 y−1), seed yield (1.7 t ha−1 y−1), stalk dry weight (7 t ha−1 y−1) and head dry weight (3 t ha−1 y−1). Our results highlighted that by combining suitable cultivar and fertilisation strategies, it could be possible to increase the production sustainability of C. cardunculus.

INTRODUCTION
An increase of crop production sustainability is one of the challenges proposed by the European Community to reduce the dependence on oil consumption, which could improve the security of energy supply in the medium and long term (Mantineo, D’agosta, Copani, Patané, & Cosentino, 2009). Biomasses used to obtain green energy on a global scale can contribute to improve environmental sustainability. In fact, when biomass is burned, they emit carbon dioxide into the atmosphere that previously was adsorbed during the crop cycle in the photosynthetic process (Royal Society, 2008). Different biomasses can be used in the EU to obtain green energy, such as those from arable crops currently grown for food: sugar, starch and oil crops, forestry or domestic waste and marine biomasses. Nonetheless, using dedicated crops called ‘energy crops’, which are able to produce the highest biomass with the highest energy value (Mantineo et al., 2009), could be possible to preserve the crops used to feed people and animals.

The use of energy crops presupposes that the obtained energy is significantly higher than that required for the crop growth, according to Lewandowski and Schmidt (2006).

Simple cropping techniques and low production costs are the main requirements to produce energy crops, and cardoon (Cynara cardunculus L.) is indicated as one of the most suitable for satisfying these requirements in the Mediterranean area (Curt, Sanchez, & Fernández, 2002; Fernández, Curt, & Aguado, 2006; Fernandez & Manzanares, 1990; Gominho, Curt, Lourenço, Fernández, & Pereira, 2018; González et al., 2004; Raccuia & Melilli, 2007). Together with globe artichoke (C. cardunculus L. var. scolymus L.) and wild cardoon (C. cardunculus L. var. sylvestris (Lamk) Fiori), cultivated cardoon (C. Cardunculus L. var. altilis DC) belongs to the family Asteraceae. Cardoon is a herbaceous plant with a polyanual cycle suitable for the Mediterranean basin (Portis, Barchi, Acquadro, Macua, & Lanteri, 2005; Raccuia, Mainolfi, Mandolino, & Melilli, 2004). Cultivated cardoon is raised from seed and handled as an annual plant. Seeds are sown in late spring and the plants over-summer in the vegetative state (Portis et al., 2005). The European agricultural area devoted to this crop (2,000–3,000 ha) is mainly confined to a small area, in particular, in Spain, Italy, France and Greece, where it is used for the preparation of traditional foods (Ierna & Mauromicale, 2010; Portis et al., 2005). Focusing on Italy, the specialised cardoon biomass production, using cv. ‘Trinaseed’, extends over 500 ha in Sardinia, Italy (Novamont, 2015).
In recent years, the species *C. cardunculus* has been considered as a multipurpose crop. Several studies have indicated that cardoon is among the most promising species for energy and cellulose production in the Mediterranean basin (Cosentino, Copani, Mantineo, Patané, & D’Agosta, 2008; Cotana et al., 2015; Fernández et al., 2006; Foti & Cosentino, 2001; Gominho et al., 2018; Raccuia, Piscioneri, Sharma, & Mellili, 2011; Toscano, Sollima, Genovese, Mellili, & Raccuia, 2015). In fact, *C. cardunculus* offers a wide spectrum of different biomass uses: for alternative energy production by combustion, pyrolysis and gasification (González et al., 2004; Ochoa & Fandos, 2004); for paper pulp (Gominho, Fernandez, & Pereira, 2001); and for feeding ruminants (Cajarville, Gonzalez, Repetto, Rodriguez, & Martinez, 1999). Moreover, achens contain oil (25–33%) with high levels of α-tocopherol, which offers stability against oxidation (Maccarone et al., 1999). These characteristics make *C. cardunculus* oil suitable for human consumption. Furthermore, research has been carried out to obtain biodiesel from *C. cardunculus* oil (Lapuerta, Armas, Ballesteros, & Fenández, 2005). After oil extraction from the seeds, the residual meal could be used for animal feed (Foti et al., 1999; Genovese et al., 2015). *C. cardunculus* has also been used for medicinal purposes (Kraft, 1997) due to its richness of polyphenols and inulin in the leaves (Jimenez-Escrig, Dragsted, Daneshvar, Pulido, & Saura-Calixto, 2003), the roots and the receptacle (Raccuia et al., 2015; Raccuia & Mellili, 2010).

The cardoon aboveground biomass yield in terms of dry weight (d. w.) is, on average, 19.0 t ha$^{-1}$ (Foti et al., 1999; Maccarone et al., 1999). In a recent study, Ottaiano et al. (2017) evaluated the productivity levels of different genotypes of cardoon (Altilis, Gigante e Trinased) in two different climatic conditions of Mediterranean cropland (plain vs hilly) during three years. At the plains site, ligneocellulosic biomass yield was 19 t ha$^{-1}$ (d. w.) and grain yield 2.7 t ha$^{-1}$, on the average of a 3-year period. On the other hand, at the hilly site, biomass yield was similar (20 t ha$^{-1}$ d. w.) while grain yield was higher ~ 3.9 t ha$^{-1}$. Moreover, other studies reported that the yield expressed as total energy obtainable by 1 ha of crop is greater for cultivated var. *altilis* (cardoon genotypes) compared to var. *scolymus* (globe artichoke) and var. *sylvestris* (wild cardoon) (Angelini, Ceccarini, Nassi o Di Nasso, & Bonari, 2009; Raccuia & Mellili, 2007). Several works carried out in Italy reported an interesting potential yield in terms of biomass and energy of *C. cardunculus* (Angelini et al., 2009; Gherbin, Monteleone, & Tarantino, 2001; Ierna & Mauromicale, 2010; Mantineo et al., 2009; Ottaiano et al., 2017; Piscioneri, Sharma, Baviello, & Orlandini, 2000); nonetheless, information on cropping techniques and crop performances showed great variability.

Efficient fertilisation is a key strategy in sustainable agriculture since fertilisation strongly influences both crop performances and environmental impact. Unfortunately, in Mediterranean regions, fertilisation is still empirically managed toward nitrogen over-dressing (Ierna, Mauro, & Mauromicale, 2012a). Some authors (Archontoulis, Danalatos, Struik, Batzogiannis, & Savas, 2010; González et al., 2004; Grammelis, Malliopoulou, Basinas, & Danalatos, 2008; Ierna & Mauromicale, 2010; Mantineo et al., 2009) investigated the effects of different levels of synthetic nitrogen applications on yield performances of cultivated cardoon. However, to the authors’ knowledge, there is a lack of information on the effects of organic fertilisers on cardoon production in the literature and, from this point of view, a more comprehensive assessment might be useful to increase the sustainability of this crop. In fact, the use of renewable sources aiming to reduce the external inputs is the main strategy involved in the reduction of the environmental impact due to agriculture, making it more sustainable.

From this point of view, organic fertilisers, especially those coming from the valorisation of agricultural by-products, might improve agricultural sustainability following the concept of a circular economy. Moreover, the production of multipurpose biomass crops also in a specialised area for the production of horticultural crops could be an opportunity to improve agricultural biodiversity and might be an alternative in crop rotation, especially for its multipurpose use. In this context, the use of compost and oilseed meals as a nitrogen (N) source, applied as organic fertilisers, could represent an opportunity to improve agricultural sustainability. Therefore, we evaluated the effects of compost and two different defatted oilseed meals applied as organic fertilisers, on cardoon production over a three-year period under Mediterranean climatic conditions. In particular, the study investigated the effects of organic fertilisers on the traits influencing the aboveground yield and assessing the production in terms of environmental impact as well.

**Materials and methods**

**Location of the trial**

Agronomic trials were performed in an open field at Sele Valley (40°35’03.8”N, 14°58’48.6”E) (Salerno, Southern Italy) during a three-year period in a Typical Haploxerepts soil (Soil Taxonomy; USDA, 2006). The physical and chemical soil properties were as follow: sand 26.8%, silt 40.8%, clay 32.4%, lime-stone 2.4%, pH 7.8, organic matter 1.6%, total nitrogen 1.3‰, P2O5 126 mg kg$^{-1}$ and K2O 324 mg kg$^{-1}$ (Table 1).
**Plant material and crop management**

Agronomic performance of two cultivated cardoon varieties using seven different types of fertilisation management was evaluated. *C. cardunculus* was transplanted on 7 May 2010 with a density of 1 plant m$^{-2}$ (Table 2). The following factors were assessed in a split-plot experimental design with three replicates: seven different forms of fertilisation management: (1) synthetic fertiliser using 100 kg N ha$^{-1}$ (N100); (2) synthetic fertiliser using 50 kg N ha$^{-1}$ (N50); (3) organic fertiliser using compost 30 t ha$^{-1}$ (C30) corresponding to 655 kg N ha$^{-1}$; (4) organic fertiliser using compost 15 t ha$^{-1}$ + synthetic fertiliser using 25 kg N ha$^{-1}$ (C15 + N25) corresponding to 340 kg N ha$^{-1}$; (5) organic fertiliser using defatted seed meal of *Brassica carinata* (*Brassica carinata* A. Braun) 3 t ha$^{-1}$ (DMB3) corresponding to 171 kg N ha$^{-1}$; (6) organic fertiliser using defatted seed meal of sunflower (*Helianthus annuus* L.) 3 t ha$^{-1}$ (DMS3) corresponding to 150 kg N ha$^{-1}$; and (7) control unfertilised (N0) and two Italian cultivars (*Gobbo di Nizza*, and *Altulis 41*, from North/Centre Italy and Sicily, respectively) (Acquadro et al., 2012).

Ammonium nitrate was used as the synthetic fertiliser. Organic fertilisers had the following main characteristics: commercial compost from the organic fraction of municipal solid waste (GeSeNu S.r.l., Perugia, Italy) (organic C, 279 g kg$^{-1}$; total N, 21 g kg$^{-1}$); defatted oilseed meal of *B. carinata* (organic C, 450 g kg$^{-1}$; total N, 57 g kg$^{-1}$); and defatted oilseed meal of sunflower (organic C, 450 g kg$^{-1}$; total N, 50 g kg$^{-1}$). Regarding the synthetic fertiliser (N100, N50 and N25), *C. cardunculus* received one-third of the nitrogen fertiliser at transplanting and two-thirds at the leaf rosette phase, in the first year of the trial. In the following years, half dose was applied at plant sprouting in September and half dose at stalk elongation in April–May. Organic fertilisers (compost and defatted oilseed meals) were administered only once before transplanting.

The fertiliser treatment was considered as the main plot (69.12 m$^2$) and the cultivar as subplot (34.56 m$^2$).

Four-week-old plants with 4 leaves were transplanted, 120 cm apart in rows 80 cm apart; each plot consisted of 36 plants. Weeds and pests were controlled according to the production rules of integrated pest management. In particular, weeds were controlled by non-chemical management using mechanical and hand hoeing control. As regards the pathogen and pest control, chemical and organic-admitted fungicides (sulphur) and pesticides (azadirachtin A) were used. The main pests and pathogens observed were aphids, noctuids and mildew. The crop was only irrigated in the first year after transplanting and again in September in the second and third year with just light watering, in order to activate sprouting.

During the crop cycle (Figure 1) and over the three years of the trial, the main weather data, such as monthly temperature and rainfall, were recorded by a weather station in the experimental field (Table 2).

**Table 1.** Soil characteristics of the investigated field.

| Soil characteristics | Sand (%) | Silt (%) | Clay (%) | pH | Limestone (%) | K2O (mg/kg) | P2O5 (mg/kg) | N. tot. (%) | Organic matter (%) | CSC (meq/100 g) |
|----------------------|---------|---------|----------|----|---------------|-------------|-------------|-------------|------------------|-----------------|
| Transplant and harvest dates and weather conditions recorded during the three trial growing seasons. |

| Year | Location (Lat Long) | Transplant date | Harvest date | Average T min (°C) | Average T max (°C) | Total rainfall (mm) |
|------|---------------------|-----------------|--------------|--------------------|-------------------|--------------------|
| 2011 | CREA Sele Valley 40°35’03.8”N, 14°58’48.6”E | 05/07/2010 | 7 Sept. 2011 | 12.4 | 21.8 | 2,406 |
| 2012 | CREA Sele Valley 40°35’03.8”N, 14°58’48.6”E | - | 28 Aug. 2012 | 11.4 | 21.0 | 3,597 |
| 2013 | CREA Sele Valley 40°35’03.8”N, 14°58’48.6”E | - | 16 Sept. 2013 | 10.0 | 17.2 | 588 |
| Average | | | | 11.3 | 20.0 | 2,197 |
(f. w.) of biomass production (stalks + leaves and heads) and its partitioning (stalks + leaves and heads). The crop was harvested when the moisture content of the crop was about 13%. In the laboratory, the moisture content was measured by weighing 100 g of plant material in a precalibrated aluminium container and placing it in a thermoventilated oven at 105°C, until constant weight was reached.

Biomass yield was expressed as g m$^{-2}$ of dry weight (d. w.). Heads were then threshed with a specific mini-thresher for separating grains.

Ash content (dry weight basis) was measured after 15 h in a muffle furnace at 550°C until constant weight.

Nitrogen content of biomass was also measured by the Kjeldahl method (AOAC, 1990). Nitrogen use efficiency (NUE), which indicates the total biomass produced per unit of N uptake, expressed as the ratio of dry matter production to nitrogen content (g g$^{-1}$), was calculated according to Beale and Long (1997).

Crop water productivity (WP), expressed as the ratio of aboveground dry biomass production at final harvest to water used by the crop (g d. w. l$^{-1}$), was calculated according to Cosentino, Patané, Sanzone, Copani, and Foti (2007).

Environmental assessment methodology

Greenhouse gas (GHG) emissions valuation by Life Cycle Assessment (LCA) considering the entire life cycle at the farm gate, providing a method to assess the different fertilisation performances, was assessed. One hectare (ha) of cultivation and one tonne (t) of harvest biomass (d. w.) were used as functional units (FU) to study the potential environmental impacts of the different fertilisers assessed in the present study on cardoon production. Global warming potential (GWP) was adopted as the impact category for this study. Functional units expressed in kg of carbon dioxide equivalents (CO$_2$-eq) were obtained using Tier 2 methodologies recommended by the Intergovernmental Panel on Climate Change (IPCC, 2006).

The study considered the process from the soil tillage to the harvest time of the crop.

Most data related to energy consumption were recorded during the crop cycles; in addition, available data were also used as electrical energy (0.57 kg CO$_2$-eq per kW h$_e$; Pehnt, 2006) gasoline and diesel (0.53 and 0.58 kg CO$_2$-eq per L of gasoline and diesel, respectively; Furuholt, 1995), lubricant (1.07 kg CO$_2$-eq per kg of lubricant; Cuevas, 2005) and fertiliser production (3.6 kg CO$_2$-eq per Kg of N; Hesq & Fossum, 2014). Direct emissions from fertiliser administration and soil management were calculated according to the method described in the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories, applying Tier 1 method (IPCC, 2006). An emission of 0.01 kg of nitrogen dioxide (N$_2$O) for each kg of N applied to the field was considered, considering a reduction of 28% observed for solid organic fertilisers (Aguilera, Lassaletta, Sanz-Cobena, Garnier, & Vallejo, 2013). The indirect N$_2$O emissions were considered according to the Tier 1 method (IPCC, 2006) also taking into account the atmospheric deposition of N volatilised from soil management, soil leaching and runoff. An emission of 0.006 kg of N$_2$O for each kg of N applied to the field was considered. N$_2$O emissions were converted to CO$_2$-eq using the relative contribution of a gas to the greenhouse effect (IPCC, 1996). The impact of seed, seedling, pesticide and fungicide productions, as well as manufacture and maintenance of farm equipment, their transport and their waste management, were omitted in the analysis due to the same contribution in the different fertilisation treatments (Meisterling, Samaras, & Schweizer, 2009).

Data analysis

Agronomic and physiological data were analysed using analysis of variance (ANOVA), where fertiliser and cultivar were regarded as fixed effects and year as a random effect. The year was considered as a random variable, due to unpredictable weather conditions under rainfed Mediterranean conditions (Gomez & Gomez, 1984). For environmental assessment, the analysis was performed considering, for each fertiliser, the average values of different replicates recorded for the cultivars and the growing seasons. Experimental data were analysed using GenStat software. Means were statistically separated on the basis of the Tukey test, when the ‘F’ test of ANOVA for treatment was significant at least at the 0.05 probability level. Experimental data were also processed for a principal component analysis (PCA) using PLS Toolbox software (Eigenvector Research Inc., Wenatchee, WA, USA), in order to evaluate the existing relationships with original variables.
Results and discussion

Aboveground biomass production, its partitioning and the related physiological traits

In the present study, the results of the analysis of variance for all studied variables showed interesting differences among fertilisers, cultivars, years and their interactions (Tables 3 and 4).

Table 3 reports the results regarding the yield-related agronomical traits recorded at harvest time. Among the most important traits, total dry weight was affected by fertiliser, cultivar, year and cultivar x year interaction. When ammonium nitrate was applied at 100 kg ha\(^{-1}\) (N100), total dry weight production increased by 66% with respect to N0 (Table 3). Treatments N50 and DMS3 showed a similar production to N100, but a lower increment (+13% and +15%, respectively) compared to N0. Cultivar ‘Altilis 41’ showed the highest value when cropped in the first year, followed by cultivar ‘Gobbo di Nizza’, also cropped in the first year. On the other hand, cultivar ‘Gobbo di Nizza’ was the lowest productive in the second and in the third year, and similar values were shown by cultivar ‘Altilis 41’ cropped in the last year (Table S3).

Another important agronomic trait in cardoon production, due to its multipurpose attitude, is the seed yield. In the present study, seed yield was affected by fertiliser, cultivar, year and fertiliser x cultivar, fertiliser x year and cultivar x year interactions (Table 3). Cultivar ‘Altilis 41’ recorded the highest value when fertilised with treatment N100, while the lowest production of seed was highlighted by cultivar ‘Gobbo di Nizza’ fertilised with treatment N50 (Table S1). Cultivar ‘Altilis 41’ showed the highest value of seed yield in the first year of production, while the cultivar ‘Gobbo di Nizza’ recorded the lowest values in each year of production (Table S2). Treatment N100 showed the highest value of seed yield in the first year of production; similar values were recorded in N100 in the second year and by DMS3 in the third year, while the lowest value was highlighted by DMB3 in the last year of production (Table S3).

The height of the plant was affected by fertiliser, cultivar and year. Treatment N100 displayed the highest value (2.4 m); however, N50 and DMS3 showed similar values to N100. Cultivar ‘Gobbo di Nizza’ showed a higher value (+5%) than cultivar ‘Altilis 41’. The greatest height of the plant was reached in the first year (data not shown).

The number of stalks was affected by cultivar and year. Cultivar ‘Gobbo di Nizza’ recorded a higher production (+29%) with respect to cultivar ‘Altilis 41’. The highest values were recorded in the second and the third years (data not shown).

The number of heads was significantly affected by fertiliser, cultivar, year and interaction cultivar x year. Treatment N100 recorded the highest value (+47%) compared to the unfertilised treatment (N0), followed by treatment N50, that showed similar values to N100.

The number of heads was the highest in cultivar ‘Altilis 41’ cropped in 2011 (14.1), followed by cultivar ‘Altilis 41’ cropped in 2012 (11.6) and cultivar ‘Gobbo di Nizza’ cropped in 2012 (10.8). The lowest value was recorded in both cultivars in 2013 (8.4 and 7.8 per cultivar ‘Gobbo di Nizza’ and ‘Altilis 41’, respectively) (Table S3).

Table 3. Yield-related agronomic traits, recorded at harvest time.

| Source of Variation | Total dry weight (g m\(^{-2}\)) | Seed yield (g m\(^{-2}\)) | Height of plant (m) | Number of stalks (no. m\(^{-2}\)) | Number of heads (no. m\(^{-2}\)) | Dry weight of stalk and leaves (g m\(^{-2}\)) | Dry weight of heads (g m\(^{-2}\)) | Fraction of total dry weight to heads (%) | Average weight of heads (g) | HI | Ash (%) |
|---------------------|-------------------------------|-------------------------|--------------------|------------------|------------------|----------------------------------|------------------|----------------------------------------|-------------------------|-----|--------|
| **Fertiliser (a)**  |                               |                         |                    |                  |                  |                                  |                  |                                        |                         |     |        |
| N100                | 12652.5 a                     | 163.8 a                 | 2.4 a              | 2.7 n.s.         | 13.5 a           | 965.6 a                          | 300.1 a          | 23.3 c                                 | 215. n.s.               | 0.1 n.s. | 15.4 cd |
| N50                 | 8642.2 ab                     | 76.5 c                  | 2.2 ab             | 2.5 n.s.         | 10.8 ab           | 617.7 b                          | 246.1 ab          | 29.4 a                                 | 22.1 n.s.               | 0.1 n.s. | 15.2 de |
| C30                 | 814.4 b                       | 104.3 bc                | 2.1 b              | 2.4 n.s.         | 9.6 b             | 613.5 b                          | 200.8 b           | 24.3 bc                                | 19.8 n.s.               | 0.1 n.s. | 16.3 a  |
| C15 + N25           | 794.6 b                       | 103.4 bc                | 2.1 b              | 2.4 n.s.         | 10.1 b            | 571.9 b                          | 222.2 ab          | 27.2 abc                               | 21.1 n.s.               | 0.1 n.s. | 16.2 a  |
| DMB3                | 780.1 b                       | 95.8 bc                 | 2.1 b              | 2.3 n.s.         | 8.9 b             | 579.2 b                          | 200.9 b           | 25.9 abc                               | 21.2 n.s.               | 0.1 n.s. | 15.9 b  |
| DMS3                | 874.6 b                       | 111.6 b                 | 2.2 ab             | 2.3 n.s.         | 10.6 b            | 633.3 ab                         | 241.1 ab          | 27.8 ab                                | 21.6 n.s.               | 0.1 n.s. | 15.5 c  |
| N0                  | 762.9 b                       | 97.5 bc                 | 2.1 b              | 2.2 n.s.         | 9.2 b             | 556.3 b                          | 206.8 b           | 26.7 abc                               | 21.7 n.s.               | 0.1 n.s. | 14.9 e  |
| **Cultivar (b)**    |                               |                         |                    |                  |                  |                                  |                  |                                        |                         |     |        |
| Gobbo di Nizza      | 797.3 b                       | 47.9 b                  | 2.2 a              | 2.7 a            | 9.6 b             | 609.4 b                          | 187.9 b           | 24.0 b                                 | 18.8 b                  | 0.1 b   | 15.2 b  |
| Altilis 41          | 961.4 a                       | 167.2 a                 | 2.1 b              | 2.1 b            | 11.1 a            | 687.5 a                          | 274.4 a           | 28.8 a                                 | 23.7 a                  | 0.2 a   | 16.0 a  |
| **Main effect**     |                               |                         |                    |                  |                  |                                  |                  |                                        |                         |     |        |
| Fertiliser (A)      | < 0.05                        | < 0.05                  | < 0.05             | < 0.05           | < 0.05            | < 0.05                           | < 0.05            | < 0.05                                 | n.s.                    | n.s.   | < 0.05 |
| Cultivar (B)        | < 0.05                        | < 0.05                  | < 0.05             | < 0.05           | < 0.05            | < 0.05                           | < 0.05            | < 0.05                                 | n.s.                    | n.s.   | < 0.05 |
| Year (C)            | < 0.05                        | < 0.05                  | < 0.05             | < 0.05           | < 0.05            | < 0.05                           | < 0.05            | < 0.05                                 | n.s.                    | n.s.   | < 0.05 |
| **Interaction**     |                               |                         |                    |                  |                  |                                  |                  |                                        |                         |     |        |
| A x B               | n.s.                         | < 0.05                  | n.s.               | n.s.             | n.s.              | n.s.                             | n.s.              | n.s.                                   | n.s.                    | n.s.   | < 0.05 |
| A x C               | < 0.05                       | < 0.05                  | < 0.05             | < 0.05           | < 0.05            | < 0.05                           | < 0.05            | < 0.05                                 | n.s.                    | n.s.   | < 0.05 |
| B x C               | n.s.                         | < 0.05                  | n.s.               | n.s.             | n.s.              | n.s.                             | n.s.              | n.s.                                   | n.s.                    | n.s.   | n.s.   |
| A x B x C           | n.s.                         | n.s.                    | n.s.               | n.s.             | n.s.              | n.s.                             | n.s.              | n.s.                                   | n.s.                    | n.s.   | n.s.   |

Notes. Fertiliser and Cultivar used as fixed factor and Year as random factor. Values within a column followed by different lowercase letters are significantly different at \(P < 0.05\), according to Tukey’s test; n.s. = not significant. N100 = 100 kg N ha\(^{-1}\); N50 = 50 kg N ha\(^{-1}\); C30 = compost 30 t ha\(^{-1}\); C15 + N25 = compost 15 t ha\(^{-1}\) + 25 kg N ha\(^{-1}\); DMS3 = defatted meal of sunflower 3 t ha\(^{-1}\); DMB3 = defatted meal of Brassica caminita 3 t ha\(^{-1}\); N0 = 0 kg N ha\(^{-1}\).
Dry weight of stalks and leaves was affected by fertiliser, cultivar, year and cultivar x year interaction. Treatment N100 recorded the higher value (+74%) followed with a similar value by DMS3 (+14%) compared to unfertilised treatment (N0). Cultivar ‘Altilis 41’ showed the highest value in the first year, followed by cultivar ‘Gobbo di Nizza’, also cropped in the first year (Table S3).

Head dry weight was affected by fertiliser, cultivar, year and cultivar x year interaction. Treatment N100 showed the highest values (45%) compared to unfertilised treatment (N0) and similar values were reported by N50, C15 + N25 and DMS3. Cultivar ‘Altilis 41’ showed the highest value in the first year of cultivation, while the lowest values were shown by both cultivars when cropped in the third year (Table S3).

Another important trait in biomass production is its partition. The fraction of total dry weight to heads was affected by fertiliser, cultivar and year. Fertilisation N50 increased the biomass allocated to heads, showing the highest value (+11%) compared to the average performance of other fertilisers. Cultivar ‘Altilis 41’ performed better than ‘Gobbo di Nizza’, allocating +20% of the total biomass to heads. The highest value of allocation to heads was recorded in the second year (data not shown).

The average weight of the heads was affected by cultivar and year. Cultivar ‘Altilis 41’ performed better than ‘Gobbo di Nizza’ (+26%) (Table 3), while the highest value was recorded in the second year (data not shown).

Total biomass is an important parameter in crop production; however, its distribution among the different organs is a crucial point in achieving satisfactory yields (Ronga et al., 2017). When referring to seeds or fruits in other crops, we name this harvest index. In the present study, harvest index was affected only by cultivar and ‘Altilis 41’ performed better (+100%) than ‘Gobbo di Nizza’ (Table 3).

Finally, the ash content is another important trait for energy production from biomass. In the present research, the ash content was affected by fertiliser, cultivar, year and fertiliser x cultivar interaction. The highest value was recorded in cultivar ‘Altilis 41’ fertilised with C15 + N25 treatment; a similar value was recorded in the same cultivar fertilised with C30 treatment. On the other hand, treatments N50 and N0 showed lower values when the cultivar ‘Gobbo di Nizza’ was cropped. The highest content of ash was detected in the first year (data not shown).

To fully assess the effect of the tested fertilisers, the main physiological parameters were also investigated. Table 4 reports the results regarding the physiological traits recorded during the crop cycle over the three years of production.

SPAD values were affected by fertiliser, cultivar and year. Treatment N100 recorded the highest value, while the lowest was shown by N0. Cultivar ‘Altilis 41’ displayed the highest values compared to ‘Gobbo di Nizza’. The lowest SPAD value was recorded in the last year (data not shown).

Total nitrogen uptake was influenced by fertiliser, cultivar, year and cultivar x year interaction. Treatment N100 recorded the highest value and a similar value was shown by C30, while the lowest was reported by N0 (Table 4). Cultivar ‘Altilis 41’ showed the highest value when cropped in the first year. On the other hand, the same cultivar also showed the lowest value when cropped in the last year, but similar values were reported by cultivar ‘Gobbo di Nizza’ when cropped in the second and third years of production.

Nitrogen use efficiency was affected by fertiliser, cultivar, year and fertiliser x year interaction. Cultivar ‘Altilis 41’ performed better than ‘Gobbo di Nizza’, showing an increment of 5% (Table 4). Treatment N0 in the last year of production showed the highest value and a similar value was recorded in treatment DMB3 also in the last year; the lowest value was shown with treatment C30 in the first year, with similar values recorded by C30 in the second and third years and C25 + N25 in each year of production (Table S2). The highest value of NUE was recorded in the last year (data not shown).

Crop water productivity was affected by fertiliser, cultivar, year, fertiliser x year and cultivar x year interactions (Table 4). Treatment N100 showed the highest value in the first year, followed by DMS3 and DMB3 both in the first year, while the lowest value was detected with N0 in the third year of cultivation (Table S2). Cultivar ‘Altilis 41’ recorded the highest value in the first year, followed by ‘Gobbo di Nizza’, also in the first year (Table S3).
Our results showed that DMS3 could be a sustainable organic fertiliser for the production of cultivated cardoon. Similar results were obtained by Mazzoncini et al. (2015), who assessed oilseed meals on vegetable crops such as lettuce, chard and spinach. The lower agronomical performance of DMB3 was putatively due to the content of glucosinolates, that may reduce the availability of nitrogen and/or inhibit the effect on nitrification processes (Mazzoncini et al., 2015). In fact, Scotti, Pane, and Zaccardelli (2018) reported that seed cakes from sunflower were characterised by a higher content of cellulosates, while Brassicaceae seed cakes were rich in more biochemical stable compounds and secondary metabolites, such as glucosinolates, that negatively affected microbial growth, generally resulting in lower soil activities. Moreover, Zaccardelli, Villecco, Celano, and Scotti (2013) reported a significant positive response of the soil enzyme activities due to the addition of seed meals for eggplant production, indicating a beneficial effect on soil quality. In the same study, defatted oilseed meals, compared to compost, highlighted an increase of soil enzymatic activities only in the first two months after application, reflecting the rate of release of nutrients, such as mineral fertilisers. However, in the present study, the lower release of nutrients shown by compost did not affect cardoon production, probably due to its long crop cycle, as nutrients shown by compost did not affect cardoon production did not affect cardoon production probably due to its long crop cycle, as highlighted in Table 3 and in Figure 2; however, further investigations are required to confirm this hypothesis.

In regard to biomass production, the results recorded in the present study are in agreement with Fernández (1998), who reported a biomass production of C. cardunculus from 10 to 20 t of d. w. ha⁻¹ year⁻¹, highlighting that a good biomass production requires at least 500 mm year⁻¹ of rainfall, in a rainfed environment. González et al. (2004) also recorded an aerial biomass production (about 11 t ha⁻¹ of d. w.) similar to our results. On the other hand, total dry biomass and seed yield recorded in the present study were slightly lower (~31% and ~40%, respectively) compared to a recent study carried out in the same region, by Ottaiano et al. (2017), who assessed the production levels of three cultivars of cardoon (Ailtis, Gigante and Trinaseed). These differences are probably due to the different amount of synthetic nitrogen applied and the different number of transplanted plants m⁻² (150 N ha⁻¹ vs 100 N ha⁻¹ and 4 vs 1, respectively), both lower in the present study.

Comparing our results with those obtained under high input management, the maximum biomass yield recorded in the present study was lower (about ~50%) with respect to the yield reported by Mantineo et al. (2009) who, however, used a different cultivar ('Cardo gigante inerme') with high irrigation and fertiliser treatments (irrigation as 75% of evapotranspirated water and fertiliser as 100 kg ha⁻¹ of nitrogen).

Nonetheless, similar to our results, a lower above-ground biomass yield (less than 1 t ha⁻¹ of d. w.) in the last year of cultivation was recorded.

Our results regarding dry weight distribution, number of heads and plant height are in agreement with those reported in a study conducted by Lerna and Mauromicale (2010). The authors cropped cultivar ‘Cardo gigante di Romanga’ under low input crop management, applying 80 kg ha⁻¹ of nitrogen as ammonium nitrate. Cardoon needs less nitrogen than many other crops. In many field experiments, high biomass yields were recorded under fertilisation dressings from 0 up to 50 kg of N ha⁻¹ (Grammelis et al., 2008). In fact, in the present study, applying 30 t ha⁻¹ of compost, corresponding to about 655 kg N ha⁻¹, a biomass production similar to the unfertilised treatment (N0) was recorded.

In general, our results highlight that cardoon production showed a good agronomic performance also in the area suitable for the production of cash crops. Moreover, the production of cardoon for biomass might be included in crop rotation to improve agricultural biodiversity. Nonetheless, for energy purposes, cardoon displays a high ash content, higher than other herbaceous energy crops, like giant reed and Miscanthus, as already reported by Angelini et al. (2009). However, being a multipurpose crop, cardoon might be used for feeding ruminants (Cajarville et al., 1999) and/or for medicinal purposes (Kraft, 1997).

In the present study, ‘Altilis 41’ performed better than ‘Gobbo di Nizza’ for all investigated traits, both agronomic and physiological, apart from the number of stalks and plant height, reflecting its suitability for the investigated environment, as previously reported by Acquadro et al. (2012).

Finally, our results confirm the hypothesis reported by Portis et al. (2005) who highlighted that cultivated cardoon can be considered as an annual crop. In fact, Raccuia and Melilli (2007) reported a reduction of cardoon biomass production after the first year of cultivation.

Regarding the effects of different fertilisers on the main physiological traits recorded in the present study, treatment N100 recorded the highest value, that was also highlighted by the highest total N uptake, confirming the usefulness of the SPAD instrument to evaluate the fertilisation treatment, as also previously reported on other crops such as basil, tomato (Ronga, Pane, Zaccardelli, & Pecchioni, 2016) and lettuce (Ronga et al., 2019). The total N uptake ranged between 101.7 and 211.9 kg N ha⁻¹ and similar results were reported by Fernández et al. (2006). On the other hand, compared to the present study, Archontoulis et al. (2010) reported higher values of the total N uptake (on average +50%) and NUE (on average +87%). These differences are putatively
ascribed to the different number of transplanted plants m$^{-2}$. In fact, compared to our work, the number was five times higher.

Finally, in the present study, crop WP showed values ranging from 1.3 and 2.4 g d. w. l$^{-1}$, and similar values were reported by Mantineo et al. (2009). The highest value shown by N100 in the first year depended on its higher yields.

**Relationships between the recorded parameters, fertilisers, cultivars and years**

The correlations between recorded parameters, fertilisation treatments, cultivars and years were studied by means of PCA. Figure 2 reports the biplots of the PCA models calculated taking into account the data (as an average of the three field replicates) recorded during the three years of cultivations. In the PCA model, the two first components represented more than half of the variation in the datasets; PC1 accounts for 48.73% and PC2 for 18.70%.

It was not possible to identify a clear separation into clusters; therefore, the results are described in relation to the most important parameters, such as total dry weight and seed yield. PC1 clearly highlights the negative correlation of the number of stalks, the biomass allocated to stalks plus leaves and NUE with the total dry weight and seed yield, while PC2 is mainly related to the difference between the seed yield and total dry weight.

Total dry weight and seed yield were both on the positive side of PC1 and both were associated with: average weight of heads, dry weight of the heads, ash content, number of heads, WP, plant height, dry weight of stalks + leaves and total nitrogen uptake (Figure 2). Cultivar ‘Altilis 41’ fertilised with N100 and DMS3 was associated with high biomass production. The correlation between seed yield and total dry weight was also already reported by Ierna, Mauro, and Mauromichale (2012b) and by Otttaiano et al. (2017), who also showed a positive correlation between total dry weight and total nitrogen uptake, as reported in the present study (Figure 2). Amendments with DMS3 provided yields comparable to those obtained with mineral fertilisers, suggesting that seed meals can be used as organic nitrogen fertiliser instead of mineral nitrogen fertilisers, as previously suggested by Zaccardelli et al. (2010), who assessed the effects of *B. carinata* and sunflower seed meals on eggplant and endive productions.

**Figure 2.** Ordination biplots of principal component analysis outputs. Labels in the graph indicate the investigated treatments, genotypes and years (red diamonds = 2011, green square = 2012 and blue triangle = 2013) and recorded traits (represented by black circles). 1 = Gobbo di Nizza; 2 = Altilis 41. N100 = 100 kg N ha$^{-1}$; N50 = 50 kg N ha$^{-1}$; C30 = compost 30 t ha$^{-1}$; C15 + N25 = compost 15 t ha$^{-1}$ + 25 kg N ha$^{-1}$; DMS3 = defatted meal of sunflower (*Helianthus annuus* L.) 3 t ha$^{-1}$; DMB3 = defatted meal of *Brassica carinata* (*Brassica carinata* A. Braun) 3 t ha$^{-1}$; N0 = 0 kg N ha$^{-1}$. NS = numbers of stalks; FTDWH = fraction of total dry weight to heads; DWH = dry weight of heads; AWH = average fresh weights of heads; TWD = total dry weight of plant; FTWDSL = fraction of total dry weight to stalks; HP = height of plants; NH = number of heads; DWSL = dry weights of stalks; NUE = nitrogen use efficiency; WP = water productivity; HI = harvest index; SY = seed yield; ASH = ash content; SPAD = estimate content of leaf chlorophyll; TNU = total nitrogen uptake.
The results for year 2012 were in the middle of those recorded in 2011 and 2013, overlapping at some points. This fact confirms the annual variation shown in Table 3. The yearly variability due to different weather condition, as reported in the present study, was also highlighted in other studies conducted in a similar area (Rinaldi, Convertini, & Elia, 2007; Ronga et al., 2015). In the present research, the site was mainly characterised by air temperatures with minimum values ranging from 10.0 to 12.4°C and maximum values ranging from 17.2 to 21.8°C. There was considerable variability in rainfall and its distribution from year to year. The total annual amounts of rainfall recorded in the first, second and third year were 2406 mm, 3597 mm and 588 mm, respectively.

The differences recorded between the two growing seasons were putatively ascribed to the different weather conditions between the three years. In fact, 2013 was drier and colder than 2012 and 2011 (Table 2), probably causing the longest crop cycle (Table 2) and the lowest biomass production (Table 3). In fact, the production of aboveground biomass on C. cardunculus depends on the presence of water in the soil, especially in dry conditions and the adequate fertilisation of the crop. In experiences carried out in several countries of the Mediterranean zone, a high correlation was highlighted between the total rainfall and the total biomass production of cardoon, especially with the rainfall that occurred during spring (González et al., 2004).

**Environmental impacts**

Farmers use huge amounts of energy for agricultural operations, contributing to global warming with the emission of carbon dioxide, methane and nitrous oxide. Therefore, the identification of key strategies to mitigate the production of GHGs is a crucial step (Ntinias, Neumair, Tsadilas, & Meyer, 2016.). From this point of view, the use of organic fertilisers, coming from the valorisation of agricultural by-products, might be one of the possible strategies to increase agricultural sustainability. The results of GWP of the present study based both on 1 ha and on 1 t of total dry weight are reported in Figure 3. The GWP of cardoon production per 1 ha of production is reported in Figure 3(a); in general, the highest impact recorded in the present study was mainly due to GHG emissions to produce fertilisers, followed by direct and indirect emission, and then by agricultural operations (data not shown). Between treatments, N0 had the lowest impact per hectare, followed by N50 and defatted oilseed meals (Figure 3(a)), whilst the highest impact was highlighted by C30.

The GWP of cardoon production per 1 t of total dry weight biomass is reported in Figure 3(b). The impact per total dry weight was obviously lower for unfertilised treatment compared to fertilised ones. Treatment C30 achieved a higher impact (+230% compared to the average impacts of other fertilisers) (Figure 3(b)), due to its low yield (−10%, compared to the average field yield) (Table 3). On the other hand, an interesting result was shown by the impact of defatted oilseed meal of sunflower that was similar to treatment N100, showing about 240 kg CO2 eq per t of d. w.

In particular, among the investigated organic fertilisers, DMS3 compared to N100 treatment showed lower impact per unit area and performed in a similar way when computed per t of harvest d. w., confirming the results reported by Mazzoncini et al. (2015) on vegetable crops. Moreover, our results regarding GWP of synthetic fertiliser, both per cropped area and biomass yield, are comparable with those reported by Cocco et al. (2014) and Razza et al. (2015), who investigated the life cycle assessment of cardoon cropped in Southern Europe and Sardinia and Sicily, respectively.

**Conclusions**

Following three years of experimentation, organic fertilisers could be a sustainable approach for cardoon production in the environment of Southern Italy. Defatted oilseed meal of sunflower may be properly used as organic fertiliser for cardoon production, ensuring yields and GWP comparable with those obtained using mineral nitrogen fertiliser. The present study showed the highest efficacy of defatted oilseed meal of sunflower in sustaining aboveground biomass yield when compared to B. carinata meal and compost and also in terms of GWP. Overall, our findings confirmed the high value of oilseed meals as a sustainable alternative to mineral fertilisers and an important nutrient source also for cardoon production. From the agricultural point of view, the success of the application of defatted oilseed meal of sunflower might increase the agricultural sustainability also along the chain of the green energy. In conclusion, the potential of cardoons as an energy crop in Mediterranean cropping systems under sustainable input management is confirmed in terms of aboveground biomass production. However, future research is required to increase and optimise the yield and GWP of cardoon production, taking into account the effects of plant density and the date of planting. Finally, other investigations regarding soil organic carbon and soil microbial trends might also help to better understand the effects of organic, mineral and organo-mineral fertilisation on cardoon biomass production and sustainability.
Acknowledgements

The authors acknowledge Prof. Sergio Lanteri and Prof. Mauromicale for providing the cultivars of cardoon used, and Bruno D’Onofrio and Tommaso Gallingani, who helped in the management, sampling and data analyses.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the [Mipaaf (Ministero delle Politiche Agricole, Alimentari e Forestali - Italy)]. The trials were performed as the activities of the Project ‘Costituzione e valutazione dell’adattabilità di genotipi di Cynara cardunculus per la produzione di biomassa e biodiesel in ambiente mediterraneo’ (CYNERGIA).

ORCID

Domenico Ronga http://orcid.org/0000-0002-0219-7420

References

Acquadro, A., Portis, E., Scaglione, D., Mauro, R.P., Campion, B., Falavigna, A., … Lanteri, S. (2012). CYNERGIA project: Exploitation of Cynara cardunculus L. as energy crop. Acta Horticulturae, 983, 109–115.

Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J., & Vallejo, A. (2013). The potential of organic fertilizers and water management to reduce N2O emissions in Mediterranean climate cropping systems. A review. Agriculture, Ecosystems & Environment, 164, 32–52.

Angelini, L.G., Ceccarini, L., o Di Nasso, N.N., & Bonari, E. (2009). Long-term evaluation of biomass production and quality of two cardoon (Cynara cardunculus L.) cultivars for energy use. Biomass & Bioenergy, 33, 810–816.

AOAC. (1990). Official methods of analysis (15th ed.). Washington, DC: Association of Official Analytical Chemists.
Archontoulis, S.V., Danalatos, N.G., Struik, P.C., Batzogiannis, D., & Savas, V. (2010). The effect of nitrogen fertilization and supplemental irrigation on seed and biomass productivity of Cynara cardunculus growing in a semi-arid environment in central Greece. In Proceedings of the 18th European Biomass Conference and Exhibition (pp. 273–279). Lyon, France, 3–7 May 2010 doi: 10.5071/18thEUBCE2010-OE4.5.

Beale, C.V., & Long, S.P. (1997). Seasonal dynamics of nutrient accumulation and partitioning in the perennial C4-grasses Miscanthus x giganteus and Spartina cynosuroides. Biomass and Bioenergy, 12, 419–428.

Cajarville, C., Gonzalez, J., Repetto, J.L., Rodriguez, C., & Martinez, A. (1999). Nutritive value of green forage and crop by-products of C. cardunculus. Annales de Zootechnie, 48, 353–365.

Cocco, D., Deligios, P.A., Ledda, L., Sulas, L., Virdis, A., & Carboni, G. (2014). LCA study of oleaginous bioenergy chains in a mediterranean environment. Energies, 7, 6258–6281.

Cossentino, S.L., Copani, V., Mantineo, M., Patané, C., & D’Agosta, G. (2008). Agronomic, energetic and environmental aspects of biomass energy crops suitable for Italian environments. Italian Journal of Agronomy, 7, 81–95.

Cossentino, S.L., Patané, C., Sanzone, E., Copani, V., & Foti, S. (2007). Effects of soil water content and nitrogen supply on the productivity of Miscanthus x giganteus greff et deu. in a mediterranean environment. Industrial Crops and Products, 25, 75–88.

Cotana, F., Cavalaglio, G., Gelosia, M., Coccia, V., Petrozzi, A., Ingles, D., & Pompili, E. (2015). A comparison between SHF and SSSF processes from cardoon for ethanol production. Industrial Crops and Products, 69, 424–432.

Cuevas, P. (2005). Comparative life cycle assessment of biolubricants and mineral based lubricants. (Dissertation). University of Pittsburgh.

Curt, M.D., Sanchez, G., & Fernández, J. (2002). The potential of Cynara cardunculus L for seed oil production in a perennial cultivation system. Biomass and Bioenergy, 23, 33–46.

Fernández, J. (1998). Cardoon, Energy plant species. pp. 113–117. London: James & James Science Publishers Ltd.

Fernández, J., Curt, M.D., & Aguado, P.L. (2006). Industrial applications of Cynara cardunculus L. for energy and other uses. Industrial Crops and Products, 24, 222–229.

Fernandez, J., & Manzanares, P. (1990). Production and utilization of Cynara cardunculus L. Biomass for energy, paper-pulp and food chemistry. In: G. Grassi, G. Gossi, & G. Dos Santos (Eds.), Biomass for energy and industry (pp. 1189–1984). New York, NY, USA: Elsevier Applied Science Publishing.

Foti, S., & Cossentino, S.L. (2001). Culture erbacee annuali e polienniali da energia. Rivista di Agronomia, 35, 200–215.

Foti, S., Mauromicale, G., Raccuia, S.A., Fallico, B., Fanella, F., & Maccaroni, E. (1999). Possible alternative utilisation of Cynara spp. Part I. Biomass, grain yield and chemical composition of grain. Industrial Crops and Products, 10, 219–228.

Furuholt, E. (1995). Life cycle assessment of gasoline and diesel. Resources, Conservation and Recycling, 14, 251–263.

Genovese, C., Platania, C., Venticinque, M., Calderaro, P., Argento, S., Scandurra, S., & Raccuia, S.A. (2015). Evaluation of cardoon seeds presscake for animal feeding. Acta horticulturae, 1147, 323–328.

Gherbin, P., Monteleone, M., & Tarantino, E. (2001). Five years evaluation on cardoon (Cynara cardunculus L. var. altiss) biomass production in a Mediterranean environment. Italian Journal of Agronomy, 5, 11–19.

Gomez, K.A., & Gomez, A.A. (1984). Statistical procedures for agricultural research. New York: John Wiley & Sons.

Gominho, J., Curt, M.D., Lourenço, A., Fernández, J., & Pereira, H. (2018). Cynara cardunculus L. as a biomass and multi-purpose crop: A review of 30 years of research. Biomass and Bioenergy, 109, 257–275.

Gominho, J., Fernández, J., & Pereira, H. (2001). Cynara cardunculus L.—A new fibre crop for pulp and paper production. Industrial Crops and Products, 13, 1–10.

González, J.F., González-García, C.M., Ramiro, A., González, J., Sabio, E., Gañán, J., & Rodríguez, M.A. (2004). Combustion optimisation of biomass residue pellets for domestic heating with a mural boiler. Biomass & Bioenergy, 27, 145–154.

Grammelis, P., Malliopoulou, A., Basinas, P., & Danalatos, N.G. (2008). Cultivation and characterization of Cynara cardunculus for solid biofuels production in the Mediterranean region. International Journal of Molecular Sciences, 9, 1241–1258.

Hesq, Y., & Fossum, J.P. (2014). Calculation of carbon footprint of fertilizer production. Design of a Pilot Plant for the Recovery of Ammonium Salts from WWTP Residual Water, 76.

Ierna, A., Mauro, R.P., & Mauromicale, G. (2012a). Improved yield and nutrient efficiency in two globe artichoke genotypes by balancing nitrogen and phosphorus supply. Agronomy for Sustainable Development, 32, 773–780.

Ierna, A., Mauro, R.P., & Mauromicale, G. (2012b). Biomass, grain and energy yield in Cynara cardunculus L. as affected by fertilization, genotype and harvest time. Biomass and Bioenergy, 36, 404–410.

Ierna, A., & Mauromicale, G. (2010). Cynara cardunculus L. genotypes as a crop for energy purposes in a Mediterranean environment. Biomass & Bioenergy, 34, 754–760.

Intergovernmental Panel on Climate Change (IPCC). (1996). Revised IPCC guidelines for national greenhouse gas inventories: reference manual. London, U.K.

Intergovernmental Panel on Climate Change (IPCC). (2006). Guidelines for national greenhouse gas inventories. In: Agriculture, forestry and other land use (Vol. 4, pp. 1.1–1.21). Japan: Intergovernmental Panel on Climate Change, IGES.

Jimenez-Escrig, A., Dragsted, L.O., Daneshvar, B., Pulido, R., & Saura-Calixto, F. (2003). In vitro antioxidant activities of edible artichoke (Cynara scolymus L.) and effect on biomarkers of antioxidants in rats. Journal of Agricultural and Food Chemistry, 51, 5540–5545.

Kraft, K. (1997). Artichoke leaf extract: Recent findings reflecting effects on lipid metabolism, liver and gastrointestinal tracts. Phytomedicine, 4, 369–378.

Lapuerta, M., Armas, O., Ballesteros, R., & Fenández, J. (2005). Diesel emissions from biofuels derived from Spanish potential vegetable oils. Fuel, 84, 773–778.

Lewandowski, I., & Schmidt, U. (2006). Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach. Agriculture, Ecosystems & Environment, 112, 335–346.

Maccaroni, E., Fallico, B., Fanella, F., Mauromicale, G., Raccuia, S.A., & Foti, S. (1999). Possible alternative utilisation of Cynara spp. Part II. Chemical characterisation of their grain oil. Industrial Crop and Products, 10, 229–237.
Mantineo, M., D’agosta, G.M., Copani, V., Patanè, C., & Cosentino, S.L. (2009). Biomass yield and energy balance of three perennial crops for energy use in the semi-arid Mediterranean environment. *Field Crops Research*, 114, 204–213.

Mazzoncini, M., Antichi, D., Tavarini, S., Silvestri, N., Lazzeri, L., & D’Avino, L. (2015). Effect of defatted oil-seed meals applied as organic fertilizers on vegetable crop production and environmental impact. *Industrial Crop and Products*, 75, 54–64.

Meisterling, K., Samaras, C., & Schweizer, V. (2009). Decision to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production*, 17, 222–230.

Novamont. (2015). Retrieved from http://ec.europa.eu/…/ws-bioeconomy-2015027_catania_bastioli

Ntinas, G.K., Neumair, M., Tsadilas, C.D., & Meyer, J. (2016). Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. *Journal of Cleaner Productions*, 142, 3617–3626.

Ochoa, M.J., & Fandos, A. (2004). Evaluation of vegetable cardoon (*Cynara cardunculus L.*) populations for biomass production under rain-feed conditions. *Acta horticul-turae*, 660, 235–239.

Otaiano, L., Di Mola, I., Impagliazio, A., Cozzolino, E., Masucci, F., Mori, M., & Fagnano, M. (2017). Yields and quality of biomasses and grain in *Cynara cardunculus* L. grown in southern Italy, as affected by genotype and environmental conditions. *Italian Journal of Agronomy*, 12, 375–382.

Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, 31, 55–71.

Piscioneri, I., Sharma, N., Baviello, G., & Orlandini, S. (2000). Promising industrial energy crop, *Cynara cardunculus*: A potential source for biomass production and alternative energy. *Energy Conversion and Management*, 41, 1091–1105.

Portis, E., Barchi, L., Acquadro, A., Macua, J.I., & Lanteri, S. (2005). Genetic diversity assessment in cultivated cardoon by AFLP (amplified fragment length polymorphism) and microsatellite markers. *Plant Breeding*, 124, 299–304.

Raccuia, S.A., Genovese, C., Leonardi, C., Bognanni, R., Platania, C., Calderaro, P., & Melilli, M.G. (2015). Fructose production by *Cynara cardunculus* inulin hydrolysis. *Acta Horticulture*, 1147, 309–314.

Raccuia, S.A., Mainolfi, A., Mandolino, G., & Melilli, M.G. (2004). Genetic diversity in *Cynara cardunculus* revealed by AFLP markers: Comparison between cultivars and wild types from Sicily. *Plant Breeding*, 123, 280–284.

Raccuia, S.A., & Melilli, M.G. (2007). Biomass and grain oil yields in *Cynara cardunculus* L. genotypes grown in a Mediterranean environment. *Field Crops Research*, 101, 187–197.

Raccuia, S.A., & Melilli, M.G. (2010). Seasonal dynamics of biomass, inulin, and water-soluble sugars in roots of *Cynara cardunculus*. *Field Crops Research*, 116, 147–153.

Raccuia, S.A., Piscioneri, I., Sharma, N., & Melilli, M.G. (2011). Genetic variability in *Cynara cardunculus* L. domestic and wild types for grain oil production and fatty acids composition. *Biomass and Bioenergy*, 35, 3167–3173.

Razza, F., Sollima, L., Falce, M., Costa, R.M.S., Toscano, V., Novelli, A., … Raccuia, S.A. (2015). Life cycle assessment of cardoon production system in different areas of Italy. *Acta horticulturae*, 1147, 329–334.

Rinaldi, M., Convertini, G., & Elia, A. (2007). Organic and mineral nitrogen fertilization for processing tomato in Southern Italy. *Acta horticulturae*, 758, 241–248.

Ronga, D., Lovelli, S., Zaccardelli, M., Perrone, D., Ulrici, A., Francia, E., … Pecchioni, N. (2015). Physiological responses of processing tomato in organic and conventional Mediterranean cropping systems. *Scientia horticulturae*, 190, 161–172.

Ronga, D., Pane, C., Zaccardelli, M., & Pecchioni, N. (2016). Use of spent coffee ground compost in peat-based growing media for the production of basil and tomato potting plants. *Communications in Soil Science and Plant Analysis*, 47, 356–368.

Ronga, D., Setti, L., Salvarani, C., De Leo, R., Bedin, E., Pulvirenti, A., … Francia, E. (2019). Effects of solid and liquid digestate for hydroponic baby leaf lettuce (*Lactuca sativa* L.) cultivation. *Scientia horticulturae*, 224, 172–181.

Ronga, D., Zaccardelli, M., Lovelli, S., Perrone, D., Francia, E., Milc, J., … Pecchioni, N. (2017). Biomass production and dry matter partitioning of processing tomato under organic vs conventional cropping systems in a Mediterranean environment. *Scientia horticulturae*, 224, 163–170.

Royal Society (2008). Sustainable biofuels: Prospects and challenges. Policy document1/08.

Scotti, R., Pane, C., & Zaccardelli, M. (2018). Short-term interaction between organic matter from biofuel defatted seed cakes and soil microbiota in two intensive horticulture systems. *European Journal of Soil Biology*, 85, 30–35.

Toscano, V., Sollima, L., Genovese, C., Melilli, M.G., & Raccuia, S.A. (2015). Pilot plant system for biodiesel and pellet production from cardoon: Technical and economic feasibility. *Acta horticulturae*, 1147, 329–334.

USDA. (2006). *Keys to soil taxonomy united state department of agriculture* (10th ed.). Natural Resources Conservation Service (NRCS). Washington, DC: U.S. Government Printing Office.

Zaccardelli, M., Campanile, F., Villecco, D., Galdo, A.D., Lupo, F., & Perrone, D. (2010). Low input nitrogen fertilization in vegetable crops: Biological nitrogen fixation and use of defatted seed meals. *Italus Hortus*, 17, 82–85.

Zaccardelli, M., Villecco, D., Celano, G., & Scotti, R. (2013). Soil amendment with seed meals: Short term effects on soil respiration and biochemical properties. *Applied Soil Ecology*, 72, 225–231.