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Temporary Intercropping With Forage or Industrial Crops Improves Yield and Weed Control in Cardoon (*Cynara cardunculus* var. *altilis* DC)

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ABSTRACT

Cardoon (*Cynara cardunculus* var. *altilis*) is a promising perennial energy crop for Mediterranean areas. Implementing temporary intercropping with selected species during the long establishment phase of the cardoon can enhance ecosystem services by promoting crop diversification, suppressing weeds, and increasing biomass production. A three-year field experiment conducted in Sardinia, Italy, compared three intercropping systems: (i) rocket (*Eruca sativa*), (ii) camelina (*Camelina sativa*), and (iii) hairy vetch (*Vicia villosa)* with a monocropped control. The study assessed the effects of temporary intercropping on weed suppression and cardoon development and production. The biomass production of the intercropped species was also measured. Temporary intercropping reduced weed biomass by 24.2% on average (compared to the control) without hindering cardoon establishment in the first year of cultivation. *V. villosa* and *E. sativa* were the most competitive against the main weeds. *V. villosa* had the highest yield. Temporary intercropping with *V. villosa*, in the following year after its establishment, increased cardoon production by an average of 55.1% compared to the other intercropped species.

1 | Introduction

The agricultural systems of the Mediterranean region are subjected to rapid societal and land use transformations while facing several critical constraints that threaten the productivity and sustainability of traditional cropping systems (Aguilera et al. 2020). The region is highly vulnerable to climate change, experiencing rising temperatures and increasing frequency of extreme weather events such as droughts and heatwaves (Lange 2020; Tramblay et al. 2020).

In this context, there has been growing interest in cultivating perennial biomass crops (Vasilakoglou and Dhima 2014), as they are well-suited to areas with nutrient and water shortages (Elbersen et al. 2017) or marginal land (Todde et al. 2024). Cropping systems based on perennial species like cardoon (*Cynara cardunculus* L. var. *altilis*) typically require a long establishment phase, limiting their attractiveness to farmers due to delayed productivity in monoculture.

Cardoon is a prominent perennial biomass crop expanding in semi-arid Mediterranean regions (Mauromicale et al. 2014) due to its low input requirements, high productivity, low biomass moisture content at harvest, and high calorific value (Mancini et al. 2023). Its biomass has applications in food, energy production, and/or oilseed extraction (Curt et al. 2002). Additionally,

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cardoon's potential for producing pharmacologically or nutritionally active compounds, alongside its suitability for pulp and paper production, has been recognized (Vasilakoglou and Dhima 2014; Curt et al. 2002; Romo-Hualde et al. 2009). Studies on seed oil quality indicate its suitability for biodiesel production and human consumption, given its high linoleic, oleic, palmitic, and stearic acid content (Raccuia and Melilli 2007; Raccuia et al. 2011; Vicente et al. 2006).

Cardoon can attain heights of up to 2.5 m and develop a deep perennial taproot reaching 3 m, along with a rosette diameter of up to 2 m (White 2004). Cultivation typically involved wide inter-row spacing from 40 to 50 cm to 100–120 cm, which exposes the soil to water erosion and to weed infestations during the long establishment phase in the first year of cultivation (Sałata et al. 2023).

Although cardoon is generally known as a competitive species against weeds (Tsiaousi et al. 2019), it still requires weed control during the establishment phase to ensure optimal growth (Deligios et al. 2017). Lack of weed management in the first year of cultivation can result in reduced dry biomass, seed, and oil yields in subsequent years (Vasilakoglou and Dhima 2014). Nevertheless, from the second year onwards, cardoon effectively competes with weeds, reducing the need for further weed control (Fernández et al. 2006; Mauromicale et al. 2014; Scavo et al. 2019).

The need for weed control, along with other agronomic operations required (plowing, fertilization, and sowing), and the low profitability during the first year of cardoon establishment are constraints for the cultivation of this crop, limiting its agronomic potential. Finding alternative management strategies for cardoon in the initial phase is therefore essential for Mediterranean contexts.

One promising approach involves temporary intercropping with species capable of suppressing weeds and producing harvestable biomass, thereby compensating for the limited productivity of young cardoon. Species such as rocket (*Eruca sativa* Mill.), camelina (*Camelina sativa* (L.) Crantz), and hairy vetch (*Vicia villosa* Roth.) emerge as promising candidates for further investigation.

Rocket and camelina are promising crops for sustainable agricultural practices and non-food agricultural product production. Both species have demonstrated effectiveness as intercrops for enhancing soil fertility, either through direct incorporation into soil or indirectly by improving soil structure and microbial diversity within intercropping or cover crop systems (Abdelrahman et al. 2021; Rathore et al. 2022). Rocket's glucosinolates exhibit pathogen-suppressive properties, contributing to soil health (Fahey et al. 2001), while camelina has been shown to increase soil microbial diversity (Georgieva et al. 2024; Pagani et al. 2024). Additionally, intercropped rocket can control nematodes and suppress weeds (Mumtaz et al. 2012). It also holds potential for industrial applications, notably as a biodiesel feedstock, due to its high seed oil content (35%) and erucic acid levels (1%–3%), making its oil suitable for industries requiring high viscosity and elevated smoke points (Lazzeri et al. 2004; Chakrabarti and Ahmad 2009).

Camelina is recognized for its adaptability to marginal lands and low-input cultivation requirements (Iskandarov et al. 2014). With a high seed oil content (35%–45%), predominantly comprising unsaturated fatty acids such as α-linolenic acid (32%–40%), it is a promising crop for biofuel and livestock feed applications (Moser and Vaughn 2010; Zanetti et al. 2020). Its biodiesel properties, comparable to rapeseed and soybean oils, make it suitable for blending with diesel, jet fuel, and industrial lubricants (Fröhlich and Rice 2005; Pecchia et al. 2014; Moser and Vaughn 2010).

Hairy vetch, a large-seeded forage legume, is widely used in the Mediterranean for forage production, fodder, and green manure due to its nitrogen (N)-fixing capacity (BenYoussef et al. 2019). Intercropping hairy vetch enhances the yields of associated cash crops by improving resource use efficiency, including light, water, and nutrients (Rad et al. 2020), and effectively suppresses weed growth (Huang et al. 2017) both in monoculture (Smith et al. 2014) and in crop mix (Lawson et al. 2015).

The hypothesis of this study was that temporary intercropping of cardoon with annual species during its establishment year could improve the agronomic performance of cardoon-based systems in Mediterranean environments by increasing biomass production and suppressing weed growth.

Thus, the three main objectives of the present study were to assess, at the field scale, the impact of temporary intercropping on (i) weed control and competition, (ii) the qualitative and quantitative yield of cardoon during its first three cropping years, and (iii) the biomass production of the three intercropped species.

2 | Materials and Methods

2.1 | Site Description

The field experiment was carried out in Ottava, Sassari, Italy (40° 46′ 48.46″ N; 8° 29′41.07″ E), at an altitude of 81 m a.s.l. from 2020 to 2023.

The soil is classified as Lithic Xerorthents according to the USDA Soil Taxonomy; it is well-drained, with a sandy clay loam texture and a relatively high organic matter content (Table 1).

The climate is characterized as hot-dry summer Mediterranean (Csa) according to the Köppen-Geiger climate classification map (Kottek et al. 2006). The long-term (1981–2018) average annual rainfall was 512 mm according to data recorded daily from the weather station located at the experimental field. During the experimental period (Figure 1), total rainfall from October to December 2020 was 315 mm. Annual rainfall measured 573 mm in 2021, 600 mm in 2022, and 357 mm from January to September 2023. Monthly average maximum and minimum air temperatures from October to March over the three experimental years (2020–2023) were 18°C and 9°C, respectively; from April to September, averages were 28°C and 16°C.

2.2 | Experimental Layout and Crop Management

The three-year research experiment (2020/21—first year, 2021/22—second year, 2022/23—third year) was laid out as a randomized complete block design with four replicates.

The experiment included four treatments where cardoon (*C. cardunculus* var. *altilis* DC 'Bianco Avorio') was intercropped with (i) *V. villosa* Roth cv Haymaker (Vv), (ii) *E. sativa* Miller cv Nemat (Es), and (iii) *C. sativa* (L.) Crantz cv Italia (Cs), along with a control with no intercropping (NC). Each plot measured 100 m^2 in size (20 m × 5 m).

TABLE 1 | Physical–chemical characteristics of the upper soil layers (0–20 and 20–40 cm depths) in the experimental site, based on pre-trial analysis.

	Soil depth (cm)	
Soil characteristics	**0–20**	**20–40**
Sand > 100 μ ($g\,kg^{-1}$)	444	455
Sand 100–50 μ ($g\,kg^{-1}$)	168	170
Silt 50–20 μ ($g\,kg^{-1}$)	66	67
Silt 20–2 μ ($g\,kg^{-1}$)	118	99
Clay < 2 μ ($g\,kg^{-1}$)	204	210
Electrical conductivity (1:5) (μS/cm 25°C)	97	102
pH	8.5	8.5
Carbonates ($g\,kg^{-1}$)	6.2	6.1
Active Ca ($g\,kg^{-1}$)	99	112
Organic Carbon ($g\,kg^{-1}$)	22	27
Organic matter ($g\,kg^{-1}$)	38	47
Total N ($g\,kg^{-1}$)	0.7	1.1

Prior to sowing, the field was plowed to a 0.3 m depth and fertilized with 418 $kg\,ha^{-1}$ of Phosfone 22 (Nutrien, IT), providing 92 $kg\,ha^{-1}$ of P_2O_5 and 138 $kg\,ha^{-1}$ of Entec 26 (Eurochem Agro, IT), corresponding to 37 $kg\,ha^{-1}$ of N, followed by harrowing seedbed preparation. Cardoon was sown on October 22, 2020, at a rate of 3.2 $kg\,ha^{-1}$, corresponding to 6 rows per plot, spaced 0.75 m, aiming to achieve a target density of 8 plants m^{-2}.

The intercropped species were sown concurrently at rates of 10 $kg\,ha^{-1}$ for both camelina and rocket and 75 $kg\,ha^{-1}$ for hairy vetch. All the intercropped species were sown in 4 rows between the cardoon rows.

The seedbed was irrigated on the 9th of November 2020 to speed up germination. After that, the experiment was run under rain-fed conditions. The intercropped species used for seed production (camelina and rocket) were harvested at seed maturity on April 6, 2021 (Harvest Time 1—HT1) for camelina and on May 12, 2021 (Harvest Time 2—HT2) for rocket. Hairy vetch was harvested at the 20%–30% flowering stage during HT1 for forage production.

At HT1, the biomass of the intercropped species was harvested using a double-blade cutter with a work front exceeding 0.75 m, simultaneously cutting cardoon at about 100–150 mm height. During HT2, only weeds covering the inter-row of NC and rocket were harvested (Figure 2).

2.3 | Plant Density, Phenology, and Aboveground Biomass

In the first experimental year (2020/2021), both cardoon and the intercropped species were monitored on 5 sampling dates (November 11, 2020; November 30, 2020; December 15, 2020;

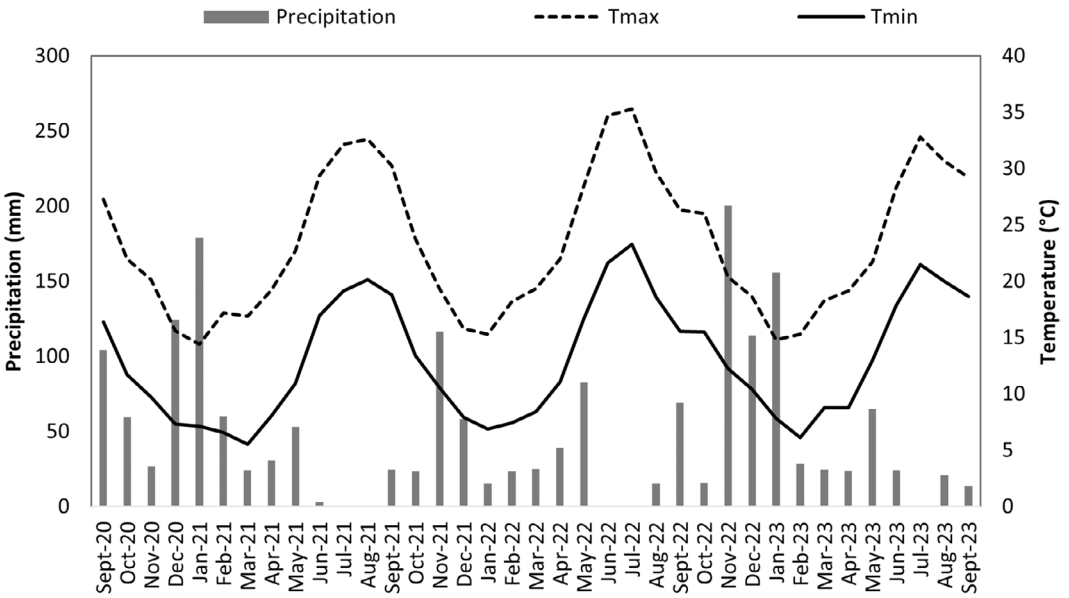


FIGURE 1 | Monthly precipitation (mm) and air maximum (T max) and minimum (T min) temperature (°C) during the experimental period in the Ottava experimental site, Sardinia (Italy).

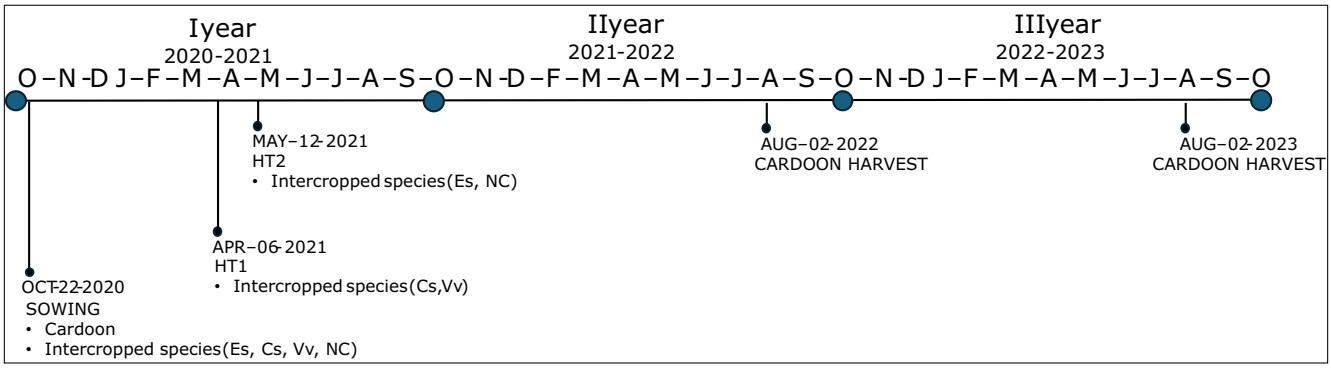


FIGURE 2 | Sowing (October 22, 2020) and harvest timelines. HT1: Harvest time for Cs and Vv; HT2: Harvest time for Es and NC in the first (I) experimental year (2020/2021) involving cardoon and the intercropped species: Cs (*Camelina sativa*), Es (*Eruca sativa*), and Vv (*Vicia villosa*). NC means not cultivated inter-row. Harvest timing of cardoon in the second (II) (2021/2022) and third (III) year (2022/2023).

January 1, 2021; June 6, 2021). Observations included plant density (n. plants m^{-2}), height, and phenology, evaluated according to the BBCH scale: cardoon was assessed following Archontoulis et al. (2010), camelina following Martinelli and Galasso (2011), and hairy vetch and rocket following Meier (2001). Data collection for cardoon involved two sampling areas per plot, each comprising 2 adjacent rows measuring 5 m in length, situated 2 m apart and 4 m from the plot's short edge. For the intercropped species, 20 plants were assessed in the same above-mentioned sampling areas.

The aboveground biomass of the intercropped species was sampled on three sampling dates during the first year. The first sampling occurred at winter's end on February 17, 2021 (Winter End—WE), involving all three intercropped species. Subsequent sampling took place on April 6, 2021 (HT1), again including all species, and on May 12, 2021 (HT2), focusing solely on rocket. Biomass was harvested from a 0.75 m × 0.75 m sampling area situated between two consecutive rows of cardoon. In each sampling area, the following data were recorded: percentage cover of the intercropped species, plant density of the intercropped species, percentage cover of each of the weed species, and weed plant density (only for the first year). Harvested biomass was split between the intercropped species and weeds to determine each species' contribution to the total biomass dry weight. Weeds were categorized and weighed by botanical family. The biomass of each intercropped species was split into its components (seed, leaves, stems, siliques, or legumes), which were weighed separately. All biomass samples were oven-dried at 65°C until a constant weight was achieved to determine dry matter (DM) content. For each date, the same protocol was applied to NC treatment, where only weed biomass was assessed due to the absence of intercropped species.

During the second (2021/2022) and third (2022/2023) experimental years, weed sampling in the inter-rows was conducted on May 10, 2022, and May 11, 2023. Sampling utilized the same 0.75 m × 0.75 m area as in the first year to measure the percentage cover of all weeds and the dry weight of each botanical family. The cardoon plant density was measured before harvesting on July 26, 2022, and August 2, 2023.

In both experimental seasons, the cardoon yield was determined at harvest time on August 2 by randomly collecting five representative plants from each plot. The plants were partitioned into stems, flower heads, seeds, and residues. The yield components were averaged per plant and multiplied by plant density to calculate the cardoon yield per unit area for each plot.

2.4 | Species Diversity and Community Similarity Indices

The differences in the diversity of the weed community among intercropping systems were analyzed using the Shannon-Wiener diversity index (H), the Simpson index (D) (Simpson 1949; Jost 2006), and Pielou's evenness index (J) (Sienkiewicz 2010). While both H and D quantify community diversity, they respond differently to species composition changes. H is more sensitive to changes in the importance of rare species, whereas D is more responsive to changes in the proportional abundance of the most common species (Nagendra 2002).

The H index was calculated by determining the proportion of individuals of each species relative to the total number of individuals, multiplying these proportions by their natural logarithm, and summing the results across all species. Since the result is a negative number, the absolute values were used, with higher H values indicating greater species diversity (Jost 2006). The D index measures species dominance within the community, representing the probability that two randomly selected individuals from the community will belong to the same species. For the D index, values range from 0 (infinite diversity) to 1 (no diversity). Therefore, a higher D value corresponds to lower species diversity (Sienkiewicz 2010).

The J index quantifies the uniformity of species abundance, ranging from 0 (complete dominance by one species) to 1 (equal abundance among species), reflecting community heterogeneity (Jost 2006).

All indices were calculated for each experimental replicate using the following equations:

Shannon-Wiener index (H)

$$H = -\sum_{i=1}^{s} pi \ln(pi)$$

Simpson's index (D)

$$D = \sum_{i=1}^{s} pi^2$$

Pielou's evenness index (J)

$$J = \frac{H'}{\ln(S)}$$

where p is the proportion of individuals of a particular species (n) divided by the total number of individuals (N), ln denotes the natural log, Σ is the sum of the calculations, and s represents the number of species.

2.5 | Response Comparison Index

2.5.1 | Cardoon vs. Inter-Row' Competition

The response comparison index (RCI) (Campiglia et al. 2014) was used to evaluate whether the intercropped species provided a competitive advantage to cardoon or competed with cardoon. This index is derived from the relative response indices for the species present in the inter-row (both weeds and intercropped species) (RRI_I) and cardoon crops (RRI_C), as outlined by Williams et al. (1998). The RCI was calculated as follows:

$$RCI = RRI_I - RRI_c \quad (1)$$

RRI_I was calculated as:

$$RRI_I = (CBM_I - TBM_I) / (CBM_I + TBM_I) \quad (2)$$

where CBM_I represents the weed aboveground biomass in the control plot (NC) and TBMI denotes the aboveground biomass of both weeds and intercropped species in each treatment (Cs, Es, Vv). RRI_w values less than 0 indicate that the treatment promotes inter-row species biomass more than the control.

Similarly, RRI_c was calculated as:

$$RRI_c = (CBM_c - TBM_c) / (CBM_c + TBM_c) \quad (3)$$

CBM_c represents the total aboveground biomass of the cardoon in the control plot (NC), and TBM_c represents the total aboveground biomass of the cardoon in the intercropped plots. RRI_c values below 0 indicate that the given treatment yielded more cardoon biomass than the control.

RCI provides insight into cardoon—inter-row competitive interactions under each treatment. Positive RCI values indicate that cardoon is more competitive than the inter-row species, while negative RCI values indicate that the inter-row species are more competitive than cardoon.

2.5.2 | Intra-Row Competition

The RCI index was further used to assess whether intercropped species competed with weeds, thereby reducing their presence (RCI_2). The calculation was performed as follows:

$$RCI2 = RRI_w - RRI_c \quad (4)$$

RRI_W was calculated as:

$$RRI_w = (CBM_w - TBM_w) / (CBM_w + TBM_w) \quad (5)$$

where CBM_w represents the total aboveground biomass in the control plot (NC) and TBM_w denotes the total aboveground biomass (weeds and CCs) in each treatment (Cs, Es, Vv).

RRIc was calculated as described in Equation 3. In this case, CBMc refers to the total weed biomass in the control plot (NC), while TBMc represents the weed biomass in each intercropping treatment plot (Cs, Es, Vv).

2.6 | Statistical Analysis

Descriptive statistics were computed for all datasets to characterize data distribution. The normality and homoscedasticity of residuals were checked using the Shapiro–Wilk test (Shapiro and Wilk 1965) and the Bartlett test (Snedecor and Cochran 1989). Data were log-transformed when assumptions were violated (Gomez and Gomez 1984).

Linear mixed models, implemented with the "lmer()" function in R software (Bates et al. 2015), included treatment and time as fixed factors and the block as a random effect (Onofri et al. 2016). These models analyzed (i) cardoon biometry and biomass at each sampling date in the first year (WE, HT1, HT2); (ii) biomass production of the intercropped species considering different yield components: leaves, siliques/legumes, stems, and seeds (WE, HT1, HT2); (iii) cardoon density (plants m^{-2}) and phenological stages at each of the five sampling dates in the first year and at harvest time of the second and third years; and (iv) cardoon biomass production for each yield component (stem, flower head, seeds, and residues) and weed biomass for each botanical family in the second and third years.

Mixed Effect Models using the 'lme4' package in R software with Gaussian distributions were used to analyze both the response comparison indices (RCI) and the weed diversity indices (H, D, J) across 3 sampling dates (time) in the first year (February 17, 2021; April 6, 2021; May 15, 2021). Treatment, time, and their interaction were used as fixed factors, and block as a random factor.

The post hoc comparisons were conducted using the 'emmeans' package (Lenth et al. 2021) for estimated marginal means, combined with 'rstatix' or 'multcomp' packages (Kassambara 2019), employing Sidak for multiple contrasts.

3 | Results

3.1 | Performance of the Temporary Intercropping System During the Cardoon Establishment

3.1.1 | Cardoon Biometric and Phenological Features

Plant height and BBCH were used as indicators of cardoon competitive ability. In the first year, at WE, cardoon was significantly

taller (> +80 mm) under Vv treatment than under all the others (Table 2). Similarly, at HT1, the cardoon was significantly taller (> +118 mm) under Vv, whereas it was lowest under Cs. Leaf area per plant showed no significant treatment differences (Table 2) but was closely correlated to plant height ($R^2 = 0.75$; $p = 0.005$) until HT1; by HT2, the cardoon plants were already senescent.

The cardoon biomass was not significantly affected by treatments.

The cardoon phenology was not significantly influenced by the intercropping, achieving mode BBCH score 12 at 27 and 39 DAS and 14 at 117 DAS. Cardoon density from November 2020 until June 2021 did not show significant differences among treatments or sampling dates, with an average of 4 plants m^{-2}.

3.1.2 | Productivity of the Intercrops

By the end of the winter period (WE, Figure 3) in the first year, the rocket showed the highest total biomass (2135 ± 419 standard deviation—s.d. kg ha^{-1} DM), with 78.8% comprising stems and the remaining portion being the leaves. Camelina showed the lowest biomass yield (1293 ± 279 s.d. kg ha^{-1} DM), made up of 81.7% stems, 9.5% siliques, and 8.7% leaves. Hairy vetch produced

TABLE 2 | Average cardoon plant height (mm), leaf area per cardoon plant (LS, mm^2), and cardoon aboveground biomass (g m^{-2} dry matter) at the three sampling times in the first experimental year (2021) (± standard deviation): winter end (WE) in February, harvest time in April (HT1), and harvest time in May (HT2).

	Plant height (mm)			Leaf area (mm^2)			Biomass (g m^{-2} d.m.)		
Treatment	**WE**	**HT1**	**HT2**	**WE**	**HT1**	**HT2**	**WE**	**HT1**	**HT2**
Cs	165 ± 90b	198 ± 28b		5490 ± 191	6780 ± 262		1.7 ± 0.09	1 ± 0.1	
Es	165 ± 17b	263 ± 32ab	282 ± 56	4420 ± 136	9540 ± 526	1430 ± 722	2.0 ± 0.2	2.0 ± 0.2	2.9 ± 0.4
NC	145 ± 16b	257 ± 9 ab	296 ± 103	5740 ± 160	11,840 ± 687	1790 ± 107	3.5 ± 0.1	2.9 ± 0.6	4.5 ± 0.9
Vv	249 ± 27a	381 ± 50a		7780 ± 201	11,660 ± 297		2.8 ± 0.1	3.9 ± 0.3	

Note: Means followed by the same letters indicate no significant differences among treatments (Sidak post hoc test, $p \leq 0.05$).

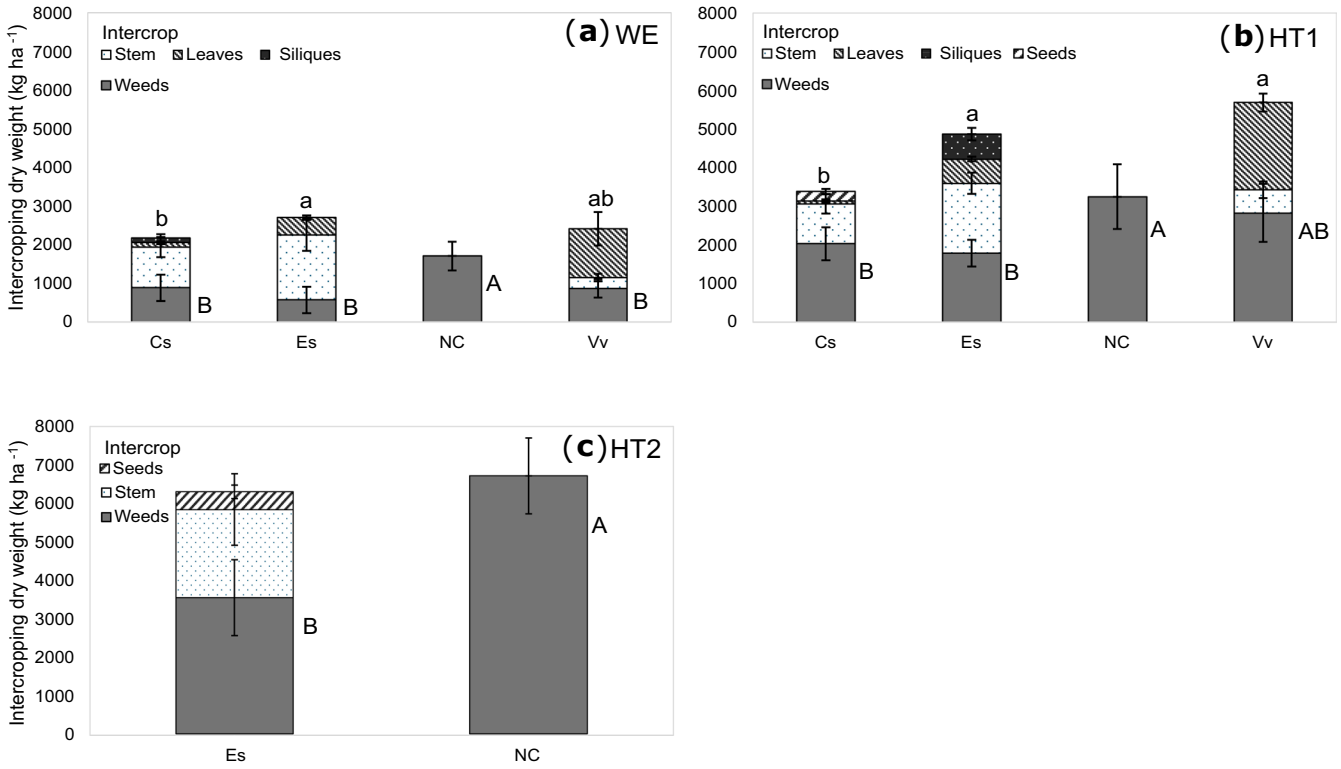


FIGURE 3 | Dry weight production (kg ha^{-1}) of each intercropped species and weeds under each treatment (Cs- *Camelina sativa*, Es- *Eruca sativa*, Vv- *Vicia villosa*, and NC- not cultivated inter-row) calculated in each intercrop treatment on the three sampling dates: WE—winter end February 2021 (a); HT1—harvest time April 6, 2021 (b); HT2—harvest time May 2, 2021 (c) (Time). Different lowercase letters indicate statistically significant differences in intercropped species production among treatments. Uppercase letters represent statistically significant differences in weed biomass production among treatments (Sidak post hoc test, $p \leq 0.05$). Vertical bars, standard error.

an intermediate biomass (1544 ± 442 s.d. kg ha^{-1} DM), not significantly different from the other intercropped species. Weed biomass under NC averaged 1709 ± 374 s.d. kg ha^{-1} DM, significantly higher than under all the other treatments (774 ± 177 s.d. kg ha^{-1} DM on average).

At the first harvest time (HT1, Figure 3), when both camelina and hairy vetch reached maturity, hairy vetch biomass was 2863 ± 322 s.d. kg ha^{-1} DM (78.5% leaves and 21.5% stems), not significantly different from eruca (3090 ± 325 s.d. kg ha^{-1} DM, 58.5% stem, 21.0% siliques, and 20.5% leaves); camelina produced 1355 ± 269 s.d. kg ha^{-1} DM, primarily stems (76.6%) and leaves (5.7%). Seeds, the most economically valuable fraction, amounted to 241 ± 66 s.d. kg ha^{-1} DM, representing 17.8% of the total biomass. Weed biomass under NC was significantly higher (3255 ± 840 s.d. kg ha^{-1} DM) than under all the other treatments (2217 ± 591 s.d. kg ha^{-1} DM on average).

In May, at the HT2, rocket seed yield was equal to 469 ± 180 s.d. kg ha^{-1} DM, exceeding camelina seed yield at HT1, and produced a total biomass of 2796 ± 963 s.d. kg ha^{-1} DM. Weed biomass under NC reached 6819 ± 999 s.d. kg ha^{-1} DM, being higher than under Es (3600 ± 900 s.d. kg ha^{-1} DM) (Figure 3).

3.1.3 | Weed Diversity and Density

Vv treatment exhibited the lowest *H* and *J* indices and the highest *D* index at WE and HT1. Cs showed an intermediate *D* value only at HT1; otherwise, it performed as NC and Es. At HT2, only the *D* index was significantly higher under Es compared to NC (Table 3).

Weed density and species composition were significantly influenced by the treatment across phenological stages (Tables 4–6). The highest weed density was recorded under NC, while the lowest was under Vv. Intermediate densities were observed when inter-rows were seeded with camelina (Cs) and rocket (Es). Across phenological stages, the highest weed plant densities were observed under NC, whereas the highest weed suppression was registered under Es and Vv, representing some 2/3 of the inter-row plant community. *Anagallis arvensis* was the most prevalent weed species across all treatments, especially under NC. Its dominance was reduced in intercropped treatments, with significant contributions from species such as *Glebionis coronaria* or *Raphanus raphanistrum*, depending on the treatment. Under Vv, the weed community was less diverse than under Cs and Es and was dominated by the main intercropped species *V. villosa*, with minor contributions from species such as *Papaver rhoeas* and *G. coronaria*. At later stages (Table 6), a drastic reduction of weed plant density was registered under Es. High weed plant densities, with diverse communities dominated by *G. coronaria*, *A. arvensis*, and *R. raphanistrum*, were kept under NC.

3.1.4 | Competition Indices

3.1.4.1 | Cardoon vs. Inter and Intrarow Competition. The RCI index at WE and HT1, used to evaluate whether intercropped species conferred a competitive advantage or hindered cardoon growth, showed no significant differences among treatments, sampling dates, or their interactions, with an average value of 0.05 ± 0.01 s.d. The RCI_2 index, used to evaluate whether intercropped species reduced weed presence, was significantly affected by the interaction between treatment and sampling time at WE and HT1. Specifically, the highest values were observed under Vv and Cs for HT1 (−0.22 ± 0.03 s.d.), while the lowest was recorded under Es for WE (−0.70 ± 0.08 s.d). The remaining treatments exhibited intermediate values, which did not differ significantly from either of the above-mentioned extremes (−0.40 ± 0.09 s.d).

At HT2, RCI and RCI_2 under ES were 0.20 ± 0.05 s.d. and 0.10 ± 0.01 s.d., respectively.

TABLE 3 | Average Shannon Index (*H*), Evenness (*J*), and Simpson Index (*D*) (± standard deviation) calculated in each intercrop treatment (Cs—*Camelina sativa*, Es—*Eruca sativa*, Vv—*Vicia villosa*, NC—not cultivated inter-row) in the three sampling dates of the first year of cardoon establishment (WE— winter end in February 2021; HT1—first harvest time in April 2021; HT2—second harvest time in May 2021).

Time	Treatment	*H*	*J*	*D*
WE	Cs	2.6 ± 0.5a	0.3 ± 0.0a	0.09 ± 0.1b
	Es	2.6 ± 1a	0.2 ± 0.1a	0.07 ± 0.5b
	NC	2.7 ± 0.5a	0.3 ± 0.05a	0.04 ± 0.02b
	Vv	1.8 ± 0.3b	0.2 ± 0.06b	0.70 ± 0.03a
HT1	Cs	1.9 ± 0.5ab	0.2 ± 0.08a	0.20 ± 0.4ab
	Es	2.2 ± 0.5a	0.2 ± 0.07a	0.08 ± 0.01b
	NC	2.4 ± 0.7a	0.2 ± 0.08a	0.04 ± 0.01b
	Vv	1.6 ± 0.3b	0.1 ± 0.05b	0.90 ± 0.05a
HT2	Es	1.9 ± 0.5	0.2 ± 0.08	0.90 ± 0.1
	NC	1.8 ± 0.3	0.2 ± 0.04	0.02 ± 0.01

Note: Means followed by the same letters indicate no significant differences between treatments within harvest time (Sidak post hoc test, $p \leq 0.05$).

TABLE 4 | Average (maximum—minimum) weed plant density and percentage (%) of each species relative to the total weed plant density in each intercrop treatment (Cs—*Camelina sativa*, Es—*Eruca sativa*, Vv—*Vicia villosa*, NC—not cultivated inter-row) identified in the seed bank assays, February 2021.

	Plant density (no. plants m^{-2})				% Total			
Species	**Cs[a]**	**Es[a]**	**Vv[a]**	**Nc[a]**	**Cs**	**Es**	**Vv**	**NC**
Camelina sativa	174 (107–232)	0	0	0	60.3	0.0	0.0	0.0
Glebionis coronaria	21 (5–38)	51 (11–146)	15 (11–27)	21 (11–27)	7.3	14.9	5.0	14.1
Raphanus raphanistrum	16 (7–25)	1 (0–5)	16 (7–21)	34 (14–64)	5.4	0.4	5.1	23.6
Papaver rhoeas	2 (0–4)	3 (0–11)	1 (0–4)	3 (0–11)	0.6	0.9	0.3	1.8
Anagallis arvensis	67 (0–116)	50 (36–66)	48 (0–80)	69 (43–100)	23.2	14.5	15.6	47.5
Fumaria officinalis	1 (0–4)	0	1 (0–4)	4 (2–7)	0.5	0.0	0.3	3.1
Vicia villosa	2 (0–9)	0	224 (139–373)	0	0.8	0.0	73.2	0.0
Ammi majus	4 (0–16)	3 (0–11)	1 (0–4)	3 (0–9)	1.4	0.8	0.3	2.1
Persicaria maculosa	0	1 (0–4)	0	7 (2–11)	0.2	0.3	0.0	4.9
Melilotus indicus	1 (0–5)	8 (4–11)	0	1 (0–4)	0.5	2.3	0.0	0.9
Eruca sativa	0	224 (139–373)	0	0	0.0	65.0	0.0	0.0
Coronilla scorpioides	0	1 (0–5)	0	3 (0–11)	0.0	0.4	0.0	1.8
Lolium rigidum	0	2 (0–7)	0	0	0.0	0.5	0.0	0.0
Hordeum leporinum	0	0	0	0	0.0	0.0	0.1	0.0

[a]Maximum and Minimum values are reported in brackets to illustrate the range variability among replicates (Raimondi et al. 2024).

3.2 | Intercropping Legacy Effect on Weeds, and Cardoon Development and Yield

3.2.1 | Cardoon Density, Biometry, and Phenology

No significant differences among treatments were observed for cardoon height, density, and phenology in the second and third years. However, cardoon height was, on average, higher (1170 ± 90 s.d. mm) in the third year than in the second (573 ± 67 s.d. mm). The cardoon density averaged 3.2 ± 0.9 s.d. plants m^{-2} in both years.

3.2.2 | Cardoon Biomass Yield Components

The total cardoon yield (Figure 4) in the second year was significantly higher under Vv (total 13.8 Mg ha^{-1} DM) compared to NC (5.9 Mg ha^{-1} DM.), while intermediate production was registered under both Cs and Es (9.3 Mg ha^{-1} DM). Cardoon seed production was also higher under Vv (0.71 Mg ha^{-1} DM) than the average of 0.43 Mg ha^{-1} DM in the other treatments.

When hairy vetch was used for intercropping (Vv), the cardoon biomass at harvest time consisted of 37.3% crop litter, 31.3% stems, 26.9% flower heads, and 4.5% seeds. Under NC, the crop litter was the largest component (38%), followed by stems (30%), flower heads (26%), and seeds (6%). Under Cs and Es, cardoon biomass was composed of 38.8% crop litter, 29.3% stems, 28% flower heads combined, and 4.6% seeds (0.52 Mg ha^{-1} DM).

In the third experimental year, the total cardoon biomass yield was significantly higher under all intercropped treatments (11.3 Mg ha^{-1}) compared to NC (9.6 Mg ha^{-1}). Under the intercropped treatments, crop litter represented 36.2% of the total biomass, flower heads 33.5%, and stems 25.5%, with seeds averaging 4.3% (0.51 Mg ha^{-1} DM). Under NC, the cardoon yield component showed a similar distribution: crop litter 34.7%, flower heads and stems 29.8%, and seeds 4.2%.

3.2.3 | Weed Community

In the second experimental year, weed biomass under NC was the highest (4872 ± 1789 s.d. kg ha^{-1} DM), significantly exceeding the values observed under Vv and Es (averaging 3354 ± 1054 s.d. kg ha^{-1} DM). Cs exhibited intermediate weed biomass (4031 ± 1206 s.d. kg ha^{-1} DM), not significantly different from other treatments. Under NC, weed biomass contributed 45.2% of the total biomass production of the cropping system, which includes all cardoon yield components plus total weed biomass. Conversely, weed biomass accounted for 19.8%, 26.9%, and 29.4% of the total biomass production of the cropping system under Vv, Es, and Cs, respectively.

Under NC, 35.3% of the total biomass was made by Compositae, 9.5% by Fabaceae, 0.6% by Poaceae, 0.5% by Apiaceae, and 1.4% by other families. Under Vv, weeds consisted of 27.8% Cruciferae, 10% Poaceae, 4.8% Compositae, 2% Fabaceae, 1% Apiaceae, and 2.5% other families. Under Es, 30.3% were Compositae, 8.3% Poaceae, 3.7% Cruciferae, 2.2% Apiaceae, and the remaining 9.8%

TABLE 5 | Average (maximum—minimum) weed plant density and percentage (%) of each species relative to the total weed plant density in each intercrop treatment (Cs—*Camelina sativa*, Es—*Eruca sativa*, Vv—*Vicia villosa*, and NC—not cultivated inter-row) identified in the weed survey, April 2021.

	Plant density (no. plants m^{-2})				% Total			
Species	**Cs**[a]	**Es**[a]	**Vv**[a]	**NC**[a]	**Cs**	**Es**	**Vv**	**NC**
Camelina sativa	213 (141–310)	0	0	0	50.4	0.0	0.0	0.0
Eruca sativa	0	225 (155–307)	0	0	0.0	65.9	0.0	0.3
Vicia villosa	0	0	225 (154–306)	0	0.0	0.0	70.6	0.0
Glebionis coronaria	28 (7–69)	17 (2–28)	26 (7–62)	20 (12–32)	6.7	5.1	8.1	13.5
Raphanus raphanistrum	10 (7–12)	19 (7–28)	12 (2–21)	21 (14–30)	2.3	5.5	3.8	13.8
Papaver rhoeas	4 (0–11)	3 (0–7)	35 (2–89)	7 (2–14)	1.1	0.8	11.0	4.5
Anagallis arvensis	151 (137–187)	66 (53–82)	13 (0–53)	80 (54–112)	35.8	19.4	4.2	53.6
Fumaria officinalis	0	0	0	2 (0–5)	0.0	0.0	0.0	1.2
Ammi majus	6 (2–11)	5 (2–9)	4 (2–7)	8 (4–18)	1.4	1.6	1.3	5.7
Persicaria maculosa	6 (2–11)	1 (0–3)	1 (0–4)	5 (0–7)	1.4	0.4	0.4	3.6
Melilotus indicus	2 (0–3)	0	0	2 (0–8)	0.4	0.1	0.0	1.5
Coronilla scorpioides	1 (0–4)	0	0	1 (0–4)	0.2	0.1	0.1	0.9
Verbascum sp.	0	0	0	0	0.1	0.0	0.0	0.0
Cynodon dactylon	1 (0–4)	0	0	0	0.3	0.0	0.0	0.0
Lolium rigidum	0	2 (2–4)	0	1 (0–3)	0.0	0.7	0.0	0.6
Convolvolus arvensis	0	1 (0–3)	0	0	0.0	0.3	0.0	0.0
Beta vulgaris	0	0	0	0	0.0	0.1	0.0	0.0
Medicago polimorpha	0	0	0	0	0.0	0.0	0.0	0.3
Avena barbata	0	0	0	0	0.0	0.0	0.0	0.3
Malva sp.	0	0	0	0	0.0	0.0	0.0	0.3
Triticum aestivum	0	0	0	0	0.0	0.0	0.1	0.0
Sonchus oleraceus	0	0	1 (0–3)	0	0.0	0.0	0.3	0.0

[a]Maximum and Minimum values are reported in brackets to illustrate the range variability among replicates (Raimondi et al. 2024).

were from other families. Under Cs, 18.3% of the biomass was Compositae, 17% Graminaceae, and 3.6% Apiaceae. Crop litter contributed approximately to half of the total aboveground biomass across treatments: 52.6% under NC, 48.7% under Vv and Es, and 60.5% under Cs.

In the third experimental year, similarly to the previous one, weed biomass was highest under NC (4325 ± 1327 s.d. kg ha^{-1} DM), followed by Cs (4156 ± 1456 s.d. kg ha^{-1} DM), and Vv and Es (3451 ± 1389 s.d. kg ha^{-1} DM on average). Weed biomass accounted for 31.1% of the total biomass production under NC and 26.2% under Cs, while contributing 24.1% and 20.9% of the total biomass production under Vv and Es, respectively.

Under NC, weeds comprised 40.6% Compositae, 4.3% Fabaceae, 2.7% Poaceae, 1.3% Apiaceae, and 3.6% other families. Under Vv, Compositae accounted for 22.2%, Fabaceae 12.1%, Poaceae and Apiaceae 3.15% each, and other families 4.1%. Under Es, Compositae contributed 36.4%, Poaceae 6.3%, Apiaceae and Poaceae 5.1% each, Apiaceae 3.8%, and other families 5.3%. Under Cs, Cruciferae dominated (32.9%), followed by Fabaceae (7.6%), Compositae (6.1%), Poaceae and Apiaceae (1.5% each), and other families (5.2%).

4 | Discussion

This study aimed to evaluate the effects of temporary intercropping on weed suppression during the cardoon establishment phase, cardoon yield over its first 3 years, and the productivity of three intercropped species.

Temporary intercropping reduced weed biomass by over 50% without affecting cardoon establishment in the first year. Intercropping with hairy vetch significantly enhanced cardoon biomass and seed production in the second and third years of cardoon development. Intercropping also proved to have the potential to generate income from seed and forage sales, making its introduction in the first year of cardoon cultivation a financially viable practice for farmers.

TABLE 6 | Average (maximum—minimum) weed plant density (plant m^{-2}) and percentage (%) of each species relative to the total weed plant density in each intercrop treatment (Cs—*Camelina sativa*, Es—*Eruca sativa*, Vv—*Vicia villosa*, and NC—not cultivated inter-row) identified in the seed survey, May 2021.

	Plant density (no. plants m^{-2})		% Total	
Species	**Es[a]**	**NC[a]**	**Es**	**NC**
Eruca sativa	283 (210–366)	0.0	93.8	0.0
Glebionis coronaria	0	31 (12–43)	0.0	36.7
Raphanus raphanistrum	0	17 (4–44)	0.0	19.7
Papaver rhoeas	1 (0–2)	1 (0–4)	0.4	1.1
Anagallis arvensis	12 (0–30)	22 (14–30)	4.0	26.1
Ammi majus	0	3 (0–4)	0.0	3.2
Persicaria maculosa	2 (0–3)	4 (0–11)	0.6	4.8
Melilotus indicus	0	1 (0–2)	0.0	1.1
Coronilla scorpioides	0	3 (0–7)	0.1	3.7
Lolium rigidum	0	0	0.0	0.5
Convolvulus arvensis	2 (0–9)	0	0.7	0.0
Beta vulgaris	0	2 (0–7)	0.0	2.1
Medicago polimorpha	0	0	0.1	0.5
Sonchus oleraceus	0	0	0.1	0.0
Avena barbata	0	0	0.0	0.5

[a]Maximum and Minimum values are reported in brackets to illustrate the range variability among replicates (Raimondi et al. 2024).

In the first year (cardoon seedling establishment), the total weed biomass in the non-cultivated inter-row (NC) was significantly higher than under the intercropped treatments, consistent with findings from the meta-analysis of Gu et al. (2021).

Consistent with prior studies, hairy vetch (Mirsky et al. 2017), which exhibited the highest dominance index (RCI_2), and rocket (Khojamli et al. 2019) demonstrated the most significant weed suppression, making Vv and Es the treatments with the lowest weed biomass.

Among the dominant weed species observed across treatments (*A. arvensis, G. coronaria*, *R. raphanistrum*, and *P. rhoeas*), hairy vetch was most effective in suppressing *A. arvensis*. Malaspina et al. (2024) reported similar results, even though these authors indicated that optimal control of the weed was achieved when hairy vetch was intercropped in a mixture with rye.

The suppression of *A. arvensis* by hairy vetch can be attributed to multiple synergistic mechanisms rather than a single controlling factor (Scavo et al. 2022). Although N fixation by legumes could theoretically enhance the growth of this ruderal species, the combined effects of intense interspecific competition for non-N resources (Koudahe et al. 2022), canopy-mediated light suppression, temporal competitive advantages conferred by establishment timing (Acharya et al. 2022), and potential allelopathic interference (Kunz et al. 2016) likely created conditions unfavorable for *A. arvensis* establishment and persistence. The autumn sowing of the intercropping species in the present study provided an additional temporal advantage, allowing these species to start developing earlier in the growing season and pre-empting available resources. These mechanisms are particularly pronounced under the resource-limited conditions characteristic of semi-arid marginal agricultural systems (Garba et al. 2022), such as those found in Sardinia, where competition for water and other limiting factors may override any potential benefits from enhanced *N* availability.

Moreover, rocket demonstrated effective control of *G. coronaria* that can be attributed to the competitive abilities of the species, which combine rapid establishment (Garg and Sharma 2014), efficient resource acquisition (Scavo and Mauromicale 2021;

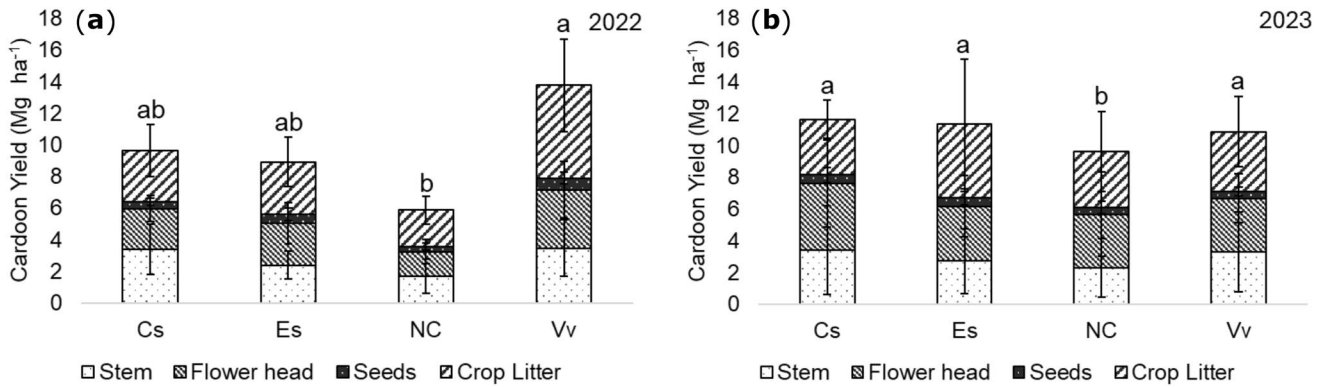


FIGURE 4 | Average cardoon total dry matter yield (Mg ha^{-1}) as influenced by the treatments (Cs—*Camelina sativa*, Es—*Eruca sativa*, Vv—*Vicia villosa*, and NC—not cultivated inter-row) in 2022 (second) (a) and 2023 (third) (b) experimental years. Bars sharing the same letters indicate no significant differences among treatment means (Sidak post hoc test, $p \leq 0.05$). Vertical bars, standard error.

Hickman et al. 2023), and potential allelopathic effects through the release of glucosinolate compounds that may suppress neighboring weeds (Bell et al. 2023). For similar reasons, *P. rhoeas* was more effectively suppressed in intercropping systems with rocket and camelina than with hairy vetch.

R. raphanistrum was the least effectively controlled by the various intercropping treatments. This persistence reflects its highly successful competitive-ruderal strategy (Owen et al. 2015), combining rapid growth with prolific seed production (Kebaso et al. 2020). This dual strategy allows it to exploit resources effectively while maintaining high reproductive output (Hashem and Wilkins 2002), making it particularly resilient to intercropping interference (Tricault et al. 2018).

Despite the effective weed control, none of the intercropped species competed with the main crop (cardoon) during its establishment in the first year, as evidenced by the low RCI values. This pattern is consistent with previous findings in semi-arid systems (Verret et al. 2017) and may be attributed to several complementary mechanisms. First, intercropped species likely contributed to microclimate buffering; in water-limited environments, partial soil cover in inter-rows can reduce evaporation and enhance soil moisture availability in adjacent crop rows (Zhang et al. 2022), particularly prior to full canopy closure. Consequently, the intercropped species may have facilitated cardoon seedling establishment rather than competing with it. Second, cardoon's deep-rooting system, initiated during early developmental stages, enables rapid and efficient exploitation of deeper soil layers for water and nutrient uptake (Rana et al. 2016; Raccuia and Melilli 2007). Despite its slower aboveground growth during establishment, this root architecture promotes spatial resource partitioning and reduces direct competition with shallow-rooted intercropped species, which likely rely on upper soil strata. This reflects a functional rather than temporal niche differentiation (Brooker et al. 2008). Additionally, the spatial arrangement, with species sown in the inter-row, may have further reduced direct competition for light and nutrients within the cardoon rows, particularly in early stages before significant lateral expansion of intercropped canopies and root systems occurred.

Altogether, these facilitative interactions, which are known to emerge under stressful conditions (Callaway 2007), suggest that intercropping may concurrently enhance weed suppression and support main crop establishment in semi-arid agroecosystems. Thus, implementing intercropping in the first year of crop establishment offers several benefits, including reduced reliance on chemical weed control and associated costs and improved soil protection without compromising cardoon establishment or future productivity. Additionally, intercropped species can provide additional income through seed and/or forage production.

Seeds of rocket and camelina have some market potential in the context of sustainable agricultural practices (as crops suitable for diversification of rotation) and industrial applications, aligning with global trends in the demand for biofuel production and industrial oils (Gulfraz et al. 2011; Zanetti et al. 2020; Pecchia et al. 2014). In this study, rocket yielded more than camelina, and its high erucic acid content makes it promising for biodiesel or biofumigant production (Mumtaz et al. 2012; Giannini et al. 2021).

However, these commercial opportunities are contingent upon the seed yields of these species. When used as intercropped species with minimal input management compared to business-as-usual practices, yields might remain low, reducing the potential economic return for farmers from the industrial oil market relative to monocultures. In this study, both crops were managed under rainfed conditions in a semi-arid region and produced lower yields than reported in previous studies (Eşİyok et al. 2013; Avola et al. 2021). In the case of camelina, the low yield could be attributed to the selected cultivar that exhibited pod-shattering issues, preventing proper harvest timing (Obour et al. 2015; Sintim et al. 2016). Those limitations have been further overcome through subsequent breeding efforts (Zanetti et al. 2021).

Hairy vetch (*V. villosa*) is widely cultivated in Mediterranean regions due to its high biomass yield and notable drought tolerance (Renzi et al. 2019, 2023). In this study, its biomass production aligned with values reported in other Mediterranean low-input systems (Bacchi et al. 2021), confirming its adaptability to such environments. Our results indicate that hairy vetch is suitable for temporary intercropping during cardoon establishment, offering both agronomic and economic advantages. In the first year, it provided a marketable forage product that meets the high regional demand for quality fodder, particularly in Sardinia (Caballero et al. 2009; Simula 2023), which may encourage farmer adoption of intercropping practices. Furthermore, in the second and third years, the weed biomass was significantly reduced under Vv than under NC, demonstrating its effective weed-suppressive capacity (Carr et al. 2013). Importantly, only hairy vetch significantly increased cardoon seed yield in the second year, highlighting a positive interaction with the main crop, consistent with similar observations in other cropping systems (Lulie 2017; Sałata et al. 2023). These findings support the use of hairy vetch as an agronomically and economically beneficial intercrop in Mediterranean low-input cardoon production.

In this study, cardoon exhibited lower biomass and seed yields compared to several other trials conducted in Mediterranean environments. This outcome was primarily attributable to differences in agronomic practices and environmental conditions. Notably, cardoon was established by direct seeding, whereas higher-yielding studies typically used transplanting methods. For example, Raccuia et al. 2007 and Angelini et al. (2009) transplanted seedlings at the three- to four-leaf stage, achieving up to 50 Mg ha–1^{-1} of cumulative dry biomass and 6.0 Mg ha–1^{-1} of seeds.

Additionally, our trial was conducted under rainfed conditions, while the above-mentioned studies applied supplemental irrigation and repeated N fertilization across growing seasons. Irrigation has been shown to improve photosynthetic efficiency and biomass accumulation (Potts et al. 2008), and consistent N input has been associated with enhanced productivity. Ierna et al. (2012), for instance, reported average yields of 26 Mg ha^{-1} of biomass and 1.2 Mg ha^{-1} of seeds using medium fertilization levels (100–150–150 kg ha^{-1} of N–P_2O_5–K_2O). In contrast, our

study applied N only at establishment, which may have limited nutrient availability in later stages.

Another limiting factor was suboptimal plant density. Although the seeding rate was designed to establish 8 plants m^{-2}, the final density averaged only ~3 plants m^{-2}. This reduction was likely due to staggered germination and poor seedling emergence, possibly induced by intense rainfall events that promoted soil crusting—a common issue in calcareous soils. Such conditions hinder early seedling development and reduce establishment success. Transplanting could help mitigate these issues by ensuring more uniform plant stands, though it remains a more resource-intensive practice.

Despite these limitations, the study provides important insights into the performance of cardoon under low-input, rainfed conditions representative of marginal Mediterranean environments. A key strength of this work lies in its relevance to sustainable land use in underutilized and marginal areas, where resource constraints limit the feasibility of intensive management. This intercropping system presents a promising option for other marginal environments, where establishment challenges in the first year have often led to the abandonment of cardoon cultivation—such as in parts of inland Tuscany and Sicily. However, future research should focus on optimizing seed quality for propagation, identifying alternative direct seeding techniques, and developing cost-effective establishment strategies. These steps are essential for enhancing the agronomic viability of cardoon in marginal landscapes.

5 | Conclusions

This three-year study is, to our knowledge, the first to evaluate temporary intercropping of cardoon with species selected for both bioenergy and forage purposes, applied exclusively during the establishment year. Temporary intercropping effectively suppressed weeds without compromising cardoon establishment under low-input and rainfed conditions in a marginal Mediterranean area. Among the tested species, hairy vetch was the most agronomically and economically favorable due to its high forage value, compatibility with local pastoral systems, superior weed suppression, and positive effects on cardoon biomass and seed yield in subsequent years. Rocket also effectively reduced weed competition during establishment without compromising cardoon performance in the subsequent years and is a promising candidate for integration into bioenergy-oriented cropping systems. Both species were the most effective in suppressing dominant weeds, except *R. raphanistrum*. *C. sativa* exhibited lower overall performance.

By the third year, all intercropped treatments outperformed the control system in terms of cardoon biomass. However, absolute yields were lower than typical Mediterranean benchmarks, likely due to limiting factors such as direct seeding, low plant density, minimal fertilization, rainfed conditions, and pest damage. These results underscore the need for improved establishment strategies, including optimized sowing methods, drought-adapted genotypes, and integrated pest management.

Author Contributions

Giorgia Raimondi: formal analysis, visualization, writing – original draft, writing – review and editing. **Pietro Todde:** data curation, investigation, writing – review and editing. **Pier Paolo Roggero:** conceptualization, methodology, writing – review and editing. **Laura Mula:** data curation, investigation, methodology, writing – review and editing. **Vittoria Giannini:** conceptualization, investigation, methodology, project administration, resources, supervision, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available at the following repository: https://doi.org/10.5281/zenodo.15791839.

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