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Effects of Restoration Through Nature-Based Solution on Benthic Biodiversity: A Case Study in a Northern Adriatic Lagoon

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Abstract: In the Caleri lagoon, a coastal lagoon in the Po River Delta, Northern Adriatic, the transplant of the dwarf eelgrass *Zostera noltei* was used as a nature-based solution to attempt the ecological restoration of a previously depleted lagoon area. A total of 135 15-cm-diameter sods were transplanted, with the donor site at the Venice lagoon. Using unmanned aerial vehicles (UAVs), eelgrass transplants were mapped and monitored with great precision. After two years, the area covered by eelgrass increased from the initial 2.5 m^2 to 60 m^2. Changes in the community structure and on the frequency of biological traits of macrobenthos occurred at the transplant site, with a higher frequency of epifaunal predators and herbivores, and of organisms with longer life spans and larger body sizes. Sensitive and indifferent taxa were always higher in the transplant site than in the bare bottom control site, where opportunistic taxa continued to dominate. Ecological quality status measured through M-AMBI and HBFI indices showed a clear improvement in the transplant site. The rapid changes in benthos demonstrate that even relatively small-scale transplantation of dwarf eelgrass can restore faunal communities very rapidly.

Keywords: nature-based solution; *Zostera noltei*; macrobenthos; biological traits; unmanned aerial vehicles

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1. Introduction

The loss of seagrass meadows from coastal and transitional waters due to human activities is a problem of global concern [1]. Seagrass loss has a significant impact on coastal biodiversity, leading to alterations in food webs and depletion of harvestable resources [2]. Seagrass meadows provide complex three-dimensional structures for benthic organisms and fish, counteract erosion by retaining sediment, remove nutrients from the water column, sequester carbon (Blue Carbon) by mitigating atmospheric CO_2 and ocean acidification [3]. Seagrass meadows are included among the internationally protected species (Bern Convention and SPAMI Barcelona Convention), and regulatory initiatives (European Habitats Directive and European Water Framework Directive) have been promoting their conservation. In line with the UN Decade on Ecosystem Restoration (2021–2030) and the new European Nature Restoration Law, restoration has been promoted to counteract habitat loss and degradation, and several initiatives have been undertaken to facilitate the reintroduction of seagrass meadows to sites where they were formally present [4,5].

Effective monitoring actions are essential for understanding the dynamic nature of seagrass meadows and evaluating their response to restoration efforts. Recent advances in remote sensing technologies, particularly the use of Unmanned Aerial Vehicles (UAVs), have enhanced the ability to monitor and map seagrass meadows with unprecedented accuracy [6,7]. UAVs provide high-resolution spatial data that enable researchers to rapidly and cost-effectively assess seagrass coverage, biomass and species composition through simple visual inspection or spectral analysis (e.g., vegetation indexes, supervised classification). As valuable complement to traditional in situ methods, UAV-based monitoring offers repeatability, accessibility to remote areas, and temporal flexibility [8,9].

The LIFE19 NAT/IT/000264-TRANSFER is a restoration through nature-based solutions project funded by the European Union, whose aim is to favor seagrass recolonization in the lagoons of the Po River Delta (Italy), of the Amvrakikos Gulf (Greece), and in Mar Menor (Spain). Within this framework, seagrass transplantations were carried out in the Caleri lagoon, a waterbody located in the norther sector of the Po Delta (Northwestern Adriatic Sea). In the past, lagoons and ponds of the Po Delta hosted extensive seagrass meadows [10,11], but, from the mid-1980s onwards, they have almost disappeared because of increased eutrophication [12]. Probably thanks to the implementation of the management measures provided for by the Water Framework Directive and other relevant directives (e.g., the Nitrate Directive), in turn implemented by national legislative decrees (D.Lgs 152/1999, 152/2006; 260/2010; 172/2015), a significant decrease in eutrophication has been observed along the coastal area of the Northern Adriatic Sea [13]. Therefore, in a restoration through nature-based solution perspective, we have recently identified limits and parameters of water and sediments that define the suitability of a recipient site for the rooting of seagrasses, in order to increase the chances of success of transplantation operations [14]. An ex-ante monitoring of water and sediment parameters, carried out at the beginning of the TRANSFER project in 2021, allowed us to identify an area in the Caleri lagoon where the restoration actions could be carried out with a likelihood of success. A UAV survey was conducted in the transplant area employing a lightweight drone equipped with a high-resolution RGB camera. Dedicated flights were planned and implemented to perform an initial evaluation of seagrass distribution after the sods transplants.

The aim of this work is twofold: (i) to assess the potential of *Zostera noltei* Hornemann, 1832, as a nature-based solution to restore a previously depleted habitat; (ii) to assess the contribution of transplanted *Z. noltei* meadows to the improvement of the ecological quality status (*sensu* European Water Framework Directive) and local biodiversity. If ecological quality status and local biodiversity improved in the transplanted area, this will also highlight the role of lagoonal seagrasses, which have very different characteristics compared to other seagrass (e.g., *Posidonia oceanica*) in ecosystem recovery, particularly in the restoration of those habitats.

2. Materials and Methods

2.1. Study Area and Seagrass Transplantation

The Caleri lagoon (Figure 1) has a surface area of about 9.8 km^2, an average depth of 1.5 m, and is separated from the sea by a large dune belt interrupted by a short 120–150 m-wide canal, through which the lagoon interacts with the sea. Fresh water supplies are scarce, and mostly come from the irrigation water used in the area surrounding the lagoon. The transplant area (45.092579°; 12.327251°) is located on a silty-sandy seabed, with an average depth of 0.5 m, a few hundred meters from the marine canal.

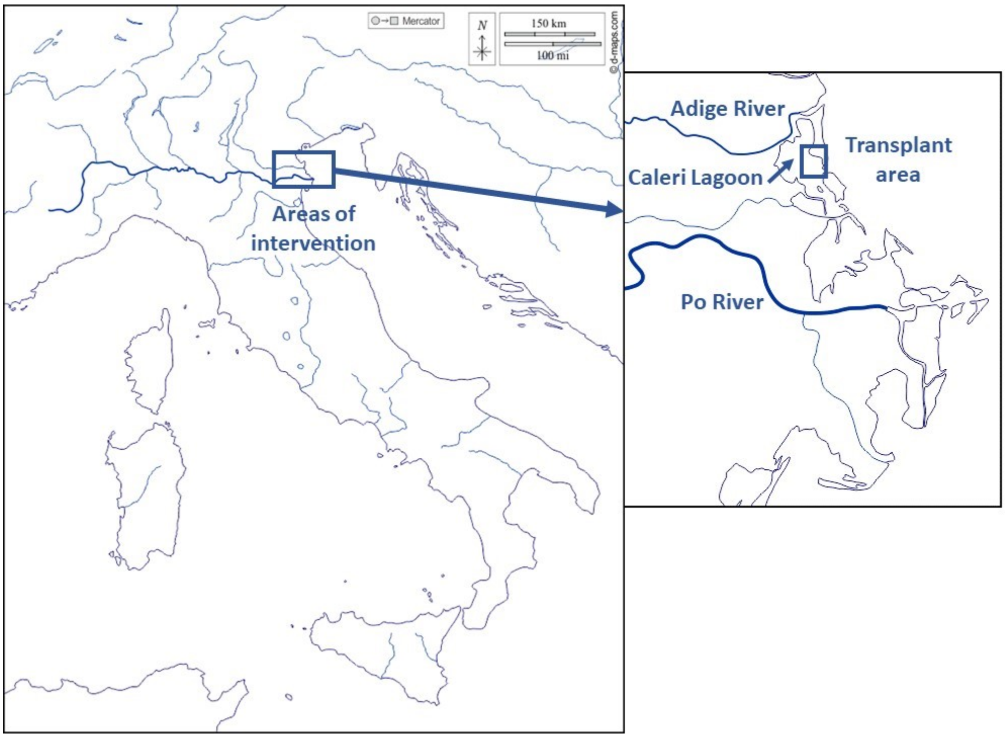

Figure 1. Intervention area (map from https://www.d-maps.com/conditions.php?lang=it; accessed on 13 December 2024).

The dwarf eelgrass *Zostera noltei* was transplanted as sods, since the root and rhizome system remains relatively intact and also provides a reserve of the original rooting medium [2,5]. Transplants were carried out in two periods [2], autumn 2022 and late spring 2023. The donor site was the Venice Lagoon, where seagrass meadows cover a surface of thousands of hectares [15] and, consequently, the removal of donation sods did not constitute damage to the ecosystem [2]. A 15 cm diameter corer was used to collect the seagrass and the underlying sediment to a depth of ~20 cm. After collection, sods were placed in perforated buckets, in turn immersed in larger baskets in order to remain moist, and immediately transported by road to the recipient site, the Caleri lagoon, about 60 km away. Here sods were manually positioned in the seabed with a corer during low tide (Figure 2a), according to a scheme that has proven effective in the previous LIFE SERESTO project [16]: sods were transplanted in 3 groups of 3 sods (triplets), each approx. 1 m from each other, and the 3 groups of sods in turn were spaced approx. 5 m (Figure 2b). Total sods transplanted were 90 (10 plots consisting of 3 triplets each) in November 2022, and 45 (5 plots consisting of 3 triplets each) in June 2023.

2.2. Sampling Environmental Parameters and the Biota

The main physical–chemical parameters of the water column [temperature; pH; Eh; salinity; dissolved oxygen (DO); dissolved inorganic nitrogen (DIN), as sum of nitrite, nitrates and ammonium; reactive phosphorus (RP); reactive silicates (RSi); total suspended solids (TSS); total chlorophyll-a (Chl-a tot), as sum of chlorophyll-a and pheophytin-a] and sediment [pH; Eh; total nitrogen (Ntot), carbon (Ctot) and phosphorus (Ptot); the fine fraction <63 µm (Fines); moisture; density] were analyzed following the procedures described in [17–19], from January to December 2023, with monthly frequency.

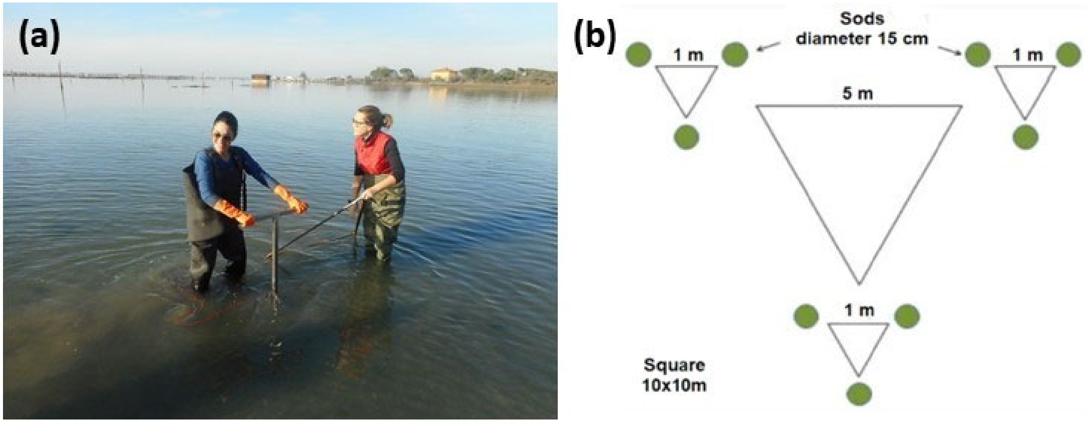

Figure 2. (**a**) Transplant operation in the Caleri lagoon; (**b**) transplant scheme of the sods.

Field monitoring of seagrass growth was carried out during daylight low tides in August 2023 by means of UAV surveys, and in June 2024 by means of ground surveys, measuring the diameter of each patch covered by the eelgrass meadow (previously consisting of a triplet of sods) with a metric cord. The UAV survey of the Caleri lagoon targeted a ~0.5 ha area where seagrass sods were transplanted. The objective was to obtain high-resolution imagery to enable georeferenced orthomosaic generation for the localisation of transplanted seagrass. The theoretical Ground Sample Distance (GSD) of ~2 mm/pixel is significantly degraded due to water presence, ripple effects, and transparency, leading to an expected realistic subcentimetric resolution. Flight parameters were configured to ensure an image overlap of around 80%, both vertically and horizontally, necessary for thorough post-processing. The surveys employed a DJI Air 2S UAV equipped with a 1-inch CMOS RGB camera (20 MP resolution, 5472 $\times$ 3648 pixels, 22 mm focal length) (DJI Sciences and Technologies, Shenzen, China). A polarizing filter was used to reduce water surface reflections. The drone, with an approximate flight autonomy of 20 min, operated on automated flight plans designed to optimize coverage and data acquisition. Flights were conducted on 6 August 2023 (after the second transplant period) during low tide and optimal weather conditions, with a water level less than 50 cm, ensuring good visibility of submerged sods. A preliminary flight, covering an area of ~5 ha, was performed at 50 m of altitude, with a 10 m track spacing and a speed of 5 m/s, to provide a wider overview of the area (Figure 3a,b). Four detailed flights were planned to fully cover the transplant area while adhering to the drone's battery limitations. The UAV flew at an altitude of 7 m with a track spacing of 2 m and a speed of 1 m/s. Images were captured at 0.5 Hz, achieving a vertical and a horizontal overlap exceeding 70% and 80% respectively.

The biota (macrobenthos and fish fauna) was sampled following a BACI (Before-After, Control-Impact) design, that is sampling, before and after the transplants, in a control site (45.096143°; 12.322183°) approximately 200 m from the transplant area, and in the area subjected to the restoration. Macrobenthos and fish fauna were sampled in June 2021 (Before), and then in January, June, September 2023, and June 2024 (After). Macrobenthos was sampled with a Van Veen grab (4 L volume, 5 replicates at each area), sieved at 0.5 mm and preserved in 96° ethanol (Carlo Erba Reagents, Emmendingen, Germany). In the laboratory, animals were carefully sorted and identified at the species level. Fish fauna was sampled using a beach seine (internode distance 2 mm in the central bag and 4 mm in the wings), 10 m long and 2 m high in the center. Two replicates per sampling area (transplant and control) were carried out. Fish were anesthetized in ice and euthanized, then in the laboratory they were identified at the species level, counted, and weighed ($\pm$0.001 g).

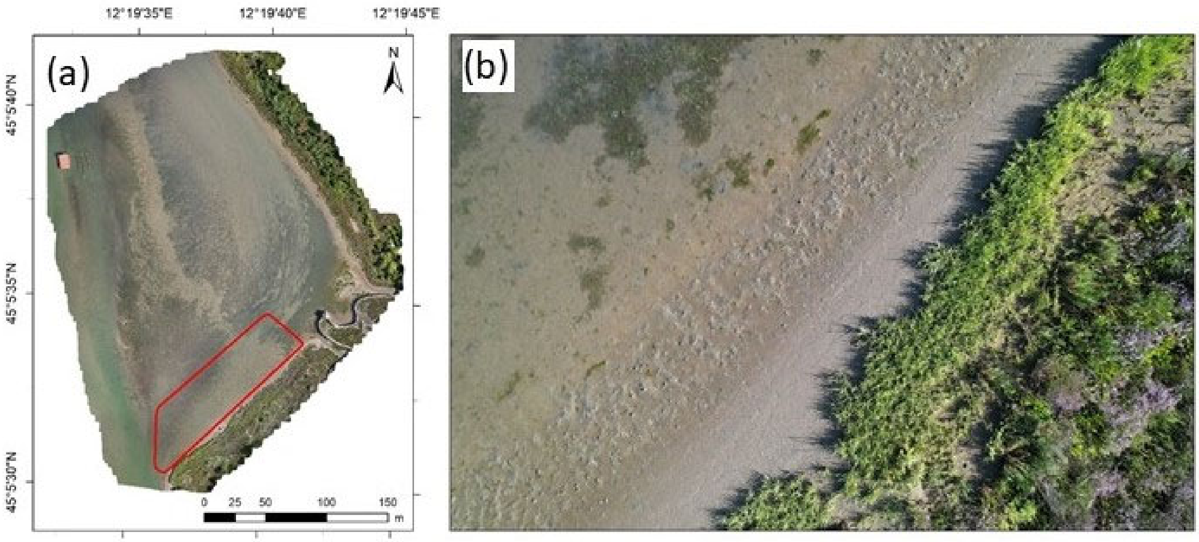

Figure 3. (**a**) Georeferenced orthomosaic obtained from the preliminary flight; the red line delimits the portion of the transplant area covered by the four detailed flights. (**b**) Aerial image acquired during one of the detailed flights; the field of view is 7 × 10 m.

2.3. Data Analysis and Ecological Quality

The Shannon–Wiener diversity index on the $\log_2$ basis (H′) and the Pielou index (J′) were calculated for macrobenthic community at each sampling date. The variability in community structure was examined by means of non-metric multidimensional scaling (MDS) ordination on the similarity matrix constructed using the Bray–Curtis index calculated on untransformed abundance data. Data were analyzed using the PRIMER v.6 software package [20].

Biological trait categories of macrobenthos were chosen related to aspects of life history and habits of the benthic fauna [21]. These categories were feeding mode, adult life habitat, adult body size, and life span. Each trait was subdivided into a number of modalities ranging from 2 to 4, for a total of 12 variable modalities. The affinity of each species for different modalities was measured using a fuzzy coding method (range 0–3), where 0 denoted full non-correspondence and 3 denoted substantial correspondence. For example, the 4 modalities of the trait feeding mode for macrobenthic species are: predator, herbivore, deposit-feeder, and filter-feeder. After choosing the functional traits and the modalities to be considered (Table 1) the "taxa by traits" matrix was compiled [21]. We also considered the ecological groups (EG) proposed for applying AMBI [22] as ecological traits, with each group (i.e., sensitive, tolerant, etc.) representing a modality of a particular trait.

The ecological status (ES) through the biological quality element "macrobenthos" was assessed by applying the index M-AMBI [23] on the species/abundance dataset. The M-AMBI index is based on a multivariate analysis in which factor analysis combines the values of AMBI [22], with those of Shannon-Wiener diversity (H′) and number of species (S). The M-AMBI is calculated by means of the dedicated software "AMBI: AZTI'S Marine Biotic Index v6.0" (www.azti.es). According to the Italian D.Lgs 260/2010, ecological quality ratio (EQR) boundaries between ES classes are: High/Good = 0.96, Good/Moderate = 0.71, Moderate/Poor = 0.57, Poor/Bad = 0.46.

The ES through the biological quality element "fish fauna" was assessed by applying the index Habitat Fish Bio-Indicator (HFBI) [24], the multi-metric fish index adopted in Italy, whose EQR boundaries between ES classes are: High/Good = 0.94, Good/Moderate = 0.55, Moderate/Poor = 0.33, Poor/Bad = 0.11 [24].

Table 1. (a) Biological traits and relative modalities and (b) ecological groups of AMBI.

(a) Biological Traits	Traits Modalities	Labels
Feeding mode	Predator	Pr
	Herbivore	He
	Deposit-feeder	DepF
	Filter-feeder	FilF
Adult life habitat	Infauna	Inf
	Epifauna	Epif
Life span	Short (<1 year)	L/S
	Medium (1–5 years)	L/M
	Long (>5 years)	L/L
Body size (g)	Small (<0.001 g)	B/S
	Medium (0.01–0.05 g)	B/M
	Large (>0.05 g)	B/L
(b) Ecological groups	Sensitive	EG-I
	Indifferent	EG-II
	Tolerant	EG-III
	2nd order opportunists	EG-IV
	1st order opportunists	EG-V

3. Results

3.1. Environmental Parameters and Success of Transplants

There was variability in water and sediment parameters at the transplant site (Table 2), but values shown in the Table, particularly those of TSS, Chl-a tot, and nutrients, confirm that the chosen site was suitable for seagrass transplantation, according to the limits described in [14].

Table 2. Mean (plus standard deviation, SD), minimum, and maximum value of water and sediment parameters (January–December 2023) at the transplant site. The values of the parameters found in the ex-ante monitoring (2021) are also reported.

			Mean	SD	Min	Max	Ex Ante
Water	Temp	°C	17.8	7.2	7.5	29	27
	pH		8.3	0.2	8.1	8.6	8.3
	Eh	mV	307.1	47.5	216.0	383.0	270.0
	Salinity	psu	18.7	2.8	15.0	23.2	14.5
	DO	mg/L	9.7	2.0	6.7	13.6	8.4
	TSS	mg/L	17.4	9.0	7.2	37.0	35.8
	RP	μg/L	0.4	0.1	0.2	0.6	0.2
	DIN	μg/L	12.5	5.7	5.4	23.9	12.8
	RSI	μg/L	24.0	14.5	2.6	44.2	17.0
	Chl-a tot	μg/L	2.5	1.2	0.9	4.7	3.4
Sediment	pH		7.6	0.1	7.4	7.8	7.4
	Eh	mV	−15.3	81.4	−162.0	122.0	115.0
	Ptot	μg/g	616.7	82.7	507.0	734.0	513.0
	Ntot	mg/g	1.4	0.3	0.9	1.8	0.6
	Ctot	mg/g	34.5	3.6	27.3	39.0	25.6
	Fines	%	36.7	7.1	28.2	50.0	12.8
	Density	g/cm^3	0.8	0.2	0.4	1.0	1.1
	Moisture	%	38.0	6.4	27.1	48.4	35.9

A total of 2380 images were captured during UAV surveys, including 630 from a preliminary flight and 1750 from detailed flights conducted at an altitude of 7 m. These images were processed using Agisoft Metashape Pro to generate georeferenced orthomosaics aligned with satellite imagery, as underwater target placement was not feasible. Although the theoretical GSD of ~2 mm/pixel was influenced by surface ripples and water clarity, the resulting orthomosaics maintained subcentimetric resolution, enabling the detection, enumeration, and georeferencing of the plants. The visual inspection of the high-resolution orthomosaics, combined with prior knowledge of the transplantation locations, enabled the accurate calibration of the method and precise mapping and identification of transplanted seagrass sods, facilitating detailed structural analysis. Of the 135 transplanted sods (90 in November 2022 and 45 in June 2023), 102 (75.5%) were identified and georeferenced (Figure 4). The high-resolution of the acquired images permitted to identify clearly the single sods and to measure the diameters (Figure 5).

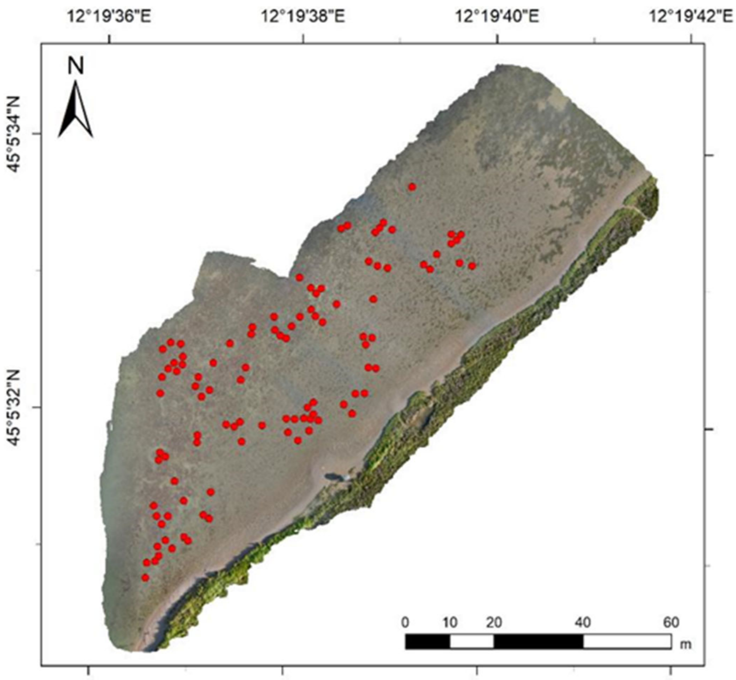

Figure 4. Georeferenced orthomosaic obtained from the detailed UAV flights. The red points correspond to the location of the 102 seagrass sods identified in the images.

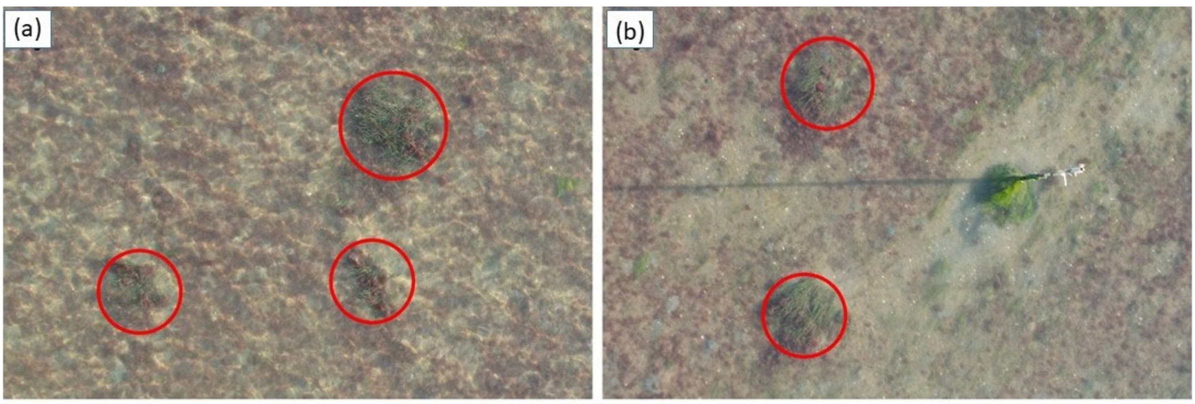

Figure 5. *Cont.*

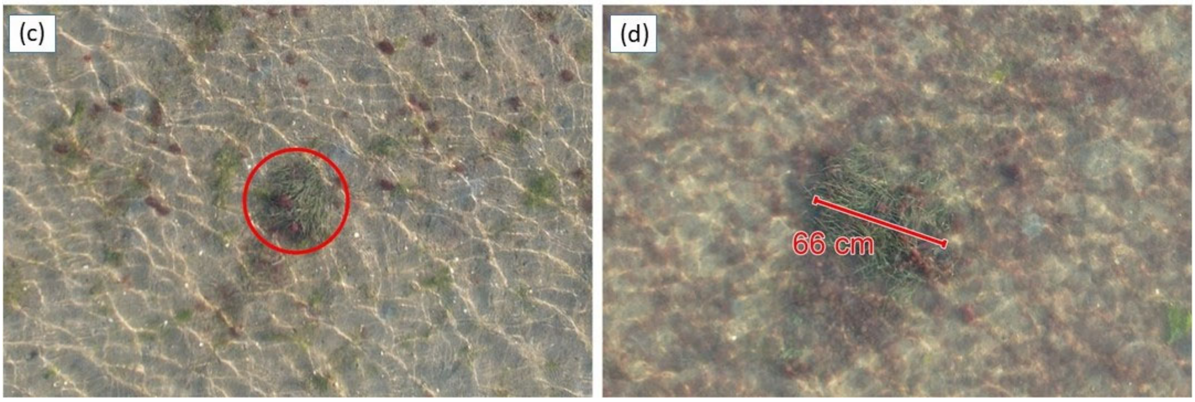

Figure 5. (**a**–**c**) Examples of seagrass sods (red circles) identified in the images. (**d**) Example of diameter measurements performed on the largest identified seagrass sod.

The frequency histogram (Figure 6) computed after the measurements, revealed a positive asymmetry of the distribution. The measured diameters ranged from a minimum of 3 cm (indicative of a decrease in leaf density of the sod) to a maximum of 66 cm (indicative of a growth in leaf cover of more than 4 times). Overall, the area covered by *Z. noltei* in August 2023 was estimated to be 3.8 m^2.

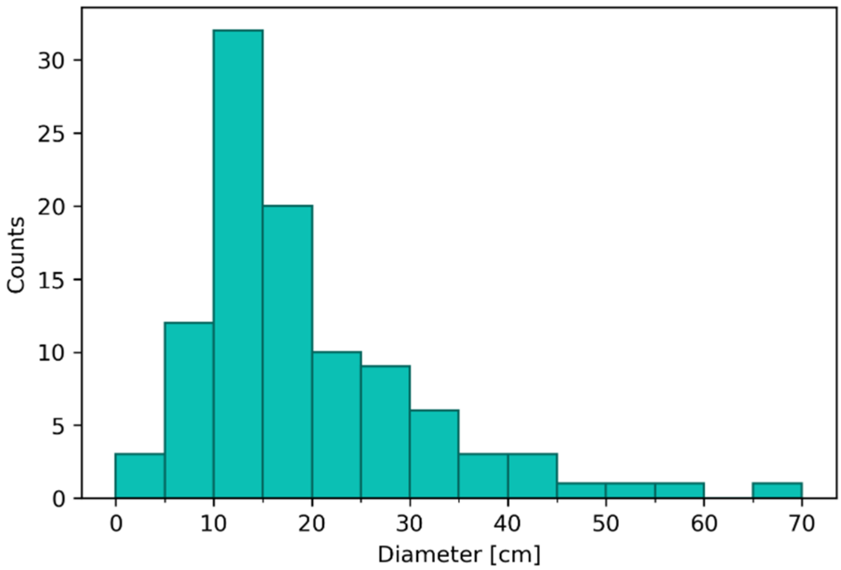

Figure 6. Frequency histogram of the measured diameters of the seagrass sods identified in the images acquired during the UAV survey.

Overall, our transplanting effort added initially about 2.5 m^2 of plant cover to the 0.5 ha-wide transplant area. Ground measurements taken in June 2024 provided a rough estimate of the eelgrass meadow extent of 60 m^2: in each triplet, the individual sods were no longer recognizable but had formed continuous meadow patches, the diameter of which varied between about 1.5 and 3 m, showing a satisfactory plagiotropic expansion of the rhizomes and the leaf system.

3.2. The Biota

A total of 115 benthic species was collected in the study period (Table S1). Consequently the matrix "taxa by traits" had 115 rows (number of taxa) and 12 columns (total number of modalities). The most abundant group was Annelida (46 taxa), followed by Arthropoda (39 taxa), Bivalvia (20 taxa), Gastropoda (9 taxa), and other less represented groups (Nemertea, Echinodermata, Ascidiacea). Diversity and evenness values are shown in Figure 7. From January 2023 onwards, both indices showed slightly higher values in the transplant site.

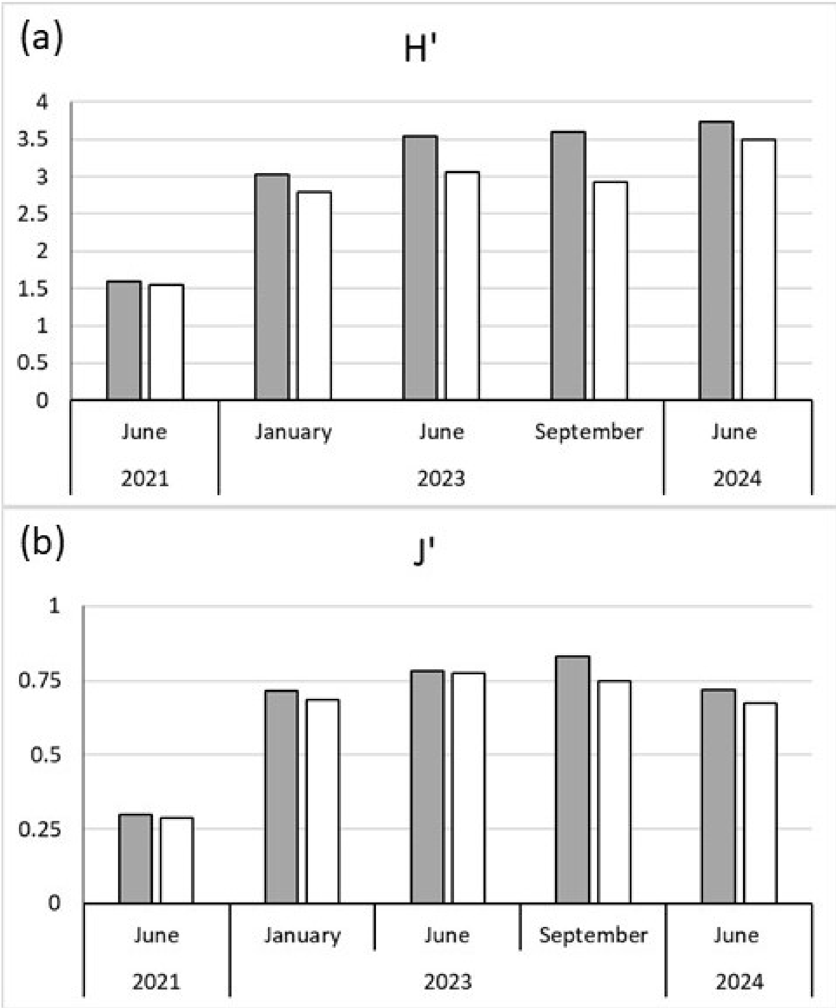

Figure 7. (**a**) Diversity (H′) and (**b**) evenness (J′) at the transplant (grey bars) and control (white bars) sites.

The MDS ordination (stress = 0.06) for the macrobenthic community at the 2 sites is shown in Figure 8. The plot highlights 3 basins of attraction, i.e., regions in space in which the system tends to remain [25]: a region corresponding to bare seabed and warm period (right of the plot, red circle), one corresponding to the autumn-winter period (center of the plot, orange circle), and one corresponding to a new partially vegetated state and warm period (left of the plot, green circle). While the community at the control site (C) shows a sort of cyclical trend in its structure and composition, with a certain degree of modification apparent in June 2024, the community at the transplant site (T) shows points conforming rather closely to a linear sequence, suggesting that the community is undergoing directional changes in its structure towards a different basin of attraction that are not dependent (only) on seasonality.

The frequencies of modalities within each biological trait are shown in Figure 9. It is evident that, particularly at the transplant site, the relative frequencies of the traits of the benthic community are changing: greater frequency of epifaunal predators and herbivores, and relative decrease of infaunal deposit-feeders, and a greater frequency of organisms with longer life spans and larger body sizes.

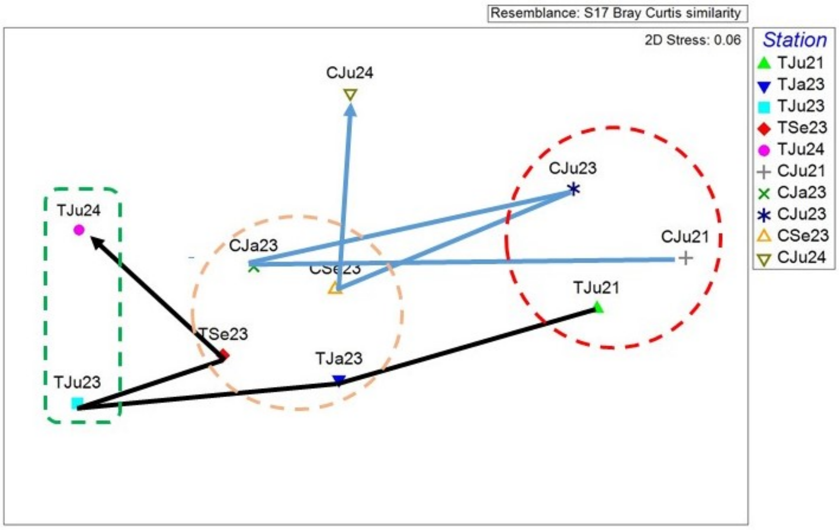

Figure 8. Ordination by MDS of the untransformed community data for transplant (T) and control (C) sites. Points are connected in time sequence. Stress value is given on the right corner of the plot.

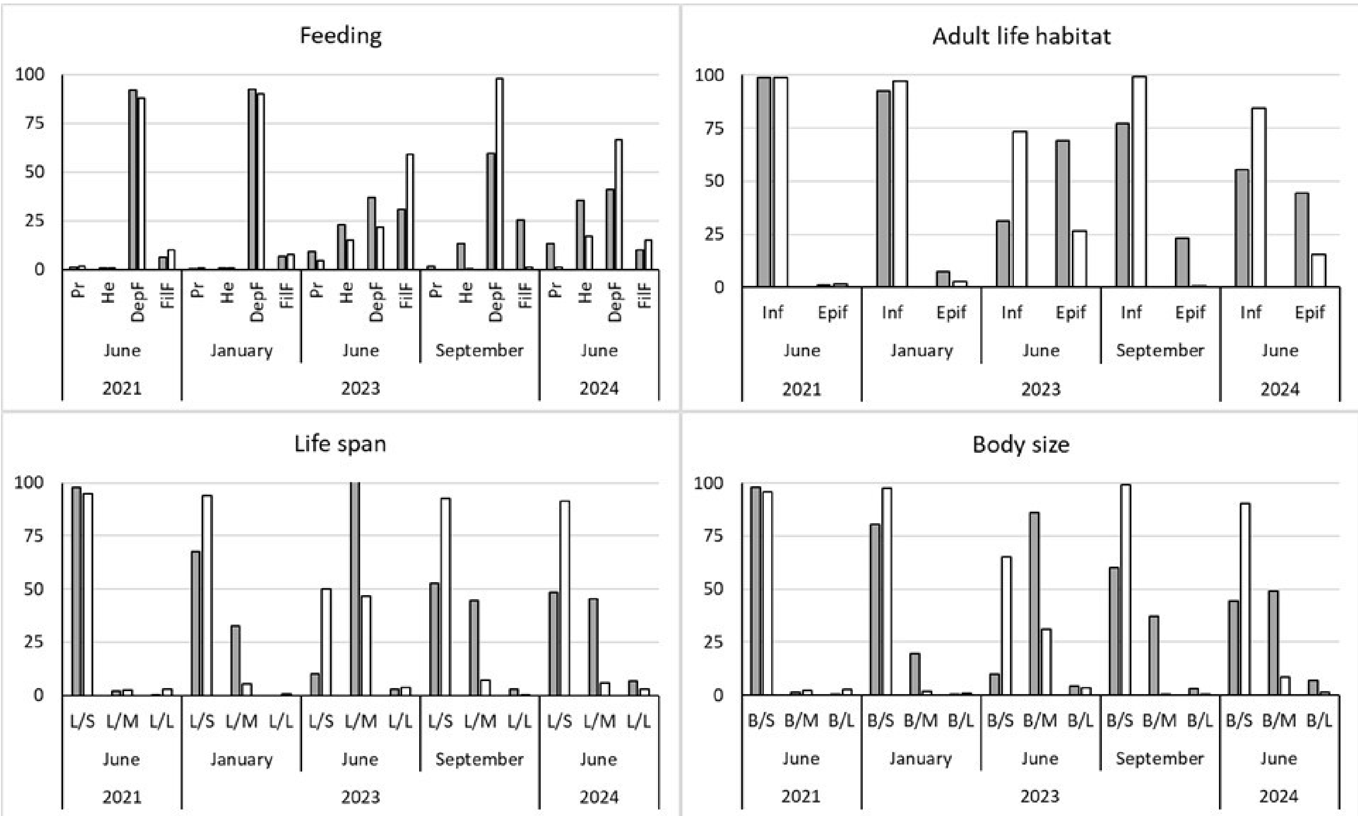

Figure 9. Percent frequencies of modalities within each trait, weighted for taxa abundance, calculated for each site (T: grey bars; C: white bars) at each sampling date. See Table 1 for labels.

Table 3 shows the distribution of macrobenthos into ecological groups (EG) according to their sensitivity to disturbance [24]. In June 2021, the benthic communities at sites T and C showed the same structure, with the clear dominance of tolerant taxa (EG-III), and the small presence of sensitive taxa (EG-I). Apart from some seasonal fluctuations due to the alternation of species more or less favored by temperature, it is evident that, from January 2023 onwards, the percentage of sensitive (EG-I) and indifferent (EG-II) taxa was always greater at the transplant (T) than at the control (C) site, while the amount of second order (EG-IV) and first order (EG-V) opportunistic species was constantly greater at C than at T.

Table 3. Macrobenthic community composition at the control (C) and transplant (T) sites by ecological groups.

Date	Site	Ecological Groups				
		I(%)	II(%)	III(%)	IV(%)	V(%)
June 2021	C	2.4	1.7	92.9	0.7	2.3
	T	4.1	1.6	90.8	1.2	2.4
January 2023	C	0	3.1	20.6	21.6	54.7
	T	0.6	0.2	53.4	24.1	21.7
June 2023	C	4.1	12.9	71	3.1	8.8
	T	25	23.7	41	9.6	0.6
September 2023	C	0.0	0.6	20.4	30.9	48.1
	T	4.0	11.3	45.2	14.8	24.6
June 2024	C	22.4	1.7	18.1	7.7	50.1
	T	26.1	5.2	35.5	15.2	18.1

In Figure 10a the values of the M-AMBI index at the transplant (T) and control (C) sites are shown. The ecological quality, similar for both sites in June 2021, i.e., before the start of transplants, was, from January 2023 onwards, always better at the T site, with values always above the Moderate/Good threshold (green line on Figure 3) defined by D.Lgs 260/2010.

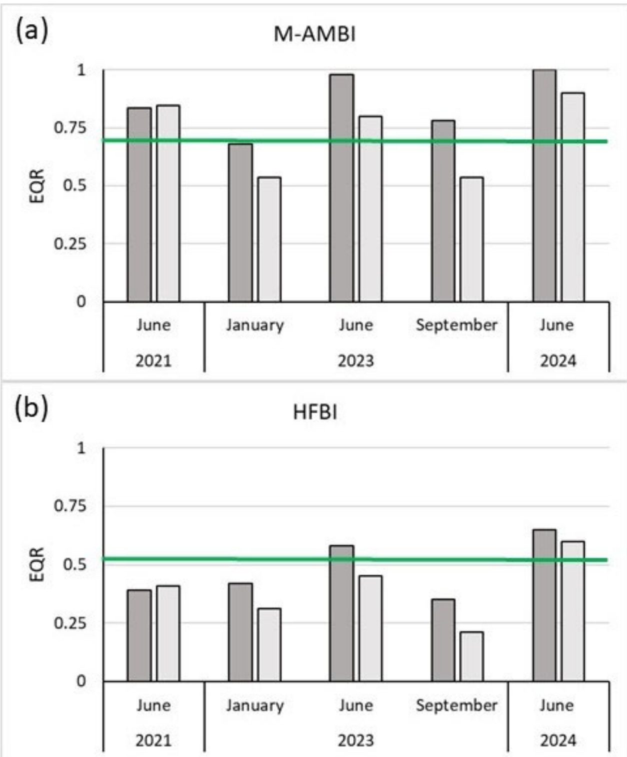

Figure 10. (**a**) Ecological quality ratio (EQR) at the transplant (T, grey bars) and control (C, white bars) sites based on the biotic index M-AMBI. The green line indicates the Moderate/Good ES threshold. (**b**) EQR at T and C sites based on the fish index HFBI. The green line indicates the Moderate/Good status threshold.

A total of 17 fish species was collected in the study period (Table S2). Lagoon resident species (gobies, pipefish, blennies, and sand smelts) accounted for a greater proportion of total abundance at both transplant and control sites, followed by marine migrant species (mullets, sea bass, herrings). In Figure 10b the values of the HFBI index at the transplant (T) and control (C) sites are shown. Although the Good quality status has been achieved only in the summer period, it seemed that the presence of seagrass patches attracted a richer and more diverse fish community than the bare seabed.

4. Discussion

Seagrass meadows form highly productive coastal habitats, and provide, among others, fundamental ecosystem supporting services for biological diversity maintenance. In the Caleri lagoon, the results of a restoration through nature-based solution support this notion for *Zostera noltei* meadows, as improving effects on the biota appear to occur after less than two years. A limitation of this study may be the relatively short time span between the transplant actions, started in 2022, and the last monitoring action, carried out in 2024, so the data we present are probably far from definitive and it will be necessary to continue monitoring over time. *Z. noltei* has been recently successfully transplanted in the Venice lagoon [16], and in the NW Atlantic coast of Portugal [26]. The results of the present study are also noteworthy for the contribution they can make to the development of seagrass transplant techniques. In fact, unlike other restoration interventions, such as the SERESTO project [16], the donor site was not in the same water basin as the recipient site, but rather about 60 km away. The sods were collected in the Venice lagoon, transported by car to the Caleri lagoon, and finally transplanted onto the bare seabed. Over 75% of the transplanted sods survived and took root, which indicates that the technique used is effective. Prior to this intervention, the site had no vegetation cover. Less than 1 year after transplants (August 2023), this increased to 3.8 m^2 of seagrass meadow. Two years after transplants (June 2024) the area covered by eelgrass meadows was roughly estimated to be 60 m^2: A continuous meadow formed by the plagiotropic growth of a triplet of sods (Figure 11). This indicates that the original transplant effort allowed for substantial growth and expansion of eelgrass at the receiving site.

Development of seagrass cover is strongly influenced by physical and ecological processes: insufficient light availability, inappropriate sediment granulometry, nutrient (N, P) and organic matter content, pore water sulfide concentration, and competition with micro- and macroalgae, are all known to affect the growth and expansion of seagrasses beds [14,27]. The chemical-physical monitoring carried out monthly for a whole year confirmed that the characteristics of the site chosen for the reintroduction of *Z. noltei* are adequate to support the growth and development of the eelgrass meadow.

UAV monitoring provides significant benefits for marine ecosystems, offering high spatial and temporal resolution for precise, non-intrusive data collection. UAVs are cost-effective for small areas (i.e., few hectares), flexible, and can safely access remote locations. They enable frequent, repeatable surveys, enhancing monitoring efficiency in time-sensitive studies. Key advantages include rapid coverage of vast areas, high spatial resolution, and real-time data for early detection of plant stresses such as drought, diseases, and nutrient deficiencies. Their adaptability to remote areas, combined with advancements in imaging and machine learning, facilitates precise analysis and decision-making. UAVs provide high-resolution, georeferenced data, not only on the seagrass but also on the overall context, and frequent monitoring capabilities, ideal for capturing fine-scale temporal changes considering the context of operations. This offers a comprehensive overview which is often not possible with ground surveys. However, UAV monitoring has limitations. It is less effective for large-scale applications due to battery life and regulatory constraints like altitude and line-of-sight requirements. Weather conditions can disrupt operations, and the high-resolution data need substantial processing capacity. UAVs must operate during low tide for optimal water clarity, and species discrimination depends on water surface conditions. Although cost-effective long-term, UAVs require significant initial investments in equipment and training. Processing large volumes of high-resolution data necessitates expertise and computational resources, making ground-based methods more feasible in some scenarios [28–30].

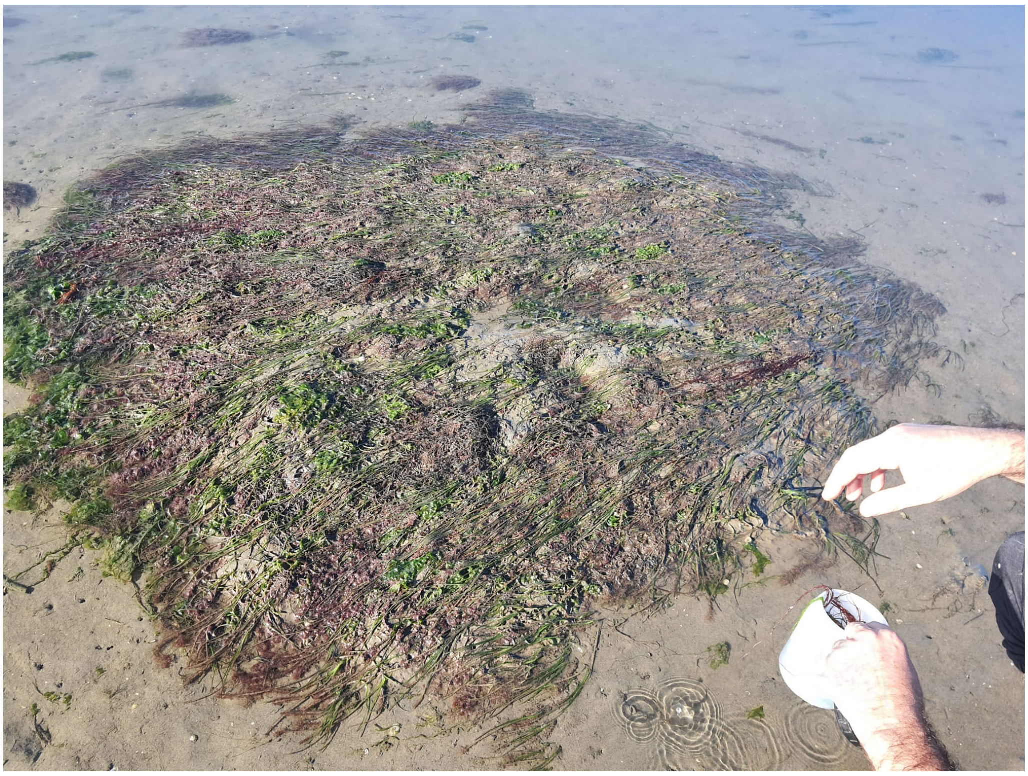

Figure 11. June 2024: continuous meadow formed by the plagiotropic growth of a triplet of sods (with some thalli of *Gracilaria vermiculophylla* and Ulvaceae entangled in the leaf layer).

Several uncertainties were inherent in the UAV survey methodology. Verification of the GSD through underwater target placement was not feasible, and advanced georeferencing corrections, such as RTK or LiDAR, were not employed. However, based on direct analysis of the UAV imagery and corroborated by findings in the literature, where degradation between theoretical and observed GSD is reported to be approximately a factor of two [31], even accounting for surface ripple, water turbidity, and orthomosaic construction artifacts, our resulting sub-centimeter resolution is sufficient to delineate the characteristic leaf structures of seagrass species. Georeferencing accuracy, constrained to standalone GNSS without ground control points and referenced to satellite-derived imagery, provided an estimated absolute orthomosaic accuracy on the metric order [32]. While this level of absolute accuracy could be optimized, it is sufficient for determining the relative spatial arrangement of vegetation within the study area, thereby meeting the objectives of this research. Advancements in artificial intelligence (AI) offer promising solutions for automated plant recognition and health assessment, particularly for submerged vegetation like seagrass meadows. AI-driven models, such as convolutional neural networks (CNNs), can process high-resolution UAV imagery to identify species, detect stress signals, and evaluate vegetation health with precision. UAVs, as optimal data acquisition platforms, provide extensive datasets critical for CNN training, significantly enhancing classification accuracy. Real-time integration of UAV imagery and AI algorithms could enable rapid analysis and dynamic decision-making in field applications. With over 90% accuracy already demonstrated in precision agriculture for crop disease detection [33,34], AI shows strong potential for monitoring and managing seagrass ecosystems.

Despite the short time since restoration began, our BACI-designed research indicates an early response by the macrobenthos to the restoration of seagrass. The macrobenthic community showed changes in its structure and composition, and although some community attributes, such as diversity and evenness, were not much higher than the bare site, the community seems clearly directed towards a different basin of attraction. At the transplant site the macrobenthos is undergoing a succession from a community dominated by opportunistic (EG-IV and EG-V) and tolerant (EG-III) species, to more sensitive species (EG-I and EG-II) [35]. This translated into an improvement in the ecological quality status measured by M-AMBI at the transplant site, which showed an ES always higher than Good even when at the control site, a couple of hundred meters away, the ES was Moderate.

At the transplant site some biological traits have shown a trend of change over time from June 2021 to June 2024 (Figure 5). In particular, a general change in the proportion of feeding guilds was observed, with a decrease of the proportion of deposit feeders (DepF, from 92% to 41%), and the increase of the proportion of herbivorous (He, from 0.7% to 35.4%), and predators (P, from 1.2% to 13.4%). A significant recruitment of filter-feeder organisms (mostly Serpulid worms) was observed at both T and C sites in June 2023 (FilF, T: 30.7%; C: 59%), but by September 2023 their proportion had already significantly decreased, particularly at the bare sediment site C (FilF, T: 25.5%; C: 1.3%). At site T, the proportion of epifaunal organisms increased (Epif, from 1.2% to 44.3%), as well as life span (LS/M, from 1.8% to 45.2%), and body size (BS/M, from 1.4% to 48.8%). Habitat heterogeneity can influence the composition of biological traits of macrobenthos, as species are selected for traits suitable for survival in that particular habitat [29]. In the Caleri lagoon the composition of biological traits of macrobenthos in the vegetated and bare bottom habitats was found, after less than two years, to be already undergoing diversification. Thus, the observed differences in biological traits of different habitats were a reflection of differences in species composition of macrobenthic communities. Moreover, the differences in the relative distributions of biological traits between the 2 sites (patchily vegetated and bare sediment) habitats are in agreement with the theoretical references of the “Habitat Model” [36], which hypothesizes that trait composition is influenced by environmental conditions that determine species-specific traits in particular habitats, and consequently shape the species composition of local communities [37].

Fish assemblages are arranged in response to cyclic variations mostly driven by seasonality, and this may have partially affected the result of the application of the HBFI index. For marine migrating species, for example, in winter the lagoon mainly exerts the function of feeding ground, while during the other seasons the lagoon exerts both nursery and feeding functions [38]. Shallow-water fish communities at our sites resulted more diversified at the end of spring, when both lagoon resident and marine migrant species coexisted, and were found to be dominated, in terms of fish abundance, by four families: Gobiidae, Syngnathidae, Mugilidae, and Atherinidae. These families have already been identified as those that mainly characterize the fish community in temperate coastal lagoons and estuaries [39]. Two of these families, Syngnathidae and Gobiidae, were found to be more present in the area where seagrass transplants were carried out, compared to bare bottoms. Despite seasonal variations in fish species and abundance, the application of the index HFBI resulted, on average, in better ES classification of the transplant area. Habitat heterogeneity contributes to the variability of fish assemblages, and the transplant area was found to host more diversified fish communities, with the presence of species typically associated with seagrass meadows [40], and characterized by higher proportions of lagoon resident species [41].

5. Conclusions

The results of this study confirm that habitat restoration through nature-based solutions, such as *Zostera noltei* transplant, is an effective tool to mitigate previously impoverished habitats, to recover lost biodiversity, and to improve the ecological quality status as required by the European Water Framework Directive. Less than two years after the restoration interventions, our results have shown clear positive signs of recovery of benthic community. Despite the encouraging results highlighted in this study, the benthic community of the transplanted area still needs time to reach the level of complexity typical of seagrass meadows, with the food web dominated by key functional groups such as herbivores and predators. Increasing biodiversity will be essential to provide stability in the restored area by increasing functional redundancy [42] and stimulating ecosystem functioning [43].

It is important to highlight that the benefits of restoration through the reintroduction of *Z. noltei* must be evaluated on a longer time scale: restoration times in estuarine and coastal systems require more time than the one we considered [44], so it would be essential to continue monitoring in the following years to detect trends that were not yet well defined after less than two years from transplants.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17030366/s1, Table S1: macrobenthos species list; Table S2: fish species list.

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