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Abstract

This Ph.D. thesis explores the interconnections between biodiversity and agro-biodiversity in rice agrosystems in North Western Italy (NWI) through a multi-scale and multidimensional approach. This work is the result of collaboration between the Rete Semi Rurali (RSR) and the Department of Life Sciences and Systems Biology (DBIOS) of the University of Turin. Current Ph.D. research compares organic and conventional rice farming systems in NWI, from the point of view of biodiversity and agro-biodiversity.Maintaining genetic diversity proceeds on two parallel tracks, that of biodiversity and agrobiodiversity. At an operational level it can be applied through the use of practices with reduced environmental impact, but also through the role of specific institutions such as community seed banks which support the presentation and dissemination of varieties suitable for low input and biodiversity friendly farming practices. Chapter 2 synthesizes knowledge on how rice cultivation, through varietal choices and related agronomic practices, affects wetland-associated biodiversity through a literature-verified expert original analysis. The study, through Multi Criteria Decision Aiding (MCDA) Approach and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), aims to identify key leverage points for biodiversity enhancement across different models of rice farming systems, developing context-specific sustainable protocols and practical decision-support tools for farmers and policymakers. In Chapter 3 particularly focus on organic rice farming, Heterogeneous Organic Materials (HOM) material with references in Article 3(18) of Regulation (EU) 2018/848 and organic rice-related farming practices results, using Pollard Transept field sampling of diurnal butterflies and dragonflies as biodiversity indicators alongside literature-based assessments on a three-level scalable approach: field, farm and landscape. Chapter 4 also examines the technical, social and economic roles of European seed banks in preserving crop diversity and supporting farmers,

considering three renowned European case studies. The work as a whole bridges gaps between scientific understanding, agricultural practice and policy implementation by combining analytical field research with participatory methods, also demonstrating how biodiversity, agro-biodiversity, and reduced environmental impacts are compatible overall. Ultimately, this integrated approach seeks to reconcile agricultural productivity with ecological resilience, offering scalable strategies for biodiversity-friendly rice cultivation and actionable recommendations for agri-environmental governance in Rural Development Plans.

Chapter I: Introduction

1.1 General Introduction

a) Biodiversity and Agro-biodiversity definitions

In general terms for biodiversity (the contraction of biological diversity) we refer to the set of wild animal and plant species. Biodiversity originates from the evolutionary process, is measured in terms of number of species and is the fruit of natural selection (Simpson, 2002; Heywood et al., 1995, 5; Wilson, 1992). The loss or extinction of biodiversity is a reversible process as a whole and in evolutionary times, while it is not for the individual species. It is called biodiversity, to specify its differences with respect to agro-biodiversity. Agro-biodiversity, or agricultural diversity, is instead the diversity in terms of botanical species and cultivated varieties, the result of a more recent artificial selection process carried out after the progress of domestication of the plants (Matthies, 2023; Ceccarelli and Grando, 2022; Wang, 2021). Agro-biodiversity is a sub-set of biodiversity in general and refers to a specific case of managed ecosystems. Agro-biodiversity is characterized by the presence of the sub-specific level of cultivated varieties or cultivars, that can be herbaceous plants) or tree plants. The conservation of agrobiodiversity depends directly on the organization of agrosystems and food value supply chains (Dasgupta et al., 2024; Jago et al., 2024; Matthies et al., 2023). Biodiversity and agrobiodiversity have been studied separately, but they represent two components of wider biological diversity. Biodiversity does not directly represent natural diversity and agrobiodiversity, but is interconnected with agricultural areas, while agrobiodiversity regroups all vegetable diversity that is directly developed and connected to agricultural activities (Tawa et al., 2024; Tibi et al., 2024; Tokuoka et al., 2024). In fact, in agrosystems separating these two related parts reflects a purely anthropocentric vision, while biodiversity is set inside natural and anthropic

ecosystems, guaranteeing Ecosystem Services for neighbouring human communities (Sutton and Costanza, 2002; Costanza et al., 1998).

b) Biodiversity and Agro-biodiversity interactions In Agro-systems

Agro-biodiversity is embedded within agrosystems and farmers' choices, and depends on environmental, climatic and socio-economic factors (Guimaraes da Silva et al., 2021; Arcieri et al., 2020; Bacenetti et al., 2016). Wetlands are specific reservoirs of biodiversity, comprising relevant percentages of the overall biodiversity, especially in biodiversity hotspots (Maltby and Barker 2009; Junk et al., 2006; Denny, 1994). In particular, paddies are considered as wetland replacement areas, that is, areas where there is the presence of unusual biodiversity associated with wetlands, as they are artificially created wetlands, maintained and dominated by the presence of human activities such as agriculture (Huynh et al., 2020; Luo et al., 2014; Natuhara, 2013). If well managed paddies contribute to the production and maintenance of crucial Ecosystem Services, namely primary food production, carbon stock, groundwater recharging, water cleaning, emission control of Green House Gases (GHGs), nitrogen mineralization, water flood control, local climate mitigation, aesthetic and recreation values, traditional landscape, heritage and cultural roles, and biodiversity support (Martinez-Eixarch et al. 2024; Bhullar, 2015; Stenert et al., 2009; Costanza et al., 1998). Rice farming relies on a consistent amount of farming inputs, including fossil fuels, fertilizers, plant protection products, herbicides, , which is an exception in italian extensive farming panorama (Vinci et al., 2023; Mariani et al., 2023; Ferrero et al., 2021; Mainini and Baici, 2021). These elements concentrate production at the territorial level in suitable areas of well-characterized landscapes. Rice is, therefore, considered the most "agro-industrial" sector in the Italian part of crop production, exacerbated by a condition of technological-cropping plateau. This exception is recognised and supported in the Common Agricultural Policy (CAP) (Eurostat, 2025; Vaglia et al., 2022; Mainini

and Baici, 2021). A key stakeholder in Italian rice farming sector is the Ente Nazionale Risi (ENR), which has been carrying out research functions since 1931, by maintaining, cataloguing and carrying out market controls between the different players involved in the sector (Mariani et al., 2023; Armiero et al. 2022; Angelini, 2008; Bevilacqua, 1991, a, b).

1.2 Key elements of rice paddies in Europe and specifically in Italy

a) Key Elements of Italian Rice Agrosystems

Rice botanical Genus sums up 19 species in the world. Asian rice (*Oryza sativa*, Linnaeus 1758) was domesticated in China from 13,500 to 8,200 years ago. African rice (*Ortyza glaberrima*, Linnaeus 1758) 3,000 years ago (Kew Garden, 2025; Ferrero and Tinarelli, 2008; Sweeney and McCouch, 2007). In 2024 over 820 million metric tons of paddy rice were produced, making it the third main crop after sugarcane and maize (FAO, 2025; Sarwar et al., 2022). Over 172 millions of hectares are annually farmed to produce rice, which represent 11% of the world's arable land (Sarwar et al., 2022; FAO, 2025; Meijide et al., 2016), with a world yield over 4 t/ha (Sarwar et al, 2022). The four main farming system typologies are: upland rice (3% of rice world production), flooded rice (19% of rice world production), deep water rice (2% of rice world production) and irrigated rice (75% of rice world production). Irrigated rice intensive farming systems are the bulk of global world production (Sarwar et al., 2022; Ferrero and Van Nguyen, 2008). About 90% of world paddy grain is produced and consumed in Asia, of which almost 60% in India and China alone (FAO, 2025; USDA, 2025; Sarwar et al., 2022). In particular, more than two billion people depend on paddy for 60–70% of their calorific requirements (Choudhary and Machavaram, 2022; Samal et al., 2022). Thus rice can be considered a staple crop in at least three continents, economically and culturally relevant, while only some 8% of rice is traded internationally (USDA, 2025, Wang et

al., 2023; Choudhary and Machavaram, 2022; Samal et al., 2022). Italy is the largest European producer of rice, with 1,236,960 tons produced on 218,420 hectares and around 4,500 farms in 2022 (Eurostat 2024; Mainini Baici, 2019), representing 61% of the total area dedicated to rice production in Europe, but just 0.3 % of world production (Eurostat, 2024). Organic rice production in Italy is constantly increasing; in 2019 the area under organic rice cultivation was 17,832 hectares, with yield ranging from 3.91 t/ha to 5.65 t/ha (Vaglia et al., 2022; Orlando et al., 2020; Bacenetti et al., 2016). While rice being farmed has been almost stable from 1870, just before and along the Green Revolution there were substantial changes anticipating agricultural intensification mechanisms predominant in the second half of the twentieth century, and defining the rice-farming environment homogenous, simplified and intensively farmed as it appears today (Mariani et al., 2023; Settele and Settle, 2018; Cinotto et al., 2011). This simplification and intensification processes concerned the following aspects: 1) Agronomic-Field Management: cultivation practices, farming system structure, reduced use of water (e.g. so-called dry sowing), etc.; 2) Genetic-Resources: focus on a limited number of varietal characteristics, dependent from high agro-chemical inputs, suitable for dry sowing in rows, with the consequent exclusion of less input-dependent varieties; 3) Environmental-biodiversity: the gradual landscape and ecological simplification of rice agrosystems, through hedge removal, elimination of semi-natural areas, increase in the size of fields, native biodiversity decline with an increase of generalist and allochthonous species; 4) Economic: farm size increase, in terms of area, production, economic value and invested capital, at the same time with a reduction of the profit margins of the farms; 5) Social: decline in the number of farms, employees and inhabitants in rice farming area, leading to real "desertification" and the creation of "inland plain areas" (e.g. Lomellina and the Po Delta) (Mainini and Baici, 2021; Mariani et al., 2021; Cinotto et al., 2011). If 50s-80s farming "copernican (green)

revolution" gave shape to current rice agrosystems, sectoral innovations did not stop there. Since the 1990s, two other substantial changes have occurred: 1) Diversification of rice varieties, also due to emergence of the herbicide-resistant technological varieties in competition with *crodo* (weedy rice present in intensive rice farming) within conventional agriculture; 2) Diversification of farming practices, namely soil tillage (conservation farming) and sowing techniques (dry sowing and green mulch), plant protection products, and more flexible irrigation management (He et al., 2023; Mainini and Baici, 2021; Grimm et al., 2020; Angelini et al., 2008). Due to the intensity of rice cultivation in its most suitable areas, the use of farming inputs, including pesticides and herbicides, is notable. The latter damages the biodiversity associated with humid areas, causing damage at both a toxicological and a genetic level, especially in the initial life stages. The massive use of such production inputs therefore compromises the adaptability of rice fields as wetland replacement areas overall (Mallet, 2022; Huynh et al., 2021; Santovito et al., 2020; Heong et al., 2007). Moreover, specific measures at the level of the Regional Rural Development Plans have gradually incorporated and included specific agri-environmental commitments, focusing on production methods and specific practices beneficial to the environment, including agroforestry practices, organic production methodologies, presence of pits and semi-natural wetlands in the proximity of paddy fields, reduced tillage, and permanent and winter submersion (Magaudda 2020; Giuliano and Bogliani, 2018; Giuliano et al., 2019). In addition, markets have opened up, and new competitive economic phenomena are emerging, both at the European and international level, in a context of general increased market complexity. The Italian main rice farming district, located in North-Western Italy between Piedmont and Lombardy Regions. It adds up to around 90% of rice farmed area and production in only seven provinces. In particular the three provinces of Vercelli, Pavia and Novara dominate the Italian rice farming sector, in terms of farmed

area and production. The other Italian rice districts, although historically and culturally important, are economically less relevant today, often limited by specific constraints (such as salt wedges or scarce water availability) (Mayer et al., 2021; Zampieri et al., 2021; Azar et al., 2016). The rice production district of North-Western Italy in its substantial contiguity extends for about 120 km in the east-west direction and 100 km in the north-south direction. It maintains its specific characteristics, due to local territorial dynamics (Zampieri et al., 2021; Mayer et al., 2019; Azar al., 2016). There are at least four distinct areas: 1) The Alta Pianura Biellese, Vercellese and Novarese: historically the northern limit of European rice farming, characterized by clay soils, medium-sized farms, often specialized, both submerged and dry seeding techniques being used; 2) The lower plains of Vercelli and Novara: characterized by a remarkable uniformity in terms of landscape and crops, being dominated by large rice specialised farms, with the predominant use of the technique of dry sowing in rows, on largely sandy soils; 3) The Lomellina: this includes the part of the province of Pavia West Ticino, characterized by largely specialized rice farms, sandy soils, with short term intensive crop rotations, and dry sowing; 4) The Bassa Pianura Lombarda: comprising the provinces of Milan, Pavia (on the left bank of River Po) Ticino and Lodi, includes medium-sized farms with soils varying from loamy-sandy to sandy, with a significant presence of cereals and zootechnical specialised farms, where rice is included within the crop rotation, and different sowing methods are implemented (Zoli et al., 2022; Mainini and Baici, 2021; Mayer et al., 2019). The nearby area in the Ticino Park is characterized by greater water availability, useful for traditional flooded sowing. In general, there is a gradient of intensification in the east-west and north-south direction within the rice district of North Western Italy (Vinci et al., 2023; Mainini and Baici, 2021; Vaglia et al., 2022).

b) European comparable rice farming contexts

Similar production contexts bring with them similar production and environmental problems. Particularly in the context of Temperate Western Europe, the Spanish productive districts (Valle del Ebro and Levante) and Provence (Camargue) emerge as important (Martinez-Eixarch et al., 2024; Mallet et al., 2022; Gómez de Barreda et al., 2021; Kraehmer et al., 2017). Their uniqueness is represented by the fact that they are coastal environments, of great environmental value, with important issues of hydraulic stability. Much of European rice cultivation is configured as coastal rice cultivation, therefore representing areas of great ecological value as a wetland area in a transition environment. They are particularly exposed to phenomena of coastal erosion, recurring water crises, salinization, eutrophication and environmental pollution (Martinez-Eixarch et al., 2024; Palma‐Guillén et al, 2024; Palma Guillén, 2023; Mallet et al., 2022). The salt wedge and coastal erosion are particularly important in this respect and are a priority for planning production activities, posing threats to future rice yields and general landscape maintenance (Genua-Olmedo et al., 2022; Genua-Olmedo et al., 2016; Alvarado-Aguilar et al., 2012). In these areas, the environmental issue of the sustainability of production has been addressed in more detail and with greater emphasis, both for issues of environmental balance and in terms of environmental valorisation of productions. Equally relevant *in situ* are the themes of the contrast of alien species and restoration and safeguarding of traditionally present humid ecosystems (Martinez-Eixarch et al., 2024; Moreno-Ramon et al., 2024; Bazzi et al., 2021; Cucco et al., 2021). Awareness of the environmental unsustainability of current rice agrosystems is also progressively increasing in other European rice contexts, as is interest in low-impact agricultural practices and methodologies, including organic management (Fusar Poli and Fontefranceco, 2024; Serrat et al., 2024; Palma Guillén, 2024; Mallet et al., 2022).

1.3 Biodiversity and Agrobiodiversity

a) Biodiversity in Rice Agrosystems

At the level of general analysis, it should be noted that, in the scientific literature, the subject of biodiversity associated with crop systems is under-represented, as biodiversity and agro-biodiversity have often been analysed separately (De Santis et al., 2022; Vitalini et al., 2020; Giuliano and Bogliani, 2019). Hydroperiod, or water management, and related seeding techniques, are crucial in determining the general water availability on the territories, which affects long-term recharging of water sheets, water balance, containment, and erosion, and biodiversity as well (Mayer et al., 2019; Azar al., 2016; Miniotti et al., 2016; Comin et al. 2014). Interaction between biodiversity and agrobiodiversity is a gradually emerging topic, especially in intensifying agrosystems. This has highlighted the inclusion of environmental issues, including biodiversity, within traditionally debated "Agrarian Issues" (Yasin, 2023; Dasgupta, 2021; Wang, 2021). The positive role of low environmental impact farming practices is noted, especially for key indicator taxa. Wetlands and replacement or temporary wetlands represent fundamental biodiversity reservoirs, in particular for birds, dragonflies, wetlands-associated butterflies, aquatic beetles, amphibians, and freshwater fish fauna. This ecological role has been known for a long time, and relevant in agricultural intensive areas (Stroud et al., 2022; Rattan et al., 2021; Ramsar, 1971). Wetlands are also greatly botanically diverse. The complexity of landscape and sub-habitats (field banks, furrows, irrigation networks, waterproofing, shrubs, trees, and hedges) means that diverse plants can be hosted, namely algae, floating aquatic plants, aquatic plants anchored in proximity to the silvering, hygrophilous plants, shaggy plants and dry or generalist plants (Tawa et al., 2024; Huynh et al., 2021; Katayama et al., 2015). Wetlands replacement areas, such as rice fields, are among the agricultural areas with greater botanical diversity; in the light of weed management practices, they also

provide relevant information for entomological biodiversity (Viggiani and Tabacchi, 2017; Natuhara, 2013; de Bastos Pazini, 2022). Many species associated with wetlands can be used as environmental quality indicators. The emerging presence of generalist or allochthonous species is an indicator of a process of ecological degradation, which is increasingly more resembling non-humid areas. It is not possible to estimate the overall health status of European wetlands through indirect means. Wetland areas specific abundance and diversity have been researched in a short time series (D'Antoni et al., 2020; Santovito et al., 2020; Sybertz et al., 2017). Estimating biodiversity trends in wetlands is a complex issue, both due to the different monitoring networks in terms of coverage and taxa considered. The only group studied at the level is represented by avifauna, a true indicator of the quality of wetlands (Karasova, 2024; Kačergytė et al., 2022; Soultan et al., 2022; Stroud et al, 2022; Rattan et al., 2021; Ramsar, 1971). For the other groups, reference may be made to the updated IUCN Red Lists at national and supranational levels (IUCN Europe, 2025; IUCN, 2025; De Knijf, G., & Sahlén, 2024; Cazalis et al, 2023). IUCN red lists are useful tools, which indicate, by geographical area, the level of conservation of the species, linked with ecosystem health. It is necessary to highlight a general scarcity of semi-quantitative data regarding the conservation status of biodiversity, including entomological biodiversity. Scientists with different estimation methodologies have also shown the difficult recovery and expansion of natural wetlands (Hase et al., 2023; van Swaay et al., 2022; Clausnitzer et al., 2009). While the Grassland Indicator Index mainly refers to areas with arable cover, parks, and pastures, a specific indicator for wetlands is still missing (van Swaay et al., 2022). Wetland areas, including those with biodiversity loss, unfortunately suffer from different data collection biases. In this sense, biodiversity-related data result from active field monitoring that rarely includes continuous time series. Organic farming practices are usually less intensive and more integrated with the landscape and biodiversity

(Bhullar et al., 2021; D'Antoni et al., 2020; Fasola, 2022; Westphal, 2015). However, beyond assessments of specific farming practices, the real drivers of biodiversity that can be promoted by farmers are often unclear. Good irrigation practices in paddy fields have been supported by the implementation of CAP through Rural Development Projects. However, the overall impact of these alternative agrosystems on a large group of taxa of indicators has not been evaluated (Mayer et al., 2019; Ranghetti et al., 2018; Azar et al., 2016). The literature also clearly shows how both the density of connections and the presence of semi-natural elements would have significant benefits beyond the specific types of business management (Magaudda et al., 2020; Kleijn et al., 2019; Sybertz et al., 2017). Crucial elements are represented by crop and landscape diversification, together with a reduction in the number and intensity of inputs used (He et al., 2023; Magaudda et al., 2020; Westphal et al., 2015). Paddies largely fail to perform the role of a replacement wetlands. Biodiversity can be promoted qualitatively in agro-systems, with different options of farming practices. These solutions are, therefore, the result of a multi-criteria analysis accessible to a wide range of different farms, matching biodiversity climate-friendly needs (Tawa et al., 2024; Magaudda et al., 2020; Toffoli and Rughetti, 2017).

b) Agrobiodiversity in Rice Agrosystems

Agrobiodiversity has often been understood as a synonym for biodiversity in agricultural work. Agrobiodiversity in rice farming systems means the genetic diversity of *Oryza sativa grown* varieties (Ceccarelli and Grando, 2022; Corrado et al., 2019). This is linked to a greater diversification of crops, production, socio-economic and landscape in relation to the farms (Mainini and Baici, 2021; Dominik et al., 2018; Ben Hassen et al., 2017). At the academic level, at least three types of values are recognized for cultivated and wild plant biodiversity: 1) Potential Scientific value: genetic reservoir of cropping species; 2) Ecosystem Services: origin and ecological network necessary

for the production and maintenance of Ecosystem Services, and derived economic benefits; 3) Cultural-Ethical-Aesthetic-Social: the value of biodiversity in itself, involving cultural, symbolic and spiritual dimensions (Yang et al., 2021; Neem et al., 2016). Similarly, agro-biodiversity can be understood as a complex of multi-level and multi-scale capital related to 1) genetic diversity; 2) species diversity and 3) ecosystem diversity, due to reciprocal interaction (Yang et al., 2021; Magaudda et al., 2020; Neem et al., 2016). The loss of complexity and diversity is problematic in several ways and at different levels of complexity (Yang et al., 2021; Neem et al., 2016). It can also represent a productive resource for territorial development, in an environmentally sustainable key. At the same time the loss of environmental value causes a general qualitative and quantitative decline in ecosystem services and land depreciation (Maran, 2020). At the same time rice farms have played a crucial role in protecting aquatic biodiversity from the risks of extinction and genetic loss (Fasola et al., 2022; Huynh et al., 2021; Giuliano and Bolgiani, 2019). On the other hand, natural and cultural biodiversity is perceived utilitaristically as an important source of genetic material for the purpose of genetic improvement (Ford-Lloyd et al. 2008). The concept of cultivated varieties as a separate group, which are stable and genetically reproducible, has dominated the market for at least 80 years, particularly after cross-lined breeding techniques spread (Ceccarelli and Grando, 2020 a-b; Wolfe and Ceccarelli, 2020; Doring et al., 2011). This specialization has not only concerned the agrosystem but also the value chain for which specific rice groups became the reference in terms of value (De Santis et al., 2022; Ceccarelli and Grando, 2020; Angelini et al., 2008). At the commercial level, this has a more relative value as the most recognized varieties were still the most requested on the market (e.g. Vialone Nano, Roma, Arborio, Carnaroli, Volano). Each variety in Italy has subjects dedicated to the preservation of purity and production at core levels (base material). In the case of traditional varieties, such as

classic ones, it may be farmers or some breeders (RSR, 2025; GIRE, 2024; Mongiano et al., 2019; Mongiano et al., 2018). This market situation has been substituted by the introduction of wider varietal grids, eliminating the precise relevance of the variety (at least in genetic terms). In the Italian context, varieties are divided into four categories: 1) Round: that is, one with a length of less than 5.2 mm and a length-to-width ratio of less than 3; 2) Medium: that is, one with a length between 5.2 and 6 mm and a length-to-width ratio of less than 3; 3) Long A: that is, one with a length of more than 6 mm and a length-to-width ratio of less than 3; 4) Long B: that is, one with a length of more than 6 mm and a length-to-width ratio of more than 3. In addition, the aromatic varieties, pigmented or destined for processing uses (such as sake) must be included, of relatively recent introduction (Kaur et al., 2021; Mongiano et al. 2020; Mongiano et al. 2019; Simonelli et al., 2017). The current Italian varietal picture is more than 50% dominated in terms of sown area by so called “technological” varieties belonging to four different groups (Clearfield®, Provisia®, FullPage®), engaging a relatively rapid varietal turnover in the last 20 years (Desantis, 2022; RSR, 2022; Mainini and Baici, 2021; Busconi et al., 2012). In 2024, about 180 varieties were cultivated, out of 234 registered. However, only seven varieties (selenium), of which six are "technological", exceeded 20,000 ha (Rice Surface Area 2024 ENR, 2024). Recently introduced technological varieties belong to seed companies, branches of the world agro-chemical groups (e.g. BASF and BAYER). These “technological” varieties imply a two-fold transition in previous cropping systems; they imply a rigidity and simplification of cropping practices related to rice farming, moving apart from non-standard management methods. They also represent the next step in the integration of inputs along the distribution chain of large agrochemical groups (Vinci et al., 2024; Mainini and Baici, 2021). These varieties have recurrent characteristics, namely low size (maximum 80 cm), tolerance of the set-up, short growing cycle, low seeding density, compulsory and

high use of productive inputs and chemical weeding for the contrast to weedy rice. iSingle varietal factors are insufficient to fully explain the impacts of rice production. However the different varieties are not completely isolated: different varieties share specific varietal traits, which are at the same time related to phenological traits expressed, and cultivation practices. These traits strongly influence farmers'choices, largely for economic and commercial reasons (Vaglia et al., 2022; Ferrero et al., 2021; Mainini and Baici, 2021; Ben Hassen et al., 2017). Varieties (and thus, indirectly, the cultivation practices chosen) have a power to model at least some elements of the rice agrosystems, defining positive or negative conditions for biodiversity. At the same time, different production requirements (for example, the management regimes (conventional or organic)) cause the variety choice to be often limited and not updated, having to largely rely on varieties with low input use and more rustic and resistant characteristics (high size, deep root apparatus, good resistance to high water, etc.) (Desantis et al., 2022; Busse et al., 2021; Dara Guccione et al., 2021).According to DL 131/2017 just the so-called "classic" varieties have the same genetic heritage of the original varieties. Similar varieties share some product parameters, but they are genetically different. The use of herbicide-resistant varieties , focused on few prevalent varietal traits such as resistances, via relatively narrow metabolic pathways, imply a short commercial life for newly patented similar varieties. This technology and related legislative framework led to a genetic loss process, and at the same time a great turnover of varieties in the field. This process usually in past decades took significantly more time.Other consequences included the decline of Medium Rice type in terms of sown area,the affirmation of Long A rice varieties, also including classic varieties, which have been grown for decades on relatively limited areas. Finally, there are recently introduced varieties that are selected by private individuals, the use of which is destined for increasingly specific food purposes (parboiled, aromatic, mochi, etc.) (Acquaverde Riso, 2024; Mongiano et al.,

2019; Kaur et al., 2016). From the European Internal Regulation 2018/848, dynamic populations were not eligible possibilities, first for research purposes then productive, which emerged instead in the last reform of the European seed system (Acquaverde Riso, 2024; ENR, 2025; Dgls 131/2017). In synthesis, in the Italian rice sector, rice varieties belong to at least four different generations: 1) Dynamic populations or varietal groups up to the end of the 19th century; 2) The first historical Italian varieties, obtained following the introduction of foreign genetic material, fruit of mass selection, and subjected to characterization; 3) Traditional varieties, partly the result of artificial fertilisation, including artificial crossing of pure lines; 4) The "technological" varieties, which are varieties that contain resistance or specific varietal characteristics (typically herbicide resistance) but obtained with traditional genetic improvement (Mariani et al., 2023; Mongiano et al., 2019; Mongiano et al., 2018). In Italy there are no widespread hybrid varieties, which are dominant in many intensive agricultural contexts such as those of East Asia, and Genetically Modified Organism (GMO) or New Breeding Techniques (NBT) varieties are not allowed, although the latter have been subject to trials since 2024, by a collaboration of the ENR and the University of Milan (Fiaz et al., 2021; Tesio et al., 2014; Breseghello, 2013). Despite the level of varietal and productive clustering, the Italian rice landscape is successful and influential in terms of production and research, especially in near European contexts (France and Switzerland), genetically based on Italian varieties. In recent rice genetic research little attention has been paid in general to the aspect of adaptation to soil-management, weed control, and low input field management, which are topics of increasing interest as a result of Climate Change, as in other regions of the world with more extreme ecological conditions (Savoini et al., 2025; De Santis et al., 2022; Wang et al., 2021). Genetic research dedicated to low-impact, organic or agro-ecological rice farming has only taken forms of dedicated scientific studies in the last 15 years. Typically, rice varieties

available to organic rice farmers have been developed in most cases through conventional breeding, as they are not well suited to organic rice farming systems. Certified organic rice seeds are available on the market in small quantities, forcing organic rice farmers to use their own seed or to use derogations for the use of untreated conventional seed. In this context, organic rice systems are characterized by environments with a high degree of heterogeneity, mainly due to farming practices (Vitalini et al., 2020; Vaglia et al., 2022). The use of rice HOM may therefore offer a concrete solution to the lack of varieties suitable for organic farming (RSR, 2025; De Santis et al., 2022).

1.4 Biodiversity and environmental impact and challenges of contemporary rice production systems

a) Italian Rice Farming Sector: Varietal Choices and Market Dynamics

The Italian rice sector has undergone notable varietal changes with crop implications in the last 15 years, driven by weed management issues (Mongiano et al. 2019; Tesio et al., 2014). Although significant in numbers, it should be underlined that this varietal change is significant as it represents the last step of varietal intensification and uniformity, as well as the final phase of integration within the agro-industrial supply chain (Savoini et al., 2025, a-b; De Santis et al. 2022; Dara-Guccione et al., 2021). Changing conditions in rice agrosystems in recent years have sought to follow more and more often environmental climate crises. In the 2000s, as a result of recurrent periods of drought, together with the low remuneration of the product, there was a spread of the organization of farm work, in terms of agricultural machinery and arrangements, as well as the choice of varieties, suitable for dry sowing. These investments aimed at reducing water consumption were financed, such as the cementing of the irrigation grid and the creation of localised reservoirs, largely private, for increasing water storage. After 2020

the results of these practices have emerged in full scale because, following a series of particularly severe droughts, irrigation saving practices have actually skewed the distribution of water use on a time-scale and territorial basis (Ali et al., 2023; Magaudda et al., 2020; Azar et al., 2016). In particular, the years 2020/2021 and 2021/2022 were marked by very serious drought phenomena. This led to the spread of dry seeding practices in the last 20 years, followed by the loss of important areas in the most difficult years. In 2022, losses of surface area were already 26,000 ha. The recovery of areas has partly occurred, even if in the face of price instability this prospect is not a certainty (ENR, 2025). Greater awareness can be achieved by increasing diversification of initiatives aimed at improving the climate resilience of the irrigation system, such as taking preventive measures by farmers, including winter submersion, improving compaction, alternate seeding methods and schedules, alternating sowing with drought-resistant and more rusticized crops, avoiding sclerotizations and crop and variety bottlenecks such as Prometheus, selected in 1990). Research institutions and farmers compared to a few years ago integrated new genetic research goals, in particular for matching production, resistance to biological adversities (particularly rice blast, weedy rice and other aggressive weeds), and new climate-environmental parameters. These environmental factors include, for example, the tolerance to salinity (very problematic in other Italian rice areas such as the Po delta and those in the centre of the South), as well as technical features that are not often considered such as low glycaemic index varieties like Argo and Selenio, and with a renewed focus on the growing topic of heavy metals (As, Cd and from 2025 Ni). At the market level, the years from 2020 to 2025 marked, on the one hand, a sharp fall in areas and production (against an increase in inputs but also in final prices of rice), the global food crisis and rising inflation, followed by a recovery in area and consumption between 2024 and 2025. Prices remain high, even above 1000 €/t, especially for the most popular variety groups, classic

varieties, especially in organic farming conditions. Another critical and unresolved issue is access to European markets for Asian rice, both from three key countries such as Pakistan, India and Thailand, but also from zero-duty countries such as Myanmar and Cambodia. (Jankulovski and Usama, 2022; ; Iocco et al., 2020).

b) Biodiversity and Crop Practices Interactions

As a result of a long series of separate studies on biodiversity and farming practices, farming practices have been shown to be harmful or beneficial to biodiversity (Ahmad et al., 2023; Fasola et al., 2022; Tscharntke et al., 2021). Conventional rice farming practices include intensive soil tillage, dry sowing, alternate wet and drying water management, fungicidal-insecticidal plant treatments, total chemical weeding and frequent mowing of embankments. This creates a more controllable agro-system, but also less climatically resilient and less welcoming for biodiversity (Fasola et al., 2022; Ferrero et al., 2021; Orlando et al., 2020; Wezel et al., 2014). Some of these farming practices are therefore considered as bottlenecks for biodiversity (Lankoski and Lankoski, 2022; Palomo et al., 2018). Conversely, rice farming practices, embedded within the agroecological paradigm, may include conservation farming or reduced farming practices, simplified levelling operations of the rice fields, restoring wetland areas, also through permanent ditches in and within nearby paddies (Habel et al., 2022 a-b; Fasola, 2022; Giuliano and Bogliani, 2019). Interventions such as long-term crop rotations, in particular including autochthonous leguminous and grassland systems, on one hand reduces the role of paddies as a replacement wetland, while on the other hand increases the agro-environmental complexity (Vaglia, 2022; Vitalini et al., 2020). Agroforestry implementation can be a great push for biodiversity if introduced with polycultural schemes, autochthonous species and reduced pruning interventions (Vagge and Chiaffarelli, 2023 a-b; Chiaffarelli and Vagge, 2021). Reduction of field sizes and the creation of frequent stepping stones, which are semi-natural wetlands areas, allow

the replacement and reconstruction of efficient ecological networks inside and around paddies, also increasing ecological networks of farmland and fallow land ecotones (Vagge and Chiaffarelli, 2023 a-b; Tscharntke et al., 2021; Chase and Leibold, 2002). The growing of green mulch in organic rice farming could have conflicting effects in terms of supporting biodiversity, since it also creates a thick layer of felt which reduces access to the soil, having as well tested allelopathic effects developed by certain mixtures (Desantis et al., 2022; Vitalini et al., 2020). If combined with the maintenance of post-harvest stubbles, green mulch allows a uniform ground cover with a proactive role for supporting avifaunal, and vice versa affecting vegetal and entomological biodiversity (Corli et al., 2022; Vitalini et al., 2020). Finally, a practice such as winter flooding, where the soil is not covered by live vegetation such as a herbage, the maintenance of the thick biomass combined with the winter submersion is doubly valuable. It reduces the weeds pressure, soil erosion and leaching of the nutrients, and of the excessive lowering of the aquifers, maintaining a humid area that is closed after harvesting in a normal productive season (Vaglia et al., 2022; Vitalini, 2020). Agrobiodiversity and biodiversity are not two separate and concurrent dimensions but they closely communicate, and their integration is necessary and desirable (Corli et al., 2021; Orlando et al., 2020; Wezel et al., 2014).

c) Rice farming Landscape and Scale Approach

The rice-growing landscape of the Italian North West is characterized by being unusual as a large-scale, irrigated, intensive and uniform landscape, in a country where small-scale systems prevail (Vinci et al., 2024; Mayer et al., 2019; Azar et al., 2016). However, if the rice field is at least theoretically a wetland replacement area, at least at a potential level, it is not at an actual ecosystem level (Giuliano and Bogliani, 2019; Giuliani et al., 2018; Schuler et al., 2013). The dominant rice cultivation systems present in the North Western Italian area include large extensions of the rice fields (up

to 4 ha on average in size), the absence of small water reservoirs, field banks and both internal and perimeter trees, intensive and repeated soil processing, mechanical and even more often total chemicals on perimetral banks (Bacenetti et al., 2016; Tesio et al., 2014; Bechini and Bastoldi 2009). The disturbance, both mechanical and chemical, is linked to the management of the embankment flora (Vaglia et al., 2022; Calcante and Oberti, 2019; Bacenetti et al., 2016). At structural level, the contemporary rice-growing landscape has stabilised in last decades in an intensive and quantitative sense, in terms of surface farmed and agrosystem simplification (Fasola et al., 2022; Mainini and Baici, 2021; Magaudda et al., 2020). This process has involved progressive erosion and fraying of the systems of hedges, land re-mergers, and rice farming intensification. Semi-natural wetlands have also been eliminated or separated from the agrosystems, and water management is not aligned with the needs of biodiversity in an overall "aridification" process. Vegetal and animal biodiversity communities in modern-day paddies are similar to those of an irrigated agricultural landscape at best, and semi-arid in the most difficult years (Chiaffarelli and Vagge, 2021; Vitalini et al., 2020; Viggiani and Tabacco, 2017). The dimension of horizontality alone has remained unchanged compared to the rotational, polycultural and humid landscapes present before the Green Revolution (Fasola et al., 2022; Bianchi, 2021; Giuliano and Bogliani, 2019). Italian rice farming landscape has been upscaled, on a territorial and productive perspective, and at the same time "downskilled" In the face of limited production increases and focus on secondary farming problems, an overall process of "territorial desertification", on an botanical and cultural basis, affected rice farming district (Vinci et al., 2023; Magaudda et al., 2020; Mayer et al., 2019). Various and more complex cultivation systems, with significant landscape implications, are however possible (Vitalaini et al., 2020; Pianca, 2019; Bianco, 2017). Agroecological farming practices contribute to making the landscape more complex, diverse, environmentally and climatically more

resilient (Polycolturae, 2025; Fasola et al., 2022; Giuliano and Bogliani, 2018).

1.5 Policy initiatives impacting rice farming in Italy and The Common Agricultural Policy framework

Under the 2023-2027 CAP, rice remains among the priority sectors that the CAP aims to support for reasons of national and European cultural, socio-economic and territorial inclusion relevance. The rice sector has been able to benefit from historical support measures over the last 30 years, among which we include: exemption from agri-environmental obligations, "greening" practices, such as that of rotation or beneficial crops for biodiversity; from the year of application 2024, the use of certified seed is required and with the expected unit amount equal to 336.46 euro/ha for the Lombardy Region. It is notably remarkable how this contribution in the last 10 years steadily decreased from almost 900 €/ha in the mid-2010s to an almost stable 660 €/ha, from 2019 to 2025, even if more and more complex in its structure (ENR, 2025). The Italian rice farming sector is therefore intensive, actors-clustered, not very flexible, but generously and publicly supported by CAP. Thus farmers' farm choices are more like combinations of individual and economical choices, rather than the result of a single farm, varietal or cultural choice, in a complex framework of impacts for biodiversity. The use of Multi-Criteria Decision Analysis (MCDA) could define the production organisational steps for farmers, playing a proactive and driving role towards biodiversity in paddies (Hamidah et al., 2022; Bigaret et al., 2017; Topping et al., 2019).

1.6 Integrated approaches for assessment and promotion of biodiversity North Western Italy

The present Italian rice farming sector is therefore characterised by numerous problems, including those at the Research level. Despite this, several research projects dedicated to sustainability in rice cultivation have recently been carried out. The main projects carried out are therefore illustrated, divided into academic and non-academic areas. The non-academic projects of the Retet Semi Rurali (RSR) seed bank are linked to the results and network legacy of the “Riso Resiliente” (Resilient Rice) project, with which the current thesis project collaborated in terms of experimental design and publications.

a) Sustainability projects of academic research authorities

The project Biosystem Rice, carried out by the University of Milan since 2016 is historically relevant. This project defined production standards in organic farming, in touch with the global networks of organic rice farming (De Santis et al., 2022; Vaglia et al., 2022; Dara Guccione et al, 2021). Riso Amico + project, promoted in partnership with ENR, Unito-DISAFA and Coldiretti, aims to work on low-impact practices in Italian rice farming in the context of North-West Italy, particularly with attention to the component of agronomic inputs used. The impact analysis included Agro-Environmental, Naturalistic and Commodity Indicators. Another project of great relevance is "Ris8: Exploiting tailored plant genotype x microbiome interaction towards sustainable increase of rice productivity and resilience to climate change", a project involving the University of Eastern Piedmont, the Sant'Anna High School (SSSUP), the University of Florence, the Institute of Biosciences and Bioresources of the CNR of Naples (IBBR/CNR) and the University of Milan, within the framework of the PRIN2022 project (Projects of Relevant National Interest) (Ris8, 2025; CREA, 2024). The issue of agrobiodiversity and varietal bottlenecks have been only marginally addressed within these designs. At the end of these projects a lasting legacy is

represented by the creation and development of the Organic District of Piedmontese Rice (*Biodistretto del Riso Piemontese*, BRP association) in 2020, including organic rice farmers and an organic rice seed company equipped with storages, a rice mill, processing and packaging machineries. The BRP has developed a close connection with citizens through projects of short supply chain (direct sale, short value chains, farm days, etc). In this multidisciplinary context, Rete Semi Rurali Communitary Seed Bank and NGO have been cooperating for years as an intermediary of innovation, through the Living Lab (LL) approach (Petitti et al., 2023; De Santis et al., 2022; Costanzo and Bickler, 2020; Costanzo et al., 2019). The latter have become a tool of the Agricultural Knowledge and Innovation System (AKIS) of the European Commission to improve the effectiveness and rapid take-up of agricultural innovations. Rice LL is part of a wider network of 17 LL on innovation in organic seed improvement and plant breeding projects and the European project LIVESEEDING (European Commission, 2024; Liveseeding, 2024; Petitti et al., 2023).

b) Sustainability projects of Rete Semi Rurali (RSR)

Partners of this Ph.D. project have carried out research, experimentation and scaling up activities in the field of sustainability in the Italian rice sector. The "Resilient Rice" project was focused on low input varieties rice and rice HOM farms adaptation and mass production in three farms. RSR activities in two rice catalogue fields focused on the adaptation of rice varieties in low input and organic farming conditions. Field catalogues included rice HOM and single cv plots. RSR also supported farmers' rice HOM adaptation in the post "Riso Resiliente Project" framework and with Organic Rice District farms support. For both projects, field monitoring activities included: the Fusarium-Bakane virus in the evaluation of vegetative growth and bud ripening; the evaluation of Rice Blast at flowering; the *Oryzae* in the evaluation of *Magnaporthe* ripening; the phenological stage assessment; flowering rate, height of plants, ear-cob

length, duration of crop cycle, and cross effects of rotation and yields. The same test was repeated in the period 2023-2024 with Japanese varieties in temperate climate (De Santis et al., 2022; Orlando et al, 2020). Laboratory and rice processing activities included cleaning and selection of materials, collection of data (weight and humidity), preparation of samples for field trials and storage of seed banks (RSR, 2025; De Santis et al., 2022). The activities were carried out in the laboratories and research facilities involved (January-October 2024), namely RSR Laboratories in Scandicci (FI) and Milan (MI), and company laboratory "Una Garlanda" in Rovasenda (VC). In the post "Resilient Rice" project, three farms participated in field trials for a complex area of 1 ha, dedicated to the reproduction of seeds and the commercial test of rice HOM. Plot monitoring included the following traits: crop height, pathogens (*Fusarium* and *Magnaporthe Oryzae*), phenological stages and degree of ripening (June-October 2024). After the harvest of the plots in October 2024, rice HOM was processed for sowing, seed bank storage or direct use. Rice HOMs were then tested for consumer acceptance on a larger scale across the farmer supply chain in 2023-2024. After having created the first supply chain that led to the commercialization of medium grain rice mixture, the objective was to support the development of the supply chain through the commercialization of long and round grain mixtures. Indeed, thanks to the European Organic Regulation (EU) 2018/848, which allows the marketing of seeds of non-uniform varieties as HOM, it will also be possible to notify and market mixtures, making them available as certified organic seed. According to this regulation, the populations obtained from on-farm evolution of dynamic mixtures may be reported as dynamic populations (to differentiate from other types of HOM) (Petitti et al., 2023; De Santis et al., 2022; Costanzo and Bickler, 2020; Costanzo et al., 2019).

1.7 The rice context and environmental impacts:

a) Study of the Environmental Impact of rice-Climate Impacts-LCA

The majority of the scientific literature on environmental impacts in rice farming has been concerned with the environmental impacts linked to the rice production cycle (Giuliana et al., 2024; Zoli et al., 2022; Zoli et al., 2021). One of the most recognized and widely used approaches in the context of environmental impact assessment is the methodology of Life Cycle Assessment (LCA). The LCA uses a set of broad-spectrum but recognised indicators (Vinci et al., 2024; Vaglia et al., 2022; Saber et al., 2020; Bacenetti et al., 2016). The merit of this estimation method is its brevity, representativeness and uniqueness of the estimation process in terms of indicators and units of measurement (Giuliana et al., 2024; Vaglia et al., 2022; Bacenetti et al., 2016) However, this method has a number of obvious limitations, which are the limited pool of indicators and estimated impact dimensions; the complexity of calculation and estimation for gaps in competence; the purely quantitative estimation approach; the absence of a territorial or farm-scale nature; and the lack of coverage of the impact on agrobiodiversity, regarding the natural one limited to some estimation processes (eutrophication, acidification, and ecotoxicity), but limited to a few taxa represented (Ferrero-Ferrero et al., 2020; Mäkeläinen et al. 2019; Verones et al., 2017). In addition, the LCA method focuses on specific production methodologies, which are classified and defined in a unique and unrepresentative way. Several LCA studies have been produced relating to the Italian context, with reference to different production areas and production techniques (Giuliana et, 2024; Vaglia et al., 2022; Zoli et al., 2022; Saber et al., 2020), in particular on three main sowing techniques (traditional flooded sowing, dry sowing, green mulch). The studies also focused on comparing organic and conventional farming methods, in several rice production districts (Vinci et al., 2024; van Der Werf et al., 2020; Bacenetti et al., 2016; Blengini et al., 2009).

b) Impacts on biodiversity

At the literature level, the analysis of impacts directed on biodiversity friendly rice practices are concentrated on taxa that are associated with wetland support areas, such as dragonflies and birds, analysing the rice practices separately. This has mainly concerned the practices already known and considered in the past, especially those included within the regional development plans of the CAP. Some practices are more established and recognized for their impact in this sense, in particular the benefits of the bird-like practices such as the presence of lateral ditches for Odonati or winter submersion for birds (Crabot et al., 2022; et al., Huynh et al., 2021). Many practices relevant to the biodiversity associated with rice fields such as hydroperiod and water management in planting plains have been investigated in detail regarding cost-benefit, and climate impacts, but less so for impacts on biodiversity.To overcome biodiversity components separation an integrated approach is needed. Scale-structured integrated approach considering biodiversity and agrobiodiversity is still missing, especially in Italian paddies (Gargano et al., 2021; Magaudda et al., 2020; Cardarelli and Bogliani, 2014; Giuliani and Bogliani, 2014).

1.8 Main goal and objectives of this thesis: Chapters and Research Questions

The current Ph.D. project, in collaboration with the non-academic Rete Semi Rurali (RSR) seed bank (more details in chapter IV section 2.21, page 140), explores the relationship between natural and agrobiodiversity. The major goal is fostering diversity at various levels, ranging from rice HOM and low input rice cultivars (cv), promoting on the long term diversified and resilient rice farming systems. In particular, this work aims to analyse rice cultivation systems at different scales (landscape, farm, field, and crop practice). The analytical part then intends to study the complex interactions between the environmental matrix and the set of field management and cultural

practices that make up the agrosystem in their entirety. Further elements of analysis involve the assessment of the role of low-impact farm-specific practices, and that of diversification at crop and varietal levels. This implies the assessment of rice agrosystems with substantially different rice farming methodologies, both conventional and organic, and the selection of suitable genetic material for low input and more sustainable rice production. More specifically the thesis has been developed in three specific chapters, with specific sub-goals:

a) Chapter II

The first paper (**Chapter II**) was characterized as a review work, able to unite and evaluate the themes of rice varieties and fields options diversity, and that of biodiversity, and not only of arthropods, associated with humid areas, through an enlarged panel of experts, assessing the impact of the crop on the production and cultivation cycle of rice with an innovative MCDA approach. The paper is structured through analytical and decision-making methods so that a comprehensive picture can be obtained of the structure of the various operational components in the field, as well as of the specific impacts along the production chain. The objectives were manifold: 1) To assess the impact of individual practices associated with rice cultivation, directly and indirectly, on the biodiversity associated with wetland substitution areas; 2) To assess the role of agrobiodiversity, in varietal, botanical and crop system terms on the overall quality of the rice agrosystem and biodiversity; 3) To define an ideal operational protocol according to different production scenarios, environmental context and conservation priorities.

b) Chapter III

The second paper (**Chapter III**) focused on the multi-scale impact (landscape, farm, and field) in the Italian rice district, comparing two-way production realities, rice organic farms, experiencing rice dynamic populations, with conventional farms. The

presence of plots containing rice HOM, although of small size, was considered and evaluated within the research. The study was structured on a double perspective: a) daily sampling of butterflies and dragonflies, used as a proxy for biodiversity in the rice-growing areas; b) the development of a pool of literature-based indicators, to assess environmental quality on a broader scale. The objectives were manifold: 1) To assess the scale gap in impact and damage mitigation, as well as the role of the surrounding environment; 2) To identify key areas for promoting or reducing the biodiversity associated with wetlands.

c) Chapter IV:

Third paper (**Chapter IV**) is focused on the role of seed banks, in the context of Italy and Europe, both at the technical support level, as a source of diversified seeds, and also for their social role economically and representative of farmers' interests within the context of agrobiodiversity. The objectives were manifold: 1) To assess the impact of individual practices associated with rice cultivation, directly and indirectly, on the biodiversity associated with wetland substitution areas; 2) To assess the scale gap in impact and damage mitigation, as well as the role of the surrounding environment; 3) To assess the role of agrobiodiversity, in varietal, botanical and crop system terms on the overall quality of the rice agrosystem and biodiversity; 4) To identify key areas for promoting or reducing the biodiversity associated with wetlands; 5) To define an ideal operational protocol according to different production scenarios, environmental context and conservation priorities.

d) Ph.D. Thesis General Perspective and Aims

Current Ph:D. Thesis objective is also strengthening awareness of biodiversity's different components and associated values.. Therefore dissemination of results through public activities such as conferences, lectures, and bioblitz, in addition to posters and dedicated articles, will be a substantial part of current research work. It therefore makes

sense to think about rice cultivation systems within the relationship between natural and agrobiodiversity through the lens of a multiple-choice system. A further final goal is to propose a feasible multi-scale action strategy aimed at defining a common technical approach for farmers, experts and public decision-makers. Therefore a decision-making tool, albeit indicative, and relatively easy to use can be considered final thesis'outcome. This can be useful to propose and promote good agricultural practices in the definition of Rural Development Plans.

Chapter II

Paddies' puzzle: A Multi Criteria Decision Aiding (MCDA) approach for enhancing natural and agro-biodiversity in Italian rice farming districts in Northern Italy

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Abstract

Rice cultivation systems in north-western Italy in recent decades have experienced a process of natural biodiversity decline, agro-biodiversity compression and simplification of cultivation practices, reducing the role of paddies as wetland replacement areas. However, this trend can be reversed if farming choices are matched with paddy-associated biodiversity needs. This study aims to analyse the relationship between varietal and agronomic choices of rice growers and their impact on natural biodiversity, through three key wetland-associated taxa, namely butterflies, dragonflies, and amphibians. Starting from historical monitoring data (2014-2022) from the Lombardy-Piedmont rice farming district to obtain a comprehensive list of species, we assessed, through expert evaluations, how different cropping and varietal systems shape natural biodiversity. The varietal analysis focuses on the most cultivated varieties and follows the full life cycle of agronomical rice farming practices. Both agronomical and varietal options have been evaluated for their role in promoting natural biodiversity, through Multi Criteria Decision Aiding (MCDA) Approach and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) (Corrente & Tasiou, 2023). Specifically, it emerges that, both in conventional and organic cultivation conditions, many agronomic choices can have a neutral impact. A limited number of practices or varietal characteristics have a significant positive or negative impact on natural biodiversity in paddies, constituting real bottlenecks or environmental catalysts in agrosystems. The methodology we proposed is flexible, being adaptable to different species and farming systems, and convertible into an app, for direct application by users in farmers and researchers. The final objective is to assess the wide-ranging impact of farmers' choices on wetlands-associated biodiversity and promote sustainable farming options with less environmental impact, allowing better reconciliation between anthropic and natural priorities in paddies.

Key words: wetlands, paddies, natural biodiversity, butterflies, dragonflies, amphibians, farmed-biodiversity, TOPSIS, Decisional Process.

Introduction

Italian Rice Farming Sector

The rice sector is a key area in the Italian and European agricultural context both in terms of production and economic importance, involving at the Italian scale, more than 200,000 hectares and 4,500 farms, with significant impacts linked to the intensive production and greenhouse gas emissions (Ranghetti and Boschetti, 2022; Mainini and Baici, 2021; Mayer et al., 2019; Azar et al., 2016). At the same time, paddies can be relevant in intensive farming contexts as replacement wetlands, hosting several taxa of natural biodiversity, including amphibians, dragonflies, birds and butterflies, among the most relevant, of which several are threatened with extinction and protected by European Union Directives (Giuliano and Bogliani, 2019; Bonelli et al., 2021; Deb, 2009).

Complex Crop Cycle

Biodiversity related to paddies has to face complex and quite often intensive series of unsustainable farming operations, including heavy soil preparation, submersion and drainage cycles, as well as recurrent weeding and crop defence intervention, more complex compared to other crops (Ferrero et al., 2021; Bacenetti et al., 2016; Bechini and Bastoldi, 2009). While sustainability is considered a pressing demand towards the productive and agricultural world, on the other hand there is the double criticality of identifying and applying - in the long term - methodologies suitable for evaluating in detail the environmental impacts of production, in particular those on natural biodiversity (Yasin, 2022; Busse et al., 2021; Dasgupta, 2021; Bianco et al., 2017). The rice farming sector in Italy is not an exception, with more sustainable, low

environmental impacts and organic rice farming emerging, with several goals, including biodiversity support through specific farming practices, timing and low-impact options. Despite this, the sector is currently dominated by dry seeding techniques, high input utilisation and disturbance to biodiversity, and poor wetland support practices (Desantis et al., 2022; Vaglia et al., 2022). At the same time, rice agrobiodiversity is also under a "genetic erosion" process, implying a genetic diversity bottleneck. Actual Italian rice cultivars panorama is composed of 200 varieties belonging to the *Oryza sativa japonica* group registered within the national variety catalogue, but just 132 of these are multiplied and commercialized as seed, 70% of the production is represented by just 20 varieties, and just 7 are cultivated for more than 20,000 ha (ENR, 2024; Desantis et al., 2022; Mainini and Baici, 2021). This narrow pool of high input, short cycle, low height, cis-genesis varieties, operationally combined with intensive tillage and dry seeding technique, is definitely changing the potential of rice farming areas as wetlands substitute (Desantis et al., 2022; Mainini and Baici, 2021; Wang et al., 2021). Rice cultivars are thus not simply a productive choice for farmers, but they imply different embedded farming choices and practices, including key farming operations as fertilisation and related machinery operations, due to different crop cycles and practices with different levels of environmental sustainability (Vinci et al., 2024; Desantis et al., 2022; Vaglia et al., 2022). Indeed, the choice of the variety directly implies the presence or absence of the crop in the field, the sequence of farming practices (e.g., irrigation, mechanical and chemical interventions), the modulation of water and input supply and the disturbing level as well (Vinci et al., 2024; Vinci et al., 2023; Ito et al., 2020). This can lead, even with the same production regime, to rough differences in the agro-system and its ecological functionality as a substitute wetland (Vinci et al., 2024; Vinci et al., 2023; Zampieri et al., 2019).

Conservation Challenges

Environmental sustainability of rice farming has so far been assessed in many cases, but mainly by focusing on individual practices or measures, taken by farmers, often driven by national or international policies, often related to specific Common Agricultural Policy (CAP) eco-schemes (D'Antoni et al., 2020; Fogliatto et al., 2019; Bacenetti et al., 2016), with studies focusing on the impact of the full crop life cycle and/or the different varieties still lacking. Moreover, issues related to the impact of rice production methods on the biodiversity hosted in the agrosystem have been studied little, if compared to other environmental issues, despite the ecological importance and vulnerability of wetland biodiversity (Vinci et al., 2023; Zoli et al., 2022; Saber et al., 2020).

Biodiversity, Crop Cycle and varieties

In this framework, our research includes a whole rice crop cycle approach analysis, on wetlands selected target taxa, to connect current knowledge on established rice farming techniques in agronomic sciences methodology and the well-known decline in natural biodiversity (Henke et al., 2023; Luo et al., 2014; Natuhara, 2013). To represent wetland biodiversity, target taxa have been selected for their known linkage to different practices in the rice crop life cycle and for their different vulnerabilities. In particular, amphibians have been selected as a proxy for water quantity and availability and low levels of pollution (Groffen et al., 2018; Natuhara, 2013; Naito et al., 2012); butterflies for their dependence on field bank management (Bonelli et al., 2021; Bonelli et al., 2018; Van Swaay et al., 2010b); dragonflies as a transitional taxon, living at field-bank-water interface (Crabot et al., 2022; Fasola et al., 2022; Huynh et al., 2021). Conversely, other taxa, usually considered highly important in wetland ecosystems, such as aquatic birds, bats and macrobenthos were not selected, firstly due to their life cycle and low direct relationship with farming practices, and secondly due to the level of complexity in monitoring and data processing (Cucco et al., 2021; Toffoli and Rughetti; 2017;

Diekotter and Crist, 2013). The choice of cultivated rice varieties and related rice farming practices should be specifically made with a view to greater resilience, also including the point of view of species linked to these habitats.

In this way, the natural biodiversity present in rice fields will be promoted and not only hosted within rice fields that act as efficient wetland replacements (Ali et al., 2024; Huynh et al., 2021; Giuliano and Bogliani, 2019). In fact, biodiversity and agro-biodiversity can be addressed at the same time, considering wetlands representative and vulnerable key taxa, farming practices and exposed functional traits, through a whole sustainability ranking and scoring process (Vinci et al., 2024; Vaglia et al., 2022; Zoli et al., 2021). The choice of varieties and cultivation practices, therefore, becomes crucial in preserving functional rearing habitat for wetland species.

MCDA Approach for Biodiversity

From this point of view, a Multiple Criteria Decision Aiding (MCDA) approach is functional to address the management complexity of the rice crop cycle, at the same time dealing with the needs for natural biodiversity associated with paddies. MCDA is an analytical approach aimed at making choices based on the inclusion of a number and type of decision criteria. Species traits and identities were included to assess the level of compatibility of agricultural activity with wetland-associated biodiversity. To follow this approach, operationally, we developed: a) a workflow to map the complexity of cultivated and natural biodiversity; b) biodiversity matrices for taxa functional traits and practice options; c) summary estimates of impacts, through sensitivity and exposure evaluations, detailed for both crop practices and varietal choices, as well as for reference taxa and their functional traits, according to the MCDA approach.

Current Research Objective

In the delineated framework, we identified three main objectives: 1) to identify the agronomic practices and varieties most detrimental to the survival of the target taxa and

where the farmer's choice may make a difference for conserving rice natural biodiversity; 2) to highlight the congruence in the response of target taxa to different cultivation options, and which functional traits make target taxa more vulnerable; 3) to propose a methodology and a workflow that can also be applied to other agricultural contexts to assess the impact of individual practices and the entire production cycle on biodiversity target elements. Current research, overcoming the concept of rice cultivars and crop cycle as a merely economic and market-oriented choice for farmers, aims to make the farmers more aware of the value of their own choices, on which they can be most influential. This targets at defining a more complex and relevant role for rice cultivars, related farming practices and crop cycle flexibility, strengthening farm multifunctionality, the ecological functionality of rice farming areas as wetlands substitute, ecosystem services supported and an increased environmental sustainability in its complex, representing a first attempt of decisional tool for rice farmers able to support at the same time cultivated and natural biodiversity.

Materials and methods

Workflow

To meet the objectives, a workflow, represented in Figure 1, was developed. It started by identifying two different pools of experts (biodiversity experts of the target taxa and agronomic experts with recognised knowledge of rice crops) and creating four different starting matrices (3 species x traits matrices, one for each target taxon; 1 rice crop life cycle and varietal list, with all possible options within our knowledge). Biodiversity experts were selected as having proven and long-term experience in the study and monitoring of target taxa (i.e. almost 10 years of proven expertise) and included among the authors (SB and CC for Lepidoptera Papilionoidea, hereafter *butterflies*; GS for Odonata, hereafter *dragonflies*; DS for Amphibia, hereafter *amphibians*). The group of

experts involved in the current study in addition to having extensive knowledge of considered taxonomic reference groups, they also have considerable theoretical and operational knowledge of rice farming in Italy. Experts have therefore integrated their knowledge and experience both in specific taxa and in the paddies and wetlands with a wide national and international literature, and reporting (ALI, 2025; Butterfly Conservation, 2025; eBMS, 2025; Farfalle Italiane, 2025; Iolas, 2025; IUCN, 2025; Odonata, 2025; Whipple at al., 2023; Bonelli et al., 2021; Tang et al., 2021; Bonelli et al., 2018; Katayama et al, 2015; Luo et al., 2014; Bambaradeniya and Amerasinghe, 2003). Agronomic experts (agronomist and farmers) were selected as having in-depth knowledge of agricultural practices and also included among the authors (MS, GD, DP, MM), integrating and validating information with literature references in the agronomic field (Vinci et al., 2024; Onorati et al., 2022; Vaglia et al., 2022; Zoli et al., 2022; Cesari De Maria et al., 2017; Bacenetti et al., 2016; Bechini and Bastoldi, 2009; Blengini and Busto, 2009), and rice varietal topic (De Santis et al., 2022; Mainini and Baici, 2021; Orlando et al, 2020; Tesio et al., 2014). The four matrices underwent the full steps of the workflow to eventually identify biodiversity vulnerability points and which passages in the rice life cycle may have the greatest impact and also which could be resources.

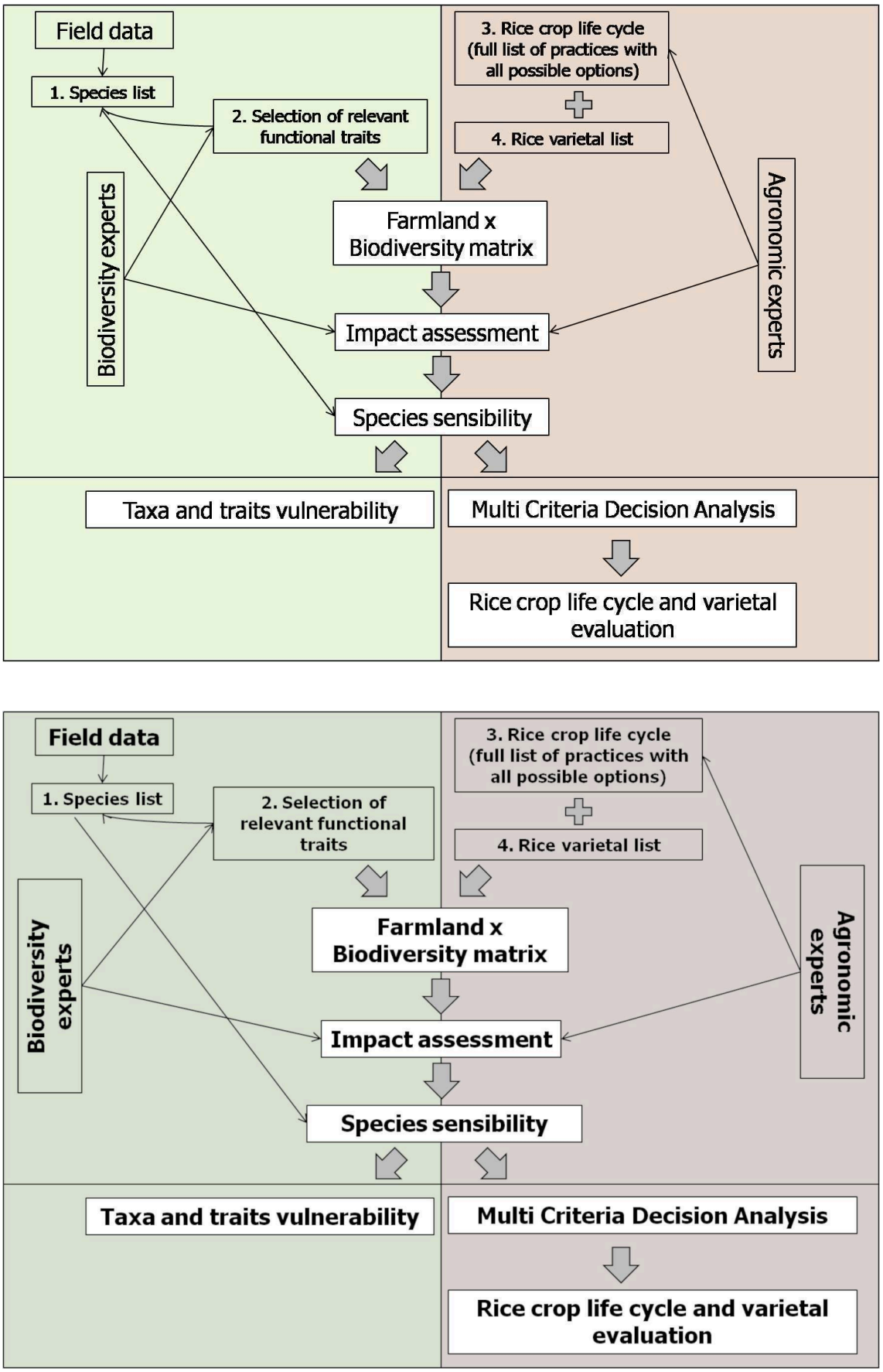

Figure 1. Overview of the methodological workflow followed in the assessment of the rice crop life cycle and varietal evaluation on target biodiversity components.

Matrix creation

Firstly, we created a "species list" for each of the three target taxa (butterflies, dragonflies, amphibians). We defined it as the reference species' pool of rice crops in NW Italy and we obtained it from long-term monitoring data belonging to and/or available to some of the authors (Supplementary Materials S1). It resulted in 49 butterflies, 28 dragonflies and 5 amphibians. They constitute a representative sample of the diversity of rice fields, including both generalist and highly specialised wetland species, as well as vulnerable rare taxa and common species. Secondly, biodiversity experts were involved in the "Selection of relevant functional traits". Relevant functional traits were identified, for each target taxon, as the ecological characteristics of the species that make them directly or indirectly interact with the rice crop life cycle. These are 11 for butterflies, 5 for dragonflies, 8 for amphibians and are fully listed, with their definition and coding, in appendix Supplementary Materials S2. The team of agronomic experts then developed the matrices of the rice crop life cycle and varietal list (Supplementary Materials S3). The matrix of the "Rice crop life cycle" follows the whole cropping cycle in NW Italy (Figure 2), which lasts from March to October and is characterised by the temporal succession of different practices (27 practices, in 16 blocks of operations according to temporal scan), all representing essential steps for rice production. For each practice, all the possible ways are listed (hereafter *practice options*) among which farmers can choose to proceed along the rice crop life cycle (fully listed and explained in S3). To see if different practice typologies may have different effects on biodiversity, practices have been grouped into seven clusters (namely soil tillage, sowing, irrigation, fertilisation, crop defence, weeding, harvesting), which group practices having similar purposes inside crop cycle (S3). The "Varietal species list" highlights the five main traits, and their options (varietal options), characterising different rice cultivars currently available (S3). We decided to list traits

instead of cultivars to be more objective in their evaluation and to make our evaluation approach more flexible even to possible new cultivars or variability among them. Functional traits, rice crop life cycle and rice varietal list merged into a double-entry table, named “Farmland x Biodiversity Matrix” (Supplementary Materials S4), in which rows correspond to all the practice options and all the varietal options, while columns correspond to the selected functional traits and their coding. This matrix represents the starting point of the impact assessment, carried out by the biodiversity experts, supported by the agronomic one.



Figure 2. Rice farming operations and wetlands reference taxa possible interactions. Rice crop life cycle in NW Italy lasts from March to October, and overlaps diurnal butterflies, dragonflies and amphibians population growth, from pre-imaginary and adult phases. Farming season can be detailed into 7 main farming clusters (brown =

soil preparation, dark green = sowing, red = fertilisation, light green = weeding, orange = crop defense, light blue = irrigation, light brown = harvest), 16 blocks of operations and 27 main different practices temporally scanned along the agrarian season (as shown in Supplementary S3). Legend: fluorescent = Butterflies; light green = Dragonflies ; dark green = Amphibians.

Impact assessment

Biodiversity experts evaluated the potential impact of each practice and varietal option on each functional trait expression (coding). The potential impact (impact score) derived from the product of two assigned values: a) exposure, expressing if the evaluating practice or varietal option has the potential to spatially and temporally influence the species carrying out the corresponding traits (with three values; 0=no exposure, 0.5=partial exposure, 1=exposure); b) sensitivity, expressing the general degree of sensitivity of the traits to the evaluating practice or varietal option. Sensitivity is organised according to a scale from -2 to 2 (possible values are -2, -1, 0, 1, 2, with successive increments of 1), where negative values correspond to a negative impact on the species carrying out the specific trait, 0 indicates the absence of impact, while positive values indicate positive effects of the evaluating options. More specifically, in the attribution of the scores, we considered the perspectives of the panels of conservationists, and of agro-growers and agronomists, until a definitive consensus was reached and shared. In this way, the operational perspectives of the 2 categories of experts involved were uniquely integrated. As in the case of cultivars and varietal traits, we decided to assign the impact of scores on functional traits instead of directly on species to be more objective and flexible. We obtained species impact score (exposure*sensitivity) to each practice and varietal option, summing all the impact scores through the functional traits of the species itself. To maintain species impact score comparable among taxa, it was necessary to normalize due to different functional

traits number per taxon (dividing the impact score per 2*number of traits). In this way, species impact score to each practice and varietal option goes from -1 to 1 among all taxa.

Data analysis

Species impact score was used as a starting point for the MCDA process. This is a typical tool widely used in social and economic sciences to help the decision process in complex situations, especially in those conditions where many criteria, with different levels of ranking and priorities, are present, for example, planning an agrarian season. Among the different possible MCDA methodologies (Haag et al., 2022; Hamidah et al., 2022; Langemeyer et al., 2016; Memmah et al., 2015; Morton and Fasolo, 2009), we selected TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), proposed by Hwang and Yoon (1981), due to its extensive use in literature and its intuitive reasoning and as farming practices options results of a preference ranking process, at different level of sustainability (Corente and Tasiou, 2023). In our approach, the species can be treated as the different evaluation criteria, grouped by the target taxon.To equally represent taxa with different numbers of species, each species receive weight reciprocal to the number of species per taxon (i.e., butterflies receive a weight of 1/49, dragonflies of 1/28, amphibians of 1/5). The output of this analysis is a TOPSIS score (from 0 to 1), allowing the ranking of the different options, based on the relative closeness to the positive ideal solution and on the relative distance to the negative ideal solution (selected as respectively 0.6 and -0.6, reducing the entire possible gradient of values, as the extremes were found never to be realized),. Such ranking has been obtained for each farming practice and for each varietal trait, allowing us to list the options from the most biodiversity-friendly to the most impacting one, equally considering all three target taxa. In farming practices and varietal traits where the possible options have a greater difference in TOPSIS score, the farmer's choice can be

considered decisive in promoting a more biodiversity-friendly agriculture. Consequently, we calculated the range of TOPSIS scores (multiplied by 100) per farming practice and varietal trait and considered a difference greater than 1 as potentially decisive in the ranking of options. This analysis was carried out using the TOPSIS function of the MCDA package (Bigaret et al. 2017), in the software R (R Core Team 2025). Then, to analyse taxa impact score among different practice and varietal options and taxa congruence in scored impacts, we firstly averaged the impact scores through all the species of each taxon. Then, to understand if the different taxa present similar scoring impact among the different practice and varietal options, we applied Pearson correlation coefficient among pairs of taxa. To compare practice clusters and varietal effects on taxa, in terms of variability and mean impact, we graphically represent average scores per taxon through box-plots, using the package ggplot2 (Wickham, 2016) of the software R. Finally, to identify the most vulnerable functional traits to the complete rice crop life cycle, we simulated 10,000 random combinations of options of all the 27 farming practices and summed all the impact scores. For each trait, we calculated the median and the Inter Quartile Range of the random distribution and we represented it through Kernel density estimation, using the package ggplot2 of the software R. The R scripts used for all the analysis and the starting data are in Supplementary Materials S6.

Results

1. MCDA: rice crop life cycle and varietal evaluation

MCDA analysis allowed us to rank the options of each varietal and agronomic practices (5 varietal and 27 agronomic practices), in reference to the three animal taxa considered (amphibians, butterflies and dragonflies). The results are summarised in Table 1, a) varietal choices and b) farming practices choices.

a) Varietal Traits

Varietal trait	Option 1: Max	Option 2: Medium	Option 3: Min	Option range*100
Plant height	Medium = 0.500	Low = 0.498	High = 0.493	0.75
Precocity	Medium-late = 0.492	Early, Medium-early, Very-early = 0.490 Medium = 0.489	Late = 0.488	0.32
Sowing density	High = 0.509	Medium = 0.506	Low = 0.503	0.61
Tolerance high water	High = 0.517	Good = 0.514 Medium = 0.502	Low = 0.496	2.07
Tolerance lodging	Very low = 0.521	Low, Medium = 0.513	Good, High = 0.505	1.61

b) Farming Practices

Farming Practice	Practice cluster	Option 1: Max	Option 2: Medium	Option 3: Min	Option range*100
Banks digging	Soil tillage	Late = 0.486	Medium = 0.485	Early = 0.484	0.17
Clump breaking	Soil tillage	Late = 0.486	Medium = 0.485	Early = 0.484	0.17
Grass removal	Soil tillage	Late = 0.500	Medium = 0.495	Early = 0.490	1.08
Plowing	Soil tillage	Superficial late = 0.501	Deep late, superficial medium = 0.499 Superficial early = 0.496 Deep medium = 0.495	Deep early = 0.491	1.07
Harrowing	Soil tillage	Disk late, Rotative late = 0.501	Disk medium = 0.498 Rotative medium, Disk early = 0.495	Rotative early = 0.490	1.14
Levelling	Soil tillage	Late, Medium = 0.496		Early = 0.491	0.49
Smoothing	Soil tillage	Late = 0.500	Medium = 0.495	Early = 0.490	1.08
Compactation	Soil tillage	Late = 0.500	Medium = 0.495	Early = 0.490	1.08
Fertilisation sowing	Fertilisation	Low = 0.495		High = 0.479	1.57

Farming Practice	Practice cluster	Option 1: Max	Option 2: Medium	Option 3: Min	Option range*100
Weeding pre-sowing	Weeding	Shallow cultivation late = 0.496	Shallow cultivation medium = 0.495 Shallow cultivation early = 0.489	Chemical early, late, medium = 0.485	1.13
Irrigation before sowing	Irrigation	Early = 0.514	Medium = 0.508	Late = 0.502	1.18
Irrigation rootage	Irrigation	Early = 0.514	Medium = 0.511	Late = 0.507	0.72
Sowing	Sowing	Green mulch late = 0.506	Broadcasting late = 0.501 Green mulch medium = 0.501 Broadcasting medium = 0.500 Green mulch early = 0.499 Broadcasting early = 0.499 Dry medium, Dry early = 0.489	Dry late = 0.487	1.89
Drainage rootage	Irrigation	Late = 0.494	Medium = 0.494	Early = 0.494	0
Fertilisation crop	Fertilisation	Low = 0.502		High = 0.477	2.5
Crop rotation	Crop defense	Absent = 0.516	Leguminous = 0.501	Cereals = 0.491	2.47
Treatment insecticide	Crop defense	Absent = 0.498		Present = 0.470	2.83
Treatment fungicide	Crop defense	Absent = 0.498		Present = 0.470	2.84
Irrigation 2nd	Irrigation	Early = 0.513	Medium = 0.510	Late = 0.507	0.63
Drainage 2nd	Irrigation	Early = 0.494	Medium = 0.494	Late = 0.494	0
Weeding crop	Weeding	Absent = 0.500	Squeezer early, medium, later = 0.495	Chemical early, medium, late = 0.484	1.64
Weeding Mechanical Squeezer	Weeding	Early = 0.494	Medium = 0.494	Later = 0.494	0

Farming Practice	Practice cluster	Option 1: Max	Option 2: Medium	Option 3: Min	Option range*100
Irrigation 3rd	Irrigation	Early = 0.513	Medium = 0.510	Late = 0.508	0.52
Drainage 3rd	Irrigation	Early = 0.494	Medium = 0.494	Later = 0.494	0
Weeding banks	Weeding	Mechanical bar (1 intervention) = 0.497	Mechanical chop (1 intervention) = 0.494 Mechanical bar (more than 1 intervention) = 0.492	Chemical early, medium, late = 0.486 Mechanical chop (more than 1)intervention = 0.486	1.13
Harvesting	Harvesting	Late = 0.491	Medium = 0.489	Early = 0.479	1.23
Winter flooding	Irrigation	Early = 0.521	Medium, Late = 0.514	Absent = 0.505	1.63

*Table 1. MCDA analysis of impacts on reference taxa for: a) varietal traits and b) farming practices, following the full agronomic life cycle. For each varietal trait and farming practice, all the options are ranked from the best (Max) to the worst (Min) and the corresponding TOPSIS score is shown. More in detail: 1) Max represents the most biodiversity friendly alternative (the highest score); 2) Min represents the least biodiversity friendly alternative (the lowest score); 3) Medium reports all the intermediate situations between the two previous ones (all the intermediate scores). The "Option range*100" is also shown, i.e. Max minus Min TOPSIS score (multiplied per 100), to highlight the highest differences in terms of choices. Differences higher than 1 are shown in bold to highlight where the farmer choice could make a difference.*

From the MCDA analysis, we observed how *Tolerance to high water* and *Tolerance to lodging* are varietal options potentially affecting rice paddies biodiversity, with varietal highly tolerant to water and lowly to lodging representing the best options (Table 1a). Following the rice life cycle, we identified bottlenecks in all the farming clusters but not in all the practices (Table 1b). Concerning *Soil tillage*, in the practices affected by the

farmer choice, all the best options are characterised by intervention executed as late as possible in the season (grass removal, plowing, harrowing, smoothing, compactation). Similarly, also a late *Harvesting* represents the best option. On the contrary, practices related to the water regime (*Irrigation* cluster), when influential, should be as early as possible in the season (irrigation before sowing and winter flooding). As expected, all practices related to *Crop defense* have the potential to be influential, with avoiding them always resulting in the best option (crop rotation, treatment insecticide, treatment fungicide), while *Weeding*, when influential, should be mechanical/practical instead of chemical and as light as possible (weeding pre-sowing, weeding crop, weeding banks). Finally, both practices related to *Fertilisation* are characterised by best options with low input of fertilizer while *Sowing* should avoid drainage.

2. Farming Bottlenecks and Taxa vulnerability congruence

The results of correlations between animal taxa showed how only dragonflies and amphibians present similar responses (Pearson correlation coefficient; butterflies-dragonflies, $r_P = 0.156$, p-value = 0.086; butterflies-amphibians, $r_P = 0.167$, p-value = 0.063; dragonflies-amphibians, $r_P = 0.842$, p-value < 0.001). Taxa congruence has been also visually assessed by means of box-plots. Box-plots show the results of the experts' group assessment (Impact assessment table), specifically highlighting the variability between negative and positive scores (Figure 3).

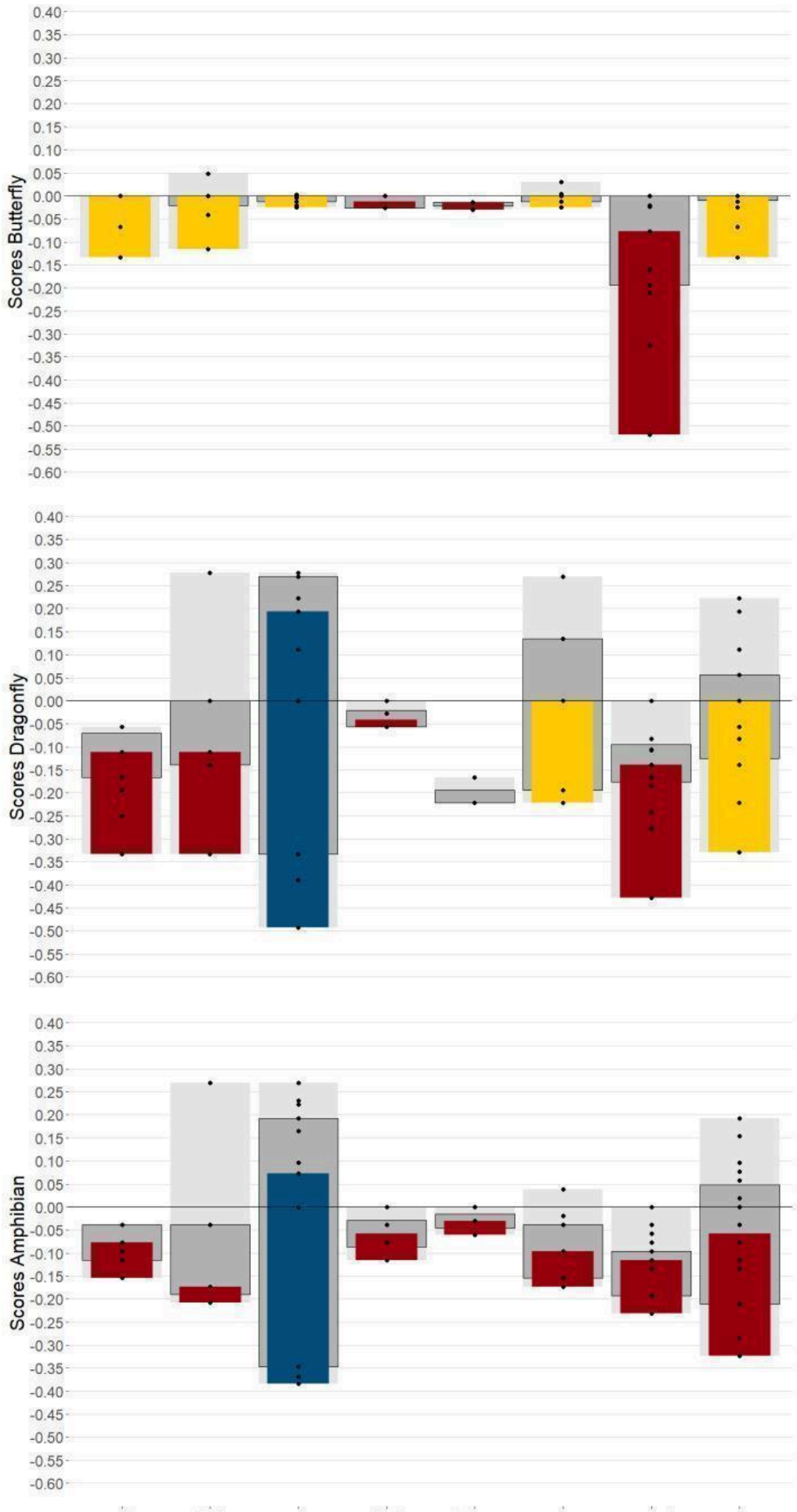
Scores Butterfly
Scores Dragonfly
Scores Amphibian
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-0.45
-0.50
-0.55
-0.60
soil
phyto
water
fert
harv
sow
weed
var

Figure 3. Butterflies (high), dragonflies (centre) and amphibians (low) boxplots impact score. For each taxon and each farming option (within varietal traits and farming practices), the mean value across all species has been calculated (S5). For each of the seven farming practice clusters (soil = soil preparation, phyto = crop defense, water = irrigation, fert = fertilisation, harv = harvesting, sow = sowing, weed = weeding) and the varietal one (var), a separate boxplot is shown. Black dots represent the calculated mean values across all the species for each option inside the cluster. Light grey boxes represent the range of observed values, while dark grey boxes represent the inter-quartile range. Coloured boxes go from the minimum value to the median one: blue is used when the median impact score is positive, red when it is negative, and yellow when it is equal to 0.

The complete scores, in a descriptive manner, are present in the Supplementary Materials S5. Among the elements of the rice crop cycle, those showing the greatest scope for action are: a) water management (for dragonflies and amphibians, where a proper management can even be highly positive); b) sowing techniques (for dragonflies); c) phytosanitary treatments (for all the taxa); d) weeding (for all the taxa, but especially for butterflies). Specifically, the TOPSIS approach agrees in observing differences in impacts for individual taxa. Compared to the simple range comparison, the TOPSIS approach also shows the best option for the decision maker at the operational level. In coherence with what we observed from MCDA, we also observed how specific varietal traits can be associated with lower or higher levels of impacts on biodiversity, especially in the case of amphibians.

3. Traits vulnerability

The analysis of the impact of full rice crop and life cycle functional traits (Fig. 4) shows that just specific functional traits make the three taxa particularly vulnerable to

agricultural practices.



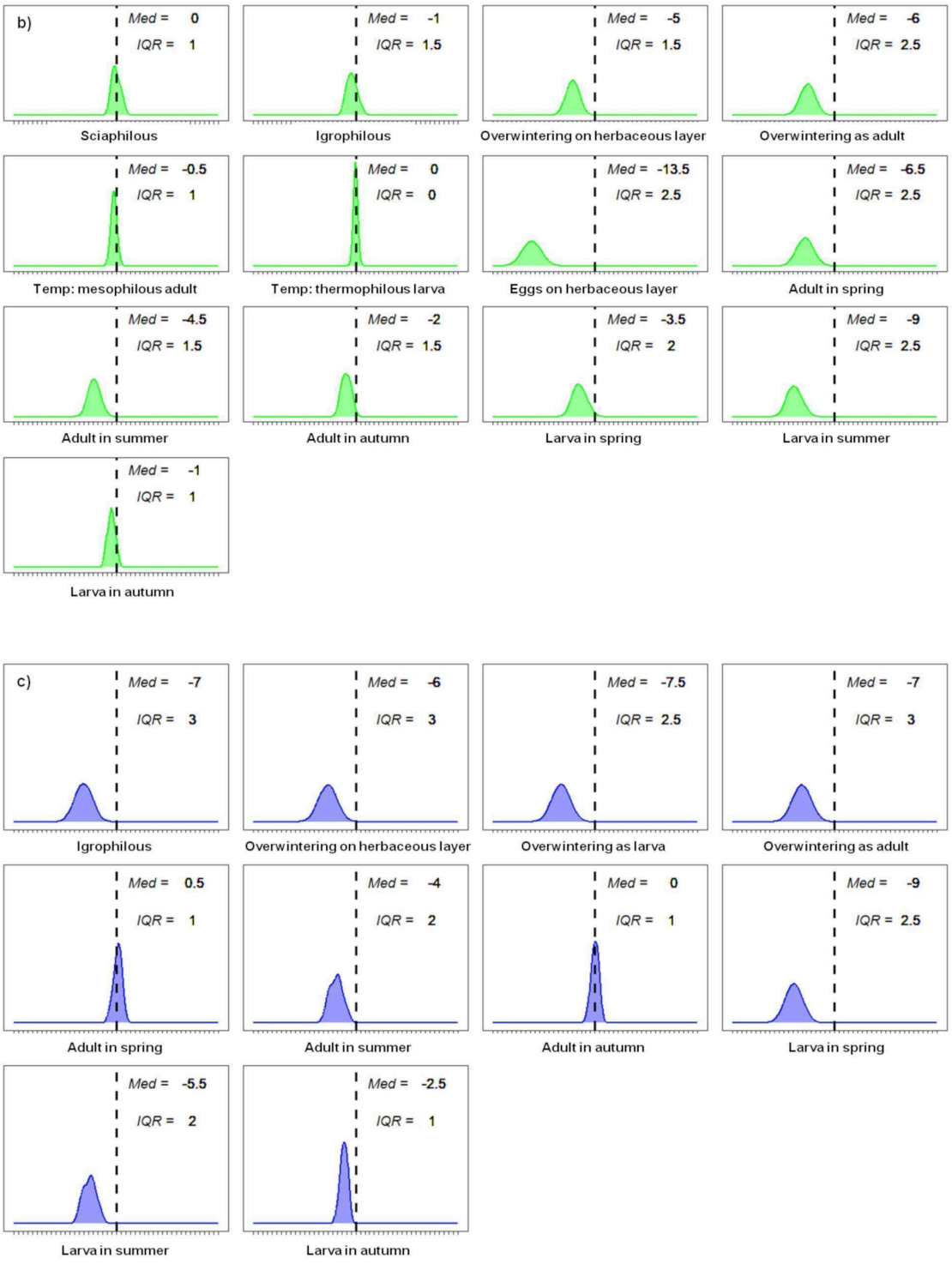

Figure 4. Kernel density distribution graphs (a) upper = butterflies, b) medium = dragonflies, c) lower = amphibians) of impact of simulated agricultural processes on considered functional traits. Specifically: a) a complete cycle of rice cultivation (considering all the 27 farming practices) was simulated for 10,000 replicates, randomly selecting one of the possible options per farming practice each time, so that there was a good sample of all the various possibilities; b) for each of these 10,000

simulations the impact on each of the considered trait option was calculated; c) each graph thus represents the frequency distribution of the impact values of the whole cycle on each trait option. Median (Med) and Inter-quartile-range (IQR) of the random distribution are shown. The vertical dotted line represents 0: Kernel distribution peaking on its left (median values lower than 0) indicates a negative impact, peaking on the right (median values higher than 0) indicates a positive impact, while 0 represents a neutral situation.

Concerning butterflies, the traits driving species vulnerability to rice life cycle are especially the one linking the species to the herbaceous layer (i. overwintering, egg laying and pupation). Also species with preferences in terms of humidity (hygrophilous and mesophilous) and with determined nutrient needs (oligrotrophic and mesophilous) are more vulnerable to the agronomic cycle. The spring emerges as a critical point both for butterfly adults and larvae, while dragonflies with summer larvae appear the most vulnerable and, in parallel, for amphibians we observed highest vulnerability for species with spring larvae and summer adults. To summarise, comparing the different taxa we observed that: a) butterflies have few weaknesses in terms of specific functional traits; b) dragonflies are very disadvantaged, even if the spring, autumn (or mixed phenology cases) species are less disadvantaged, showing a seasonal pattern; c) amphibians are very disadvantaged in practice for any tract. This clearly shows that there are common criticalities for some traits, but amphibians and dragonflies are particularly exposed at different points in their development cycles and independently of their specialisation.

Discussion

Methodological Achievements

To our knowledge, this study is the first to map the impact on natural biodiversity of all

the different agronomic and varietal options, following the entire rice crop cycle. The choice of key taxa made it possible to map the rice-bank-hedge interface in an effective and comprehensive manner (Giuliano et al., 2018; Bonelli et al., 2018). Through this approach, we reached our main objectives : (a) to identify the most biodiversity friendly options; (b) to identify practices where agronomic choice is crucial for biodiversity; (c) to propose a flexible methodology, that is "immediate" (maintaining the same analytical procedure, with a subset of different species) and "reasoned" (applicable to other cultivation contexts after adaptation of the whole life cycle matrices and the species involved). The analysis allowed us to identify the most impacting of practice clusters. These categories have greater differences in score (both according to MCDA, and for raw scoring, according to box plots). In particular, from MCDA analysis, the most influential practices clearly emerge as long cycle varieties, the heavier and earlier interventions (on soil tillage cluster) if late, crop defense and chemical weeding and practices related to early and late irrigation

Rice Variety Role and Impacts

Therefore, it is necessary to carefully choose the agricultural practices because the quantity of water and the disturbance caused by more intensive practices can affect the taxa more intensely, key elements that have already emerged from previous studies related to the rice paddy agro-system (Martínez-Megías et al., 2025; Katayama et al., 2019; De Stefano et al., 2014; Asghar et al., 2013). The variety, understood as variability of practices linked mainly to the length of the growing cycle, can also make a great difference for amphibians and dragonflies in terms of creating a suitable habitat for the two taxa (Ibidem). Farming bottlenecks for natural biodiversity in paddies and connected to varietal choice are typically varieties with higher input use, fit for dry and late sowing, low size and short crop cycles, such as herbicide resistant varieties that have dominated the Italian varietal landscape in the last 10 years (De Santis et al., 2022;

Vaglia et al., 2022). In fact, current predominant varietal traits, especially in the newly introduced varieties, meet agronomic efficiency criteria (dry sowing, short cycle, late interventions, low size, etc.), but less than those that are functional to the maintenance of an ecologically efficient replacement wetland in paddy fields (De Santis et al., 2022; Vaglia et al., 2022). The modulation of such impacting farming practices is possible, but for technical limitations and related representation is realistically reduced (typically according to a simplified High-Medium-Low scale) and, therefore, characterised by a restricted system modulability. The impact of the latter is then exacerbated by short crop cycles, and thus, there is late sowing and less water is used, especially in the central part of the crop cycle. In this sense, the damage can be contained through adequate zoning in the typology of practices selected by the companies, and favouring, in any case, an adequate water supply since mid-spring (Martínez-Megías et al., 2025; De Stefano et al., 2014). It would be necessary to rethink the choice of varieties in the context of impacts on natural biodiversity through the preference for climate resilient and genetically non-uniform varieties capable of combining rusticity traits suitable for agro-ecological systems, adapted for low use of external inputs, but also capable of supporting natural biodiversity, fully fulfilling paddies role as a wetland replacement (De Santis et al., 2022; Huynh et al., 2021; Pianca, 2019; Piano et al, 2017).

Farming Practices Role and Impacts: Bottlenecks for Biodiversity

Farming practices can be impartial or neutral, and as with a strongly differentiated impact, clearly showing the presence of real "bottlenecks" in the rice cropping cycle (Vaglia, 2022; Pianca, 2019; Piano et al, 2017). The main bottlenecks highlighted by agronomic practices are: soil tillage cluster operations related to the creation of the wet area of substitution, irrigation interventions, mechanical and chemical herbicides, phytosanitary treatments, and harvesting (Ibidem). In particular, the clusters of practices associated with negative scores are certainly those associated with herbicides,

plant-health treatments, intensive soil tillage and harvesting (Martínez-Megías et al., 2025; Orlando et al., 2020; Bacenetti et al., 2016). Conversely, irrigation practices are at the opposite extreme (Martínez-Megías et al., 2025; De Stefano et al., 2014; Lou et al., 2014). The former represent crucial moments both for the crop and for the taxa of natural biodiversity hosted in rice fields, so it is in the latter cases that the choice of the farmer can make a difference (Casali et al., 2016; Lou et al., 2014; Bambaradeniya and Amerasinghe, 2003). Other options can include machinery suitable for superficial soil tillage operations, and in general use of less disruptive machines such as towed and non-rotating machines (Martínez-Megías et al., 2025; Lu et al., 2022; Katayama et al., 2019). In this sense, the possibilities of farming practices modulation exist and vary from intensive to minimum disturbance of soil tillage, to methods for fungal and insect control, as well as for chemically-resistant weeds, if crop operations are reconsidered more precisely and repeatedly during the production season (Onorati et al., 2022; Lu et al., 2022; Bacenetti et al., 2016). A rice life cycle with a biodiversity-friendly approach should therefore include later soil tillage operations in the initial planning of the crop cycle and be characterized by the use of towed and non-rotating tillers, systems that guarantee a minimum continuity in rice cultivation (and therefore also in the organic farm should adopt medium-short crop rotation inserting in soil improving and biodiversity friendly rotations such as legumes), and the use of broadcasting seeding, whenever is possible, with reduced fertilising inputs (Katayama et al., 2019; Goded ,2019; Kaneko et al., 2014). More intensive but concentrated work and late in the season, such as shallow cultivation in particular if late, can be a good low-impact alternative for low-input crop systems, and at the same time consistent for wetlands taxa's life. The same trends emerge with elements that are related to the indirectly irrigated management component, especially in the earlier stages of taxa.

Agronomic Practices Role and Impacts: Neutral and Controversial Practices for

Biodiversity

Actually, there are many practice choices with a limited or neutral impact on the taxa considered. These include soil tillage, and sowing practices (for more specific observations see the sub-chapter on taxa). This, on the one hand, must push decision-makers at different operational levels, especially farmers, to focus on the technical-economic level, on "biodiversity" bottlenecks. At the same time, this result is a positive sign as it indicates how agricultural activity, even intensive, in humid areas is possible while safeguarding biodiversity. Moreover, certain practices may have contradictory and diverging effects, even good farming practices that are recognised and confirmed in the literature, such as the choice of rotations. These are emblematic of the specific cultivation and ecological characteristics of the wet agrosystem of rice fields. Similarly, organic farms, bound to crop rotations for reasons of opportunity and internal regulations, from this point of view, although in their choice of low-impact practices, can have greater impacts than conventional farms, at least for natural biodiversity (Vaglia et al., 2022; Zoli et al., 2022; Orlando et al., 2020). Equally critical for natural biodiversity is the choice of green mulch technique at sowing, often linked to rice growing systems in rotation, which, with its submerged grass layer in mid-spring time, determines a strong physical barrier and asphyxiating conditions in paddy fields unfit for many biodiversity taxa. Impacts on biodiversity can be limited with late operations, and avoiding dry techniques approaches if water is available (Orlando et al., 2020; Piano et al., 2017). While this technique is now considered almost a standard as a reference in the field of organic rice farming (De Santis et al., 2022; Vaglia et al., 2022), the environmental impacts in terms of GHGs emissions are not negligible, and similar to traditional methodologies such as submersion, but lower than the most recent ones that are widespread at the operational level such as dry, and often early, seeding, with vice versa higher impacts for biodiversity (Zoli et al., 2022; Vinci et al, 2014). Finally,

late harvests followed by immediate winter flooding could represent appropriate strategies to support natural biodiversity in paddies as substitute wetlands even in the period before wintering (Claudia Martínez-Megías et al., 2025; Katayama et al., 2015; Bambaradeniya and Amerasinghe, 2003).

Taxa-Specific Analysis

For butterflies, some farming practices with positive effects are emerging: sowing on green mulch, crop rotation with legumes and autumn soaking have positive effects. In this sense, an effective strategy could be to try to reduce the impact of the main practices, possibly with a greater focus on the dam-field sector. Weeding is the most critical practice for all taxa, but especially for butterflies. Similar results were observed in previous scientific literature (Mallick et al., 2023; Mäkeläinen et al., 2021; Robinson et al., 2012). On the other hand, for dragonflies, the most impactful practices are represented by early varieties, soil tillage operations (including false sowing) if early, dry, insecticidal treatments, weeding and harvesting, as also supported by prior experimental works (Giuliano and Bogliani, 2019; Giuliano et al, 2018; Casale et al., 2016). Instead, the selection of varieties with high water tolerance, the application of no rotation, early irrigation and autumn submersion can have strong positive effects. Our observations are supported by past relevant rice farming studies (Claudia Martínez-Megías et al., 2025; Katayama et al., 2015; Bambaradeniya and Amerasinghe, 2003) that, through experimental work on rice farming and water management, have observed the pivotal role of water management and maintenance. Finally, for amphibians, the most critical practices include irrigation followed by drying and herbicides (Hartel et al, 2020; Guerra and Araoz, 2015; Schuler et al., 2013). Partly similarly to dragonflies, for amphibians, positive effects are represented by varieties with high water tolerance and lodging, and the application of sowing in submersion, the absence of rotations, irrigation and autumn submersion, as previously observed in

literature (De Stefano et al., 2014; Lou et al., 2014). In general, dragonflies and amphibians include greater variability of environmental impacts as taxa, ranging from very negative to very positive. In this sense, their development needs a habitat that is unusual and closely dependent on water, and characterised by pre-adult stages more sensitive to the changing conditions of the environment (Giuliano and Bogliani, 2019; Giuliano et al, 2018; Casale et al., 2016). In synthesis, different taxa require combinations of different farming practices to achieve the same environmental sustainability level. Amphibians and dragonflies appear to be more closely related to paddies and vulnerable to rice farming, while butterflies represent a passage taxon, less exposed and sensitive as indicators, except for igrophilous species, effectively mapping out practices outside the paddies.

MCDA as flexible assessing methodology

This newly proposed MCDA-based approach includes a set of modulation options feasible both by biological farms and conventional farms, by selecting the potentially most critical cropping operations and reducing their related impacts on natural biodiversity (Vaglia et al., 2022; Orlando et al., 2020; Bacenetti et al., 2016). Therefore, an MCDA approach could further allow better calibration of the scope and outcome of choices based on the real, individual choices and reference policies. This approach is methodologically original, based on the cooperation between agronomists and biodiversity experts, and flexible according to farmers' needs, assessing specific farming criticalities in and out of the rice sector, possibly translatable into an app for immediate interface for users too. This study also represents a step forward in the field of environmental impact research, particularly by consolidating work on Life Cycle Assessment (LCA) and introducing an MCDA approach to environmental impact assessment in the category of natural and agrobiodiversity. It would be necessary to reshape the agrarian season structure through the choice of an operational chain aiming

at minimising impacts on biodiversity, identifying the most suitable specific varietal and farming practices options for each geographical area of the Italian rice district and the structure of the farm, and selecting the least-impactful practices for the key considered taxa (Vaglia et al., 2022; Orlando et al., 2020; Bacenetti et al., 2016). This can also play a relevant step towards a general re-evaluation of rice production at the economic and social level with added value activities, also in a logic of greater value of the product and attention to consumers aware of the environmental impacts of agricultural production, including those on natural biodiversity (Tokuoka et al., 2024; Herring et al., 2022; Mameno et al., 2021). In synthesis, the dual phenomenon of genetic erosion, natural and cultivated, is parallel and negative and must both be reversed to make the agro-system, both productive and food and natural, more resilient from the dual perspective of climate and biodiversity. This process of evaluation and integration of trade-off can and must also consider the synergy of the varietal and cultural choices with the semi-natural elements, present and restored, also promoted in the framework of the CAP itself (Agriregionieuropa, 2025; Ballesteros et al., 2025; Nature Restoration Regulation, 2025).

Conclusions

Rice farming practices are crucial in supporting or reducing the natural biodiversity associated with substitution wetlands. The impact or actions of interaction with biodiversity have, in this sense, a modulability both in qualitative and quantitative terms, in the sense of methodologies and crop intensification. The most relevant practices are related to the creation of artificial wetland habitats and the management of embankments and connections with other landscape elements. The results of our research show not only the need but also the concrete possibility of a dynamic, punctual and flexible management of the biodiversity in rice fields. In this sense, the presence of

production bottlenecks makes it possible to modulate production sites in rice fields, intervening with the least degree of productive and economic disturbance for the rice farm. The economic costs of a different agricultural practice in paddy fields, more respectful of natural biodiversity, are already estimated and have little impact when compared to the total production costs, even configuring itself as a business model with low use of productive inputs, while at the same time, having high efficiency of the inputs themselves and high environmental added value (Zoli et al., 2022; Vaglia et al., 2022; Bacenetti et al., 2016). The agricultural practitioners, through an MCDA approach, have the possibility of acting in support of natural biodiversity, with a logic of priority interventions, based on the ecological and naturalistic needs of the area considered. The logic of a "compromise for biodiversity" can also be integrated into a framework of valorisation and protection of other ecosystem services associated with wetland replacement areas (production, water balance, carbon storage, etc.), as well as in integration with other good agronomic and agroecological practices, such as agroforestry, the presence of semi-natural areas or fosses and water reservoirs within wetlands. The use of good practices for natural biodiversity can be seen as continuity with less environmental impact on agriculture, also in relation to other impact categories, namely greenhouse gas emission, carbon farming eutrophication, acidification, support to the pollinators bred, etc. Such research can play an important role in linking researchers and farmers, with the broader aim of providing concrete guidance for safeguarding the natural biodiversity associated with wetlands, at the same time, reducing possible economic losses and loading additional ecosystem values linked through low environmental impact business choices. In accordance with Article 11 of the Nature Restoration Law, European agricultural policies should be aligned towards maintaining ecosystem services in agro-systems, including in particular actions aimed at the restoration of natural habitats and integration with low-impact and more sustainable

farming practices for natural biodiversity, promoting more environmentally sustainable options within local implementation of CAP in national and regional regulations (Nature Restoration Regulation, 2025). In conclusion, the methodology proposed in the present study is: (a) flexible (adaptable to different crop cycles, target taxa and functional traits); (b) translatable into an app that can be used by farmers to choose the most biodiversity-friendly options; always following the double LCA-MCDA methodology based on functional traits, innovative and applicable to different agricultural contexts, combining conservationists and farmers' different perspectives, for a more sustainable agricultural approach on long term.

Supplementary Materials

- Supplementary Materials S1: Life Cycle Butterflies, Dragonflies and Amphibians Matrix
- Supplementary Materials S2: Crop Operations and Taxa Calendar
- Supplementary Materials S3: Rice Variety Traits
- Supplementary Materials S4: Analysis Matrix
- Supplementary Materials S5: Descriptive Statistics Matrix
- Supplementary Materials S6: R Script and data for analysis

Supplementary Materials are available to the author upon request in the repository: https://github.com/michelesalvan/Supplementary-Materials---Michele-Salvan-Ph.D.-

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Data Availability Statement

Data derived from public domain resources

The data that support the findings of this study are available in **References/Bibliography**. These data were derived from the following resources available in the public domain: **Supplementary Materials.**

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Chapter III

Biodiversity and Agro-Biodiversity Assessment at Different Spatial Scales in a Rice Farming District in Northern Italy

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Abstract

Reconciling natural biodiversity conservation with agroecosystems is a challenge for sustainable food systems. Organic rice production is increasing in Italy, promoting natural and agro-biodiversity. Rice fields can be considered wetland surrogates, crucial as biodiversity hotspots, and thus represent natural or semi-natural habitats within intensively farmed districts. The ecological role and value of rice fields increase when combined with agroecological farming practices. The aim of the current research was to assess the role of paddy fields in biodiversity promotion at different spatial scales in organic and conventional farming conditions, from surrounding environmental matrices to the sustainability of single farming practices. We developed a pool of scalable ecological indicators to assess wetlands-associated biodiversity according to the reference agro-system. Butterflies and dragonfly taxa were used as the main biodiversity and ecosystem services proxy. All low-impact rice farming practices on field banks such as improved soil cover and water level, reduced grass cutting and weeding, and increased botanical diversity prove to be effective for promoting biodiversity. We argue that insect monitoring can be integrated into rice farm appraisal to quantify crop and natural diversification levels. These data, correlated with biodiversity-friendly practices on a scalable field, farm, or district/landscape level, could become a useful tool to weigh the measured benefits of biodiversity-friendly rice management practices and related ecosystem services. Agro-ecological low-input rice farming practices can improve food system resilience against abiotic and biotic stresses caused by climate change, and enhance biodiversity and resilience at both farm and landscape scales.

Keywords: organic rice farming, butterflies, dragonflies, good farming practices, environmental indicators, climate change organic rice farming, butterflies, dragonflies, environmental indicators, climate change.

Introduction

Agricultural pressures on biodiversity in wetlands and paddies

Due to increased agricultural and urban soil occupation, biodiversity has been driven into urban areas and agrosystems, which tend to assume natural ecosystems' functions for wildlife (Hughes et al. 2023; Dasgupta 2021; Hasan et al. 2020).

Agricultural pressures on biodiversity in wetlands and paddies

Under agricultural and urbanism pressure, biodiversity has been driven into urban areas and agrosystems, Fields tend to assume natural ecosystems' functions for wildlife (Hughes et al. 2023; Dasgupta 2021; Hasan et al. 2020). However, the role of agriculture and global interactions with the environment and biodiversity are not fully investigated in public agricultural policies and farmers' priorities, despite severe environmental impacts (Mashilingi et al. 2022; Gemmill-Herren et al. 2021; Yaşın 2021). However, the role of agriculture and global interactions with the environment and biodiversity are not fully investigated in public agricultural policies and farmers' priorities, despite severe environmental impacts (Mashilingi et al. 2022; Gemmill-Herren et al. 2021; Yaşın 2021). The quantitative decline of species and species communities simplification associated with intensive agricultural activities is well documented for invertebrates and other animals (Whipple and Bowser 2023; Eisenhauer et al. 2019; Piccini et al., 2019; Zingg et al. 2018). The quantitative decline of species and species communities simplification associated with intensive agricultural activities is well documented for invertebrates and other animals (Whipple and Bowser 2023; Eisenhauer et al. 2019; Piccini et al.2019; Zingg et al. 2018). Notably, the change in the use of the soil, also related agricultural activities, is a major cause of invertebrate biodiversity decline, due to habitat change that involves feeding source depletion, host plant and hosting sites availability, inserting itself into the debate "land sharing" versus

“land sparing” options (Mallick et al. 2023; Whipple and Bowser 2023; Folke et al. 2021). The change in the use of the soil, also related to agricultural activities, is a major cause of invertebrate biodiversity decline, within the debate “land sharing” versus “land sparing” options. Habitat change involves feeding source depletion, host plant and hosting sites availability (Mallick et al. 2023; Whipple and Bowser 2023; Folke et al. 2021). This is particularly true for taxa highly dependent on grasslands and wetlands in Europe, including 71 threatened or nearly threatened species out of 435 (Schils et al. 2022; Davidson et al. 2021; Warren et al., 2020; Hochkirch et al., 2016; van Swaay et al., 2011). This is particularly true for taxa highly dependent on grasslands and wetlands in Europe, including 71 threatened or nearly threatened species out of 435 (Schils et al. 2022; Davidson et al. 2021; Warren et al., 2020; Hochkirch et al., 2016; van Swaay et al., 2011). In this sense, applying agri-environmental schemes, as the structuring in set of specific proposals of farms' support within the Common Agricultural Policies (CAP), intended as the whole set of agricultural policies implemented by the European Union (EU), could be strongly effective in reproducing biodiversity (Kleijn et al. 2019; Borsching et al. 2013; Delattre et al. 2013). In this sense, applying agri-environmental schemes, as the structuring in set of specific proposals of farms' support within the Common Agricultural Policies (CAP), intended as the whole set of agricultural policies implemented by the European Union (EU), could be strongly effective in reproducing biodiversity (Kleijn et al. 2019; Borsching et al. 2013; Delattre et al. 2013). Their increasingly propulsive function can act on multiple levels integrating farming practices, and on a wider landscape scale with a biodiversity-based agricultural approach (Tibi et al. 2024; Pelacho et al. 2013; Rundlöf et al. 2008). Their increasingly propulsive function can act on multiple levels integrating farming practices, and on a wider landscape scale with a biodiversity-based agricultural approach (Tibi et al. 2024; Pelacho et al. 2013; Rundlöf et al. 2008).

Therefore, agronomic and landscape complexity, as well as the increase of interfaces with semi-natural and the restoration of buffer areas are also able to provide Ecosystem Services in support of biodiversity itself (Tibi et al. 2024; Pianca 2019; Vasseur 2013). Therefore, agronomic and landscape complexity, as well as the increase of interfaces with semi-natural and the restoration of buffer areas are also able to provide Ecosystem Services in support of biodiversity itself (Tibi et al. 2024; Pianca 2019; Vasseur 2013). For instance, rice cultivation systems in Europe are historically associated with cultivated landscapes within high biodiversity floodplains and wetlands (Corli et al. 2021; Orlando et al. 2020; Mayer et al. 2019). For instance, rice cultivation systems in Europe are historically associated with cultivated landscapes within high biodiversity floodplains and wetlands (Corli et al. 2021; Orlando et al. 2020; Mayer et al. 2019). These landscapes work as a relevant reservoir for species most closely associated with wetlands, including amphibians, birdlife, and several arthropod taxa (Huynh et al. 2021; Giuliano et al. 2019; Piano et al. 2017). These landscapes work as a relevant reservoir for species most closely associated with wetlands, including amphibians, birdlife, and several arthropod taxa (Huynh et al. 2021; Giuliano et al. 2019; Piano et al. 2017). In particular, dragonflies and specific species of butterflies are strictly marsh-dependent (Bonelli et al. 2021; Bonelli et al. 2018; Giuliano et al. 2018). In particular, dragonflies and specific species of butterflies are strictly marsh-dependent (Bonelli et al. 2021; Bonelli et al. 2018; Giuliano et al. 2018). Thus, they are particularly sensitive and rely on rice field bank flora and grass cover maintenance, with a preference for poorly disturbed agricultural habitats (Mallick et al. 2023; Bonelli et al. 2021; Piano et al. 2017). Thus, they are particularly sensitive and rely on rice field bank flora and grass cover maintenance, with a preference for poorly disturbed agricultural habitats (Mallick et al. 2023; Bonelli et al. 2021; Piano et al. 2017). On this basis, it is crucial to identify and protect most wetlands-representative butterfly species, such as *Lycaena dispar*

(Haworth, 1803) (Bonelli et al. 2021; Bonelli et al. 2018; Giuliano et al. 2018). On this basis, it is crucial to identify and protect most wetlands-representative butterfly species, such as *Lycaena dispar* (Haworth, 1803) (Bonelli et al. 2021; Bonelli et al. 2018; Giuliano et al. 2018). A subsequent step may include developing specific farming practice recommendations, and identifying precise environmental indicators for the rice-focused agro-systems too (Orlando et al. 2020; Magaudda et al. 2020, Bianco and Bellucci 2017).A subsequent step may include developing specific farming practice recommendations. Identifying precise environmental indicators for the rice-focused agro-systems is crucial for assessing real impacts too (Orlando et al. 2020; Magaudda et al. 2020, Bianco and Bellucci 2017).

Rice farming sector's environmental role

From this point of view, Italy is prominent in rice farming and wetlands-related biodiversity in Europe, with 240,000 rice hectares (Ranghetti and Boschetti 2022; Mainini e Baici 2021; Mayer et al. 2019).

Rice farming sector's environmental role

From this point of view, Italy is prominent in rice farming and wetlands-related biodiversity in Europe, with 240,000 rice hectares (Ranghetti and Boschetti 2022; Mainini e Baici 2021; Mayer et al. 2019). Rice is often intensively farmed in a strategic geographical position in the Mediterranean-Central Europe interface (Ranghetti and Boschetti 2022; Mayer et al. 2019; Bacenetti et al. 2016). Rice is often intensively farmed in a strategic geographical position in the Mediterranean-Central Europe interface (Ranghetti and Boschetti 2022; Mayer et al. 2019; Bacenetti et al. 2016). In this unique farming context, the spread of "Green Revolution" farming practices has driven a massive loss of natural and cultivated biodiversity (De Santis et al. 2022; Canella et al. 2022; Orlando et al. 2020). In this unique farming context, the spread of "Green Revolution" farming practices has driven a massive loss of natural and

cultivated biodiversity (De Santis et al. 2022; Canella et al. 2022; Orlando et al. 2020). In recent years, the Italian rice farming sector has been built within a consolidated water balance (Mayer et al. 2019; Kritee et al. 2018; Azar et al. 2016). In recent years, the Italian rice farming sector has been built within a consolidated water balance (Mayer et al. 2019; Kritee et al. 2018; Azar et al. 2016). This plateau situation has been threatened by changing agro-climate conditions and low resilient business-as-usual rice farming practices (Ranghetti and Boschetti 2022; Orlando et al. 2020; Fusi et al. 2014). This plateau situation has been threatened by changing agro-climate conditions and low resilient business-as-usual rice farming practices (Ranghetti and Boschetti 2022; Orlando et al. 2020; Fusi et al. 2014). In this respect, the rice sector must deeply rethink the effect of its agricultural practices in global terms of climate and biodiversity impacts (Vaglia et al. 2022; De Santis et al. 2022; Mainini and Baici 2021). In this respect, the rice sector must deeply rethink the effect of its agricultural practices in global terms of climate and biodiversity impacts (Vaglia et al. 2022; De Santis et al. 2022; Mainini and Baici 2021). This effort will match increasing pressure for a reduction in environmental impacts carried out by public opinion and theEU's CAP (Magaudda et al. 2020; PSR 2014-2022 Piedmont; PSR 2014-2022 Lombardy). This effort will match increasing pressure for a reduction in environmental impacts carried out by public opinion and theEU's CAP (Magaudda et al. 2020; PSR 2014-2022 Piedmont; PSR 2014-2022 Lombardy).

State of the art and research demand

In this regard, good farming practice protocols promoting arthropods, and particularly butterflies, have been partially studied and proposed for mixed crop systems and mosaic landscapes, both intended as cropping systems that involve more than one crops and therefore create a diversified landscape (Tibi et al. 2024; Luppi et al. 2018; Sybertz et al. 2017). In this regard, good farming practice protocols promoting arthropods, and

particularly butterflies, have been partially studied and proposed for mixed crop systems and mosaic landscapes. The latter can be intended as cropping systems that involve more than one crops and therefore create a diversified landscape (Tibi et al. 2024; Luppi et al. 2018; Sybertz et al. 2017). Functional agri-environmental schemes for sustaining biodiversity within the fields are in place (Tibi et al. 2024; Gemmill-Herren et al. 2021; Couvillon et al. 2014). Functional agri-environmental schemes for sustaining biodiversity within the fields are in place (Tibi et al. 2024; Gemmill-Herren et al. 2021; Couvillon et al. 2014). Wide-range monitoring protocols on wetlands-associated taxa in Europe have been already successfully produced (Séchaud et al. 2022; Fabian et al. 2019). Wide-range monitoring protocols on wetlands-associated taxa in Europe have been already successfully produced (Séchaud et al. 2022; Fabian et al. 2019). However, a complete and representative series of studies concerning rice farming practices and associated biodiversity is still missing (Onorati et al. 2022; Giuliano and Bogliani 2019; Miniotti et al. 2016). However, a complete and representative series of studies concerning rice farming practices and associated biodiversity is still missing (Onorati et al. 2022; Giuliano and Bogliani 2019; Miniotti et al. 2016). Studies are mainly focused on crop climate impacts and resilience (Dara Guccione et al. 2021; Miniotti et al. 2016; Bechini and Bastoldi, 2009). Studies are mainly focused on crop climate impacts and resilience (Dara Guccione et al. 2021; Miniotti et al. 2016; Bechini and Bastoldi, 2009). Finally, a crucial step will be to define and include low-impact rice farming practices into specific agri-environmental schemes (Onorati et al. 2022; Huynh et al. 2021; Giuliano and Bogliani 2019). Finally, a crucial step will be to define and include low-impact rice farming practices into specific agri-environmental schemes (Onorati et al. 2022; Huynh et al. 2021; Giuliano and Bogliani 2019). The present study aims to identify the impacts of cultivation, in organic and conventional conditions, and landscape management practices associated with rice cultivation on biodiversity at

different territorial scales. The goal is to identify farming practices with positive effects, in particular for low-mobility arthropods that depend on the rice system for their life cycle. Another objective is to understand the minute interactions between entomological butterfly and dragonfly biodiversity and localized farming practices associated with paddies as substitutes for natural wetlands. The present study aims to identify the impacts on biodiversity of rice cultivation, in organic and conventional conditions, and scalable landscape management practices. The goal is to identify farming practices with positive effects, in particular for low-mobility and rice-dependent arthropods. Another objective is to understand the minute interactions between entomological butterfly and dragonfly biodiversity and localized farming practices associated with paddies as substitutes for natural wetlands.

Materials and Methods

Study Areas

The study area is located in north-western Italy inside the most relevant Italian rice cultivation district (Piedmont and Lombardy regions; see Fig. 1). Rice is the dominant crop in the north-western part (Provinces of Novara and Vercelli), while in the south-eastern area mixed crop systems include rice, corn, soybean, wheat, barley, and permanent meadows (Provinces of Pavia and Milan). Rice indeed dominates the agricultural landscape from the beginning of April to the end of May (when seeding is performed depending on the variety) up to harvesting time from late August to mid-October, depending on the variety and the climate of that year (Azar et al. 2016). Ten farms were selected to evaluate the impact of the practice of rice farming on butterfly and dragonfly biodiversity. The study area was in NW Italy (WGS84: 45.546492 - 45.256954 N, 8.321866 - 9.021354 E). Altitude varied between 221 and 98 above sea level, belonging to the lower part of the alluvial plain that originated during

the Würm glaciation, which started about 100,000–80,000 years ago. The landscape was the Po Plain (Po, Ticino, Sesia, Agogna, Macchiazza) mixing related valleys and sand depositions of fluvial origin, and important historical canals, notably Naviglio Grande and Naviglio di Bereguardo (Ranghetti and Boschetti 2022; Mayer et al. 2019; Azar et al. 2016). Soil textures were typically from sandy to medium and coarse in the southern part up to medium to clay in the upper plain part, with fluctuating phreatic groundwater in space and time. The climate of the Po Plain humid subcontinent was classified according to the Köppen climate classification (Kottek et al. 2006). In general, selected farms were scattered along the entire Piedmont-Lombardy Rice Farming Area, belonging to three different rice farming systems: 1) East Ticino River: mixed farming context, integrated with Po plain forest and small wetlands areas with medium-quality hedges and rows systems; 2) Lomellina: specialized rice farming context, with low-quality Po plain forests and hedges and rows systems; 3) Baraggia Vercellese: mixed farming context integrated with Po plain forest and small wetlands, with medium-quality hedges and rows systems. Farm photographic description is available in Supplementary Materials S1.

Farm Selection

Within these contexts ten farms were selected; five organic and five conventional farms. The organic farms were selected according to three principles: a) absence of chemical inputs (organic farms); b) availability to cultivate heterogeneous rice materials as trial; c) availability to carry out environmental monitoring on butterflies and dragonflies, detailing through GIS farming contexts and land cover. Buffer zones of 6 km were identified around each selected organic farm, considering three levels of scale: landscape (complete buffer zone, 6 km), farm (composed of different fields, hundreds of metres-1 km), and single experimental field (single farming units, hundreds of meters). Buffer distances were selected on the basis of entomological behaviour and ecological

buffer distance relevance (Zingg et al. 2018; Vasseur et al., 2013; Kadlec et al. 2011). Essentially the couple of transects (organic-conventional farms) in the experimental plan were selected to be specular, comparable, and proxy but not directly neighbouring (at an average distance of 1600 m) within 6 km buffer zones (Ibidem). Farms and farming contexts are shown in the Italian rice district map (Fig. 1):



Figure 1: General map of Italian Rice Farming District with farms involved (Green = organic; Red = conventional) mainly set in Lombardy and Piedmont regions in current research (Source: Authors elaboration 2025).

Taxa Selection

Butterflies and dragonflies were selected as indicators-taxa, being well-known indicators (e.g. Macri et al., 2023), and easy to monitor with standardized methods in a

wide range of ecosystems, farmland included, also due to high farming inputs sensitivity, including agrochemicals (Sevilleja et al. 2019; Sybertz et al. 2017). Butterflies are linked to the vegetation surrounding the rice field and some of them are linked to wetlands, such as *Lycaena dispar* (Bonelli et al. 2021). Dragonflies are linked to water management and aquatic vegetation for their reproduction (Huynh et al. 2021; Giuliano and Bogliani 2019; Giuliano et al. 2018). We monitored both of them with the Pollard standard linear transect, widely recognized as the standard method of entomological sampling on linear pathways (Pollard 1993; Pollard, 1977).

Transect Selection

Within each farm, five (organic) and five (conventional) transects were selected, from 580 to 1000 metres long . Despite the distances and differences in production methods, all the farms involved in monitoring, biological and conventional, were united by constant and recurring elements at the three scale levels considered. In particular, transects were selected within farms according to the following criteria: a) presence of ecotopes and ecotones presence; b) diversity of rice cultivars and rice farming practices; c) different crop systems; d) landscape-related elements: hedges, unpaved roads, water supply canal, etc. Transect GPS positions were recorded with a Garmin eTrex 20 with a precision of 3 m. Within each plot transect, operatively following actions were carried out: a) identification and count of butterflies (abundance and species richness); b) identification and count of dragonflies (abundance and species richness), simultaneously with the butterfly count; c) environmental data measurement (fixed); d) environmental data measurement (variables), simultaneously with entomological counts. In particular: a-b) butterfly and dragonfly communities were monitored from May to September 2022 for a total of 50 days of transect repetitions with favourable weather conditions. Functional traits and rarity criteria were considered to evaluate community composition and individual abundance (Datto Liberato et al. 2024; Sevilleja et al. 2019); c) variable

environmental data: a) pollard transect weather conditions data: time, temperature, wind, cloud cover; b) field conditions data: % nectar resources, mowing and weeding, water, crop, and grass height. At the same time, fixed environmental data on transect section characteristics (local flora composition, edge and row length, density and quality, neighbouring cultivation systems, presence of human artefacts, etc.) were collected. Subsequently, a farms-referred survey was performed to detect farm economic sustainability, also in a CAP scenario (Desantis et al. 2022; Graskemper et al. 2021; Luppi et al. 2018). Farm environmental sustainability, referred to 2021-2022, was detected according to ten categories, namely drought relevance, drought impact, soil tillage, pesticide treatments, irrigation, cover crop, crop rotation, common agriculture policy measures adherence, common agriculture policy measures inefficiency, impacts on biodiversity. Lastly, a survey-detected baseline referred to environmental impact score was defined (0=min; 5=max) and plotted in a graph (Tab. 2).

Statistical Analysis Steps

Type and steps of statistical analysis

Multivariable analysis in multiple phases was carried out with the aim of: a) understanding differences in terms of entomological diversity according to different production methods (biological and conventional) and different agro-environmental matrix features, through a pool of indicators at different scales (field, farm, landscape); b) to analyse specific impacts on butterfly and dragonfly biodiversity of the specific agro-environmental variables, at different landscape scales, with particular focus on open fields and management practices of field banks. To provide this spatial analysis we considered environmental variables collected in the field, integrated with environmental literature-based variables in farms and surrounding landscapes, creating three groups of differentiated and scalable variables: 1) Env1: landscape-farm scale; 2) Env2: local-field bank scale; 3) Env3: farm-field scale (Bacenetti et al. 2016; Santoro 2016; Mancinelli et

al. 2015; Schleuter et al. 2010; Bechini and Bastoldi 2009; Bockstaller et al. 2008; Gozdowski et al. 2008). The environmental indicator clusters of the farms (Env1, Env2, Env3) can be observed in Table 1:

Env 1: Farm Agrosystem	**Env 2 : Local-Field Bank**
Field Surface	Water Height
Hedges Score	Grass Height
General Disturb	% Covered Soil
Crop Number	% Bare Soil
% Rice Area	% Cut Surface
% Rice Field	N Flower
Index Landscape Complexity	
Index Crop Complexity	**Env 3 : Environmental Impact**
T Factor (Indigo Method)	Energetic Output
Shannon Index Area	Climate Change
Evenness Area	Ozone Depletion
Simpson Index Crop	Particulate Matter
Simpson Reciprocal Index Crop	Photochemical Ozone Formation
Simpson Diversity Index Crop	Freshwater Eutrophication
Margalef Index	Freshwater Ecotoxicity
Berger Parker Complementary Index	
Ecotope Richness Index	

Rice Connectivity
Environmental Impact Score

Table 1: Environmental indicator clusters:Env1= farm agro-system, Env2= local field bank, Env3= environmental impacts (Bacenetti et al. 2016; Santoro 2016; Mancinelli et al. 2015; Schleuter et al. 2010; Bechini and Bastoldi 2009; Bockstaller et al. 2008; Gozdowski et al. 2008).

Env 1, Env 2, and Env 3 environmental indicators are described in detail in Supplementary Materials S2 Table 2.

Type and steps of statistical analysis

Consequently, to fulfil the two major research aims the following analyses were performed: a) cluster analysis of environmental and context variables with a dataset without time references; b) correlation and regression analysis between entomological and agro-environmental, with a dataset containing separate information on a time and farm basis. In detail, statistical analyses included: 1) as a first step res. pca, scree plot, biplot, and ef-input analysis (separately on all Env1, Env2, and Env3 variables); 2) as a second step Env1, Env2, and Env3 variables were correlated, and later mutually independent variables, largely from Env2, were kept for subsequent regression analysis (glm and glmer). Specifically within linear and non-linear regressions the variables tested were: a) abundance and specific diversity of butterflies and dragonflies from the point of view of biodiversity; b) env 2 non-correlated variables: control condition (organic or conventional method), water height, grass height, % nectar, % rice field, % bare soil, % covered soil, % chemically weeded soil, number of essences, number of blooms, on the side of farmed agro-biodiversity and environmental and crop management practices at different scale levels. As the variables were recorded on transects of different length, which were considered as off-sets in the analysis, they were

standardized and tested to be not correlated with each other. At each hierarchical level (field, farm, landscape), variables related to butterfly and dragonfly abundance and richness were plotted versus all parameters, allowing us to establish which variables were linear and which were non-linear. Functional traits and rarity criteria were considered to evaluate community composition and individual abundance (Datto Liberato et al. 2024; Sevilleja et al. 2019). Statistical analyses were carried out with R statistical software, v.3.2.1 (R Development. Core Team, 2015). Each model was fitted using the "vegan" package in R (Oksanen, 2019). The dispersion of models was evaluated with the Poisson distribution with the "Dharma" package in R (Hartig 2019).

Results

A total of 31 butterfly species and 708 individuals, along with 24 dragonfly species and 4460 individuals were monitored from May to September 2022. A complete list of species and abundance is outlined in Supplementary Materials S2 Tables 3 and 4 by species, and 5 and 6 are detailed by transect. Species panorama was strongly dominated by generalist species, and less dependent on drought-affected botanical diversity on rice fields. As shown in Tables 3-4, the most abundant species is *Pieris rapae* (Linnaeus, 1758) for butterflies and *Sympetrum fonscolombii* (Sélys-Longchamps, 1776) for dragonflies. Among the least numerous there is a group of three species for butterflies and five for dragonflies, generalist and not particularly rare species. Many species are present with low numbers of individuals: one-third of the total captured individuals belong to *Sympetrum fonscolombii* and a quarter of the observations of butterflies are attributable to *Pieris rapae*. The situation is highly beta-diversity clustered. Generalist species for butterflies, typical of plain-agricultural areas, were associated with observed ecotonal species such as those belonging to the Genus *Thymelicu*s and *Ochlodes sylvanu*s (Esper, 1777). Conversely, the genus *Sympetrum* species typically associated

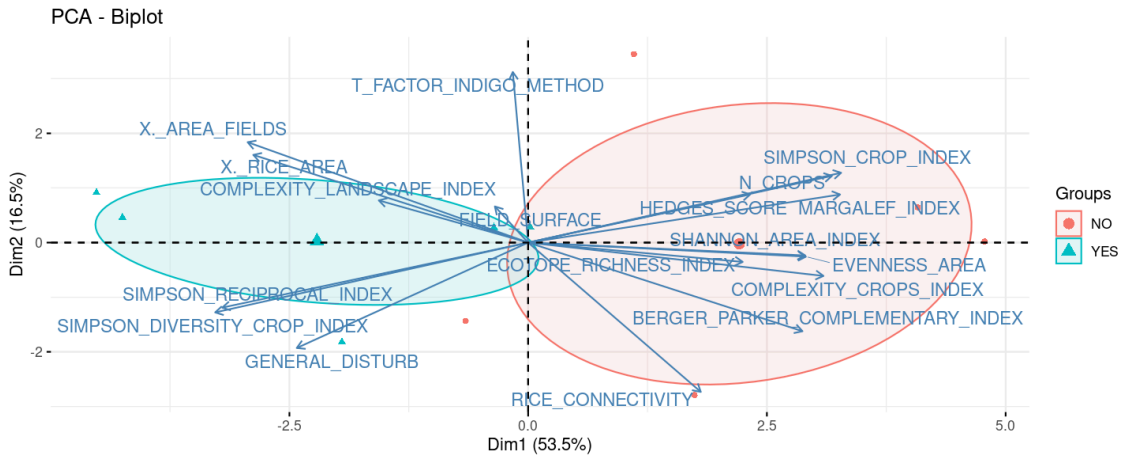
with surrogate wetlands appear separate from the already mentioned exceptions in a relatively small number. Environmental scores of the farms, from semi-structured survey information, are summarised in a sustainability radar chart (Tab. 2):

Fig. N. 2	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	Farm 7	Farm 8	Farm 9	Farm 10
10 - Biodiversity	5	3	1	1	5	3	3	2	2	4
9- CAP Efficiency	3	3	1	3	5	2	2	5	3	4
8 - CAP Measures	2	3	1	2	5	2	2	5	3	2
7 - Crop Rotation	2	2	2	1	5	1	4	5	5	4
6 - Cover Crop	4	1	2	1	5	1	5	5	5	5
5 - Irrigation	2	4	5	3	5	3	4	5	3	4
4 - Pest Management	1	1	1	1	5	2	2	5	4	4
3 - Soil Tillage	2	1	2	2	5	1	3	5	4	3
2 - Drought Impact	4	4	4	1	4	3	3	3	3	5
1- Drought Severity	5	5	5	5	5	5	5	5	5	5

Tab. 2: Farming practices and environmental impacts involved in current research. Organic farms are on the right side of the radar (1-5), conventional (6-10) on the left. Criteria include: 1 - drought severity, 2- drought impact, 3 - soil tillage, 4 - pest management, 5 - irrigation, 6 - cover crop, 7 - crop rotation, 8 - CAP measures, 9 - CAP efficiency and 10 - biodiversity. Score: 1 = min; 5 = max.

As in Tab. 2 the farms generally coded from 1 to 5 (organic) are characterized by higher scores related to the impact of agro-environmental practices, due to diversified farm choices and priorities. Farms from 6 to 10 (conventional) have lower scores in a framework of substantial uniformity, to simplified agro-climatic adaptive and environmental-positive practices. The first statistical analysis step results on crop and landscape variables (Env1 variables, Fig. 2 a), rice field bank-related indicators (Env2 variables, Fig. 2 b), and climate resilience farm-related indicators through data clusterization (PCA) are shown in Fig. 2 a-b:

a)



b)

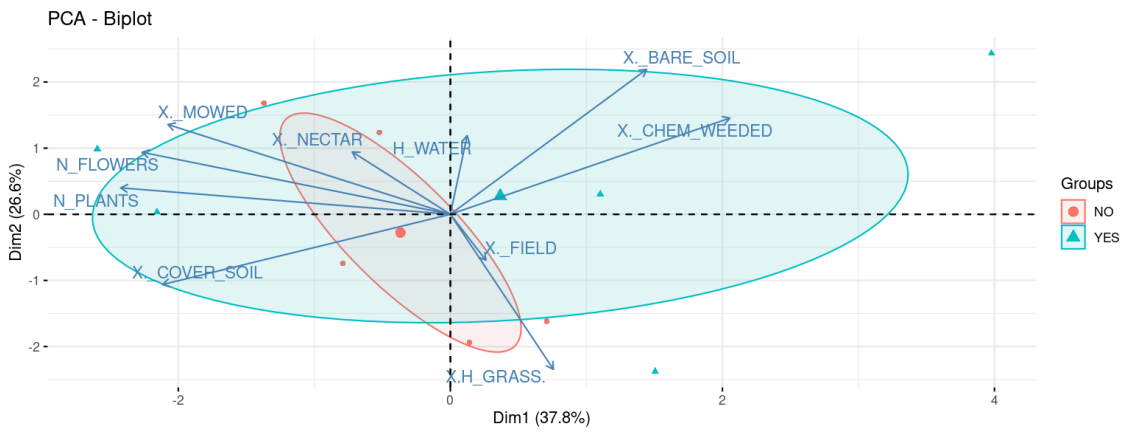


Fig. 2:

a) Farm clusterization PCA biplot graphs (Groups: Blue-SI= conventional farms; Rose-NO= organic farms). Env 1 variables include: Field Surface, Hedges Score, General Disturb, Crop Number, % Rice Area, % Rice Field, Index Landscape Complexity, Index Crop Complexity, T Factor (Indigo Method), Shannon Index Area, Evenness Area, Simpson Index Crop, Simpson Reciprocal Index Crop, Simpson Diversity Index Crop, Margalef Index, Berger Parker Complementary Index, Ecotope Richness Index, Rice Connectivity and Environmental Impact Score.

b) Farm clusterization PCA biplot graphs (lue-SI= conventional farms; ed-NO= organic farms). Env 2 variables include: % of Bare, Covered, % Mowed, % Weeded and % Flowered Soil, Grass, Crop and Water Height, and Number of Vegetable and Flowering Species on rice fields' banks.

According to the first step spatial and cluster analysis (Fig. 2 a-b), conventional and organic farm groups were merged into two clearly separated groups (organic and conventional farms) according to two levels of different environmental impacts, and driven by the local environmental matrix (Env 1 variables, Fig. 2 a) and site specific farming practices (Env2 variables, Fig. 2 b). Afterwards, time-detailed 2021/2022 entomological and farming season data were used in the second step of statistical analysis through linear and non-linear regressions, identifying significance (significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 "n.s." i.e.) for the following variables: a) butterfly abundance: % nectar*** (Fig. 3 a), number of essences*** (Fig. 3 b), number of blooms* (Fig. 3 c) % field , % bare soil (AIC= 497, BIC= 515.9, D = 0.090386, p-value = 0.6771, uniformity in Kolmogorov-Smirnov test); b) dragonfly abundance: % nectar*** (Fig. 4 a), number of essences*** (Fig. 4 b), number of blooms*** (Fig. 4 c), % bare soil***, % field**, Water height r* (AIC= 3151,8, BIC= 3170.6, D = 0.076086,

p-value = 0.8519, uniformity in Kolmogorov-Smirnov test); c) butterfly species richness: number of essences. (AIC= 265. 2, BIC= 284, D = 0.076086, p-value = 0.8519, uniformity in Kolmogorov-Smirnov test); d) dragonfly species richness: none (AIC= 244, BIC= 262.9, D = 0.076086, p-value = 0.8519, uniformity in Kolmogorov-Smirnov test).

Statistical analysis results graphs (non-linear regression, glmer) are shown in Fig. 3-4:

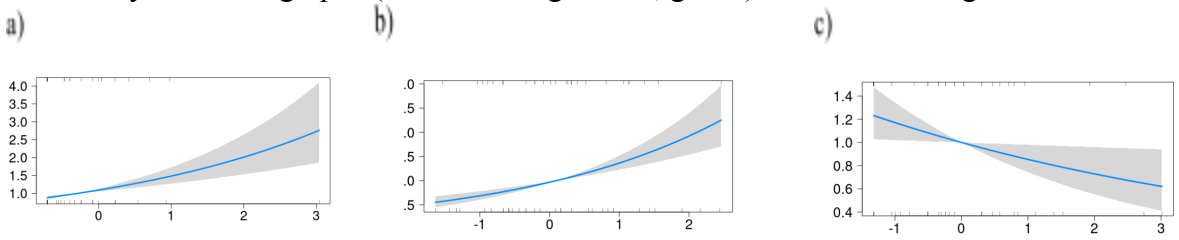


Fig.3:

a) Butterfly abundance (y) and flower abundance (% grassy strips) (x) nonlinear regression (lmer) graph.

b) Butterfly abundance (y) and vegetation species richness (N.) (x) nonlinear regression (lmer) graph.

c) Butterfly abundance (y) and flower species richness (N.) (x) nonlinear regression (lmer) graph.

Lines represent the best-fit models, shadows are the 95% confidence interval.

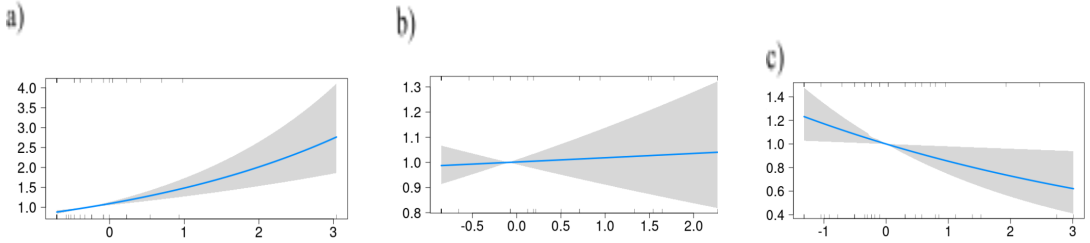


Fig. 4:

a) Dragonfly abundance (y) and flower abundance (% grassy strips) (x) nonlinear regression (lmer) graph.

b) Dragonfly abundance (y) and vegetation species richness (N.) (x) nonlinear

regression (lmer) graph.

c) Dragonfly abundance (y) and flower species richness (N.) (x) nonlinear regression (lmer) graph.

Lines represent the best-fit models, shadows are the 95% confidence interval.

The results of the regressions clearly illustrate how both butterflies (Fig. 3 a, b, c) and dragonflies (Fig. 4 a, b, c) show parallel trends in relation to the abundance, diversity of vegetation and nectar sources availability, showing the pivotal role of environmental variables monitored on a field scale (Tab. 1, Env 2) as most relevant in modelling the entomological butterfly and dragonfly biodiversity associated with wetlands. Given the relevance of mowing and chemical weeding practices in rice cultivation operations, it is evident how cropping systems, and their level of intensity in the level of inputs, interact directly with the natural component and potential level of biodiversity hosted in paddies.

Discussion

Entomological monitoring season

It is important to note that the season of 2022 was marked by severe drought conditions and low crop and vegetation growth. This resulted in the recording of fairly unbalanced data, with reduced butterfly and dragonfly population abundance and species richness. Data generally showed low biodiversity contexts, both for ecological conditions and for agro-climatic conditions in the 2021/2022 field season. As a caveat, we note how the 2022 spring-summer seasons were marked by thermic anomalies registered in Europe, severe drought from winter up to August, and heat stress for the crops. This posed bias to 2022 data collection: a) several constraints to the rice growing season; b) reduced rice emergence, slowed vegetative, postponed flowering, and grain ripening (Aghamolki et

al. 2014); c) severe infestation of weeds (particularly for *Echinochloa crus-galli* (L.) P.Beauv.) and *Cyperus spp.*), with reduced rice productivity; d) controlled pressure of pathogens both by high temperature and pre-seeding chemical (for conventional farms) or thermic (for organic farms) treatments (Viggiani and Tabacchi 2017; Bregante 2003).

a) Landscape-Farm scale

General 2022 entomological season conditions

It is important to note that the season of 2022 was marked by severe drought conditions and low crop and vegetation growth. This resulted in the recording of fairly unbalanced data, with reduced butterfly and dragonfly population abundance and species richness. Data generally showed low biodiversity contexts, both for ecological conditions and for agro-climatic conditions in the 2021/2022 field season. As a caveat, we note how the 2022 spring-summer seasons were marked by thermic anomalies registered in Europe, severe drought from winter up to August, and heat stress for the crops. This posed bias to 2022 data collection: a) several constraints to the rice growing season; b) reduced rice emergence, slowed vegetative, postponed flowering, and grain ripening (Aghamolki et al. 2014); c) severe infestation of weeds (particularly for *Echinochloa crus-galli* (L.) P.Beauv.) and *Cyperus spp.*); d) controlled pressure of pathogens with pre-seeding techniques (Viggiani and Tabacchi 2017; Bregante 2003). Other biases included reserved economic data availability and standardization, and a rigid monitoring protocol for involved farms, which limited the inclusion of conventional farms in experimental design. Other biases included: a) reserved economic data availability and standardization; b) rigid experimental design, limiting conventional farms involvement.

Butterflies Diversity

Data relevant to the butterflies collected during the 2022 field season were dominated by generalist low-mobile species (Supplementary Materials S2, Table 3). A significantly greater abundance of butterflies were found on less disturbed and more diversified field

embankments. Generally lower inputs and conditions of farming practices positive for biodiversity include major soil cover, flora, and diversity of nectar resources, and proximity of well-connected to semi-natural local landscape elements (Fig. 2 a). In addition, regarding butterflies, severe drought conditions on rice fields affected insect abundance, therefore the first counting months were marked by fewer clustered observations compared to a standard climatic season. In particular for butterflies, the most abundant species such as *Pieris rapae*, *Coenonympha pamphilus* (Linnaeus, 1758), and *Colias croce*a (Geoffroy, 1785) are unsurprisingly, being favoured by the presence of very abundant cultivated cruciferous plants, also present in areas adjacent to that strong disturbance. No other crops were used as host plants by butterfly larvae. The abundance of species more closely related to herbaceous cover such as those linked to meadows, pastures, and grassland is low, as well as the specific species referred to as species especially suitable for wetlands (Gatti et al. 2021; Zing et al. 2018; Börschig et al. 2013).

Dragonflies Diversity

Generally, the lack of water supply (and surface irrigation systems) up to late August 2022 severely reduced biodiversity in terms of species richness also for dragonflies. Dragonfly communities were similarly dominated by generalist lowland-still water species with a clear unique mid-summer peak (Supplementary Materials S2, Tab. 4). Regarding dragonflies, the dominant species were the very common *Sympetrum fonscolombii*, *Calopteryx splendens* (Harris, 1780) and *Orthetrum albistylum* (Sélys-Longchamps, 1848). Dragonflies' beta diversity is much more clustered than that of butterflies. This bottleneck of species is much more pronounced, and probably indicates the major impact of uniformity of cultivation and landscape practices on this taxon. Dragonflies seem much more dependent on favourable agro-environmental conditions determined to low-impact practices and, in particular, water management.

They lack alternative habitats to rice fields and irrigation networks compared to butterflies (Onorati et al. 2022; Huynh et al. 2021; Giuliano and Bogliani 2019; Giuliano et al. 2018). The specific richness of both butterflies and dragonflies is much less sensitive to environmental conditions, and more closely dependent on the management practices of the embankments of the fields. In this case, a richer agro-environmental matrix is probably a key factor in explaining this phenomenon (Tibi et al. 2024; Castellano et al. 2022; Labeyrie et al. 2021; Luppi et al. 2018; Vasseur et al. 2013).

Plants and Butterflies Diversity

Based on statistical regressions, major plant diversity can increase larval survival and development through a wider host plant range. At the same time, more individuals are sustained due to greater nectar availability, habitat diversification, and protection (Fig. 3-4). Regarding the second objective and analytical step, it is evident how the referred variables of rice field banks (env 2) are the most relevant to defining local environmental conditions determining abundance and specific diversity, both for butterflies and dragonflies. In particular Lepidoptera (Fig. 3) are more exposed and sensitive to field management practices, in particular those concerning water, soil cover, and botanical diversity management, compared to Odonata (Fig. 4). This was apparently demonstrated to be less dependent on the disturbance due to human activities. The control variable was not significant in any case, placing the focus on single practices more than general farming methods. For example Fig. 3 a and c, the percentage of flowered strips emerged to be key elements in promoting butterfly abundance, probably in terms of nectar and host plant availability, while in Fig. 3 a and b, flower and plant diversity seem to play reverse dynamics. Plants and non-flowering plant diversity seem to be the key to promoting butterfly alpha diversity, probably because they are more linked to the life cycle of butterflies in terms of food resources for larvae. In detail

lower soil cover (<40%), especially after frequent mowing and chemical weeding intervention offers lower quality, simplified habitats, and ultimately less entomological-friendly habitats (Fig. 3 a, b, c). More precisely, the heterogeneity of rice bank flora was preferred by both taxa, particularly butterflies (Fig. 3 a,b, c). Conversely, high input and farming pressure on rice field banks offer more disturbed and environmental network-weakened habitats, less attractive for butterflies.

Plants and Dragonflies Diversity

Viceversa for dragonflies in Fig. 4 c, flower diversity is a very weak variable to explain the alpha-diversity of dragonflies. Due to their feeding habits, in Fig. 4 a and b, the percentage of flowered strips and plant diversity are consistently aligned in associating with a greater alpha-diversity with the presence of habitats less disturbed by intensive agricultural practices and richer in hunting and refuge microhabitats, particularly relevant for dragonflies. In synthesis, different variable clusters for regression essentially underline agronomic practices. In particular, those referring to the management of rice field banks (Fig. 4) are relevant, even if indirectly, as well as the indices of cultural-landscape diversity (Fig. 2-4) for biodiversity support and promotion. Dragonflies in terms of individual abundance, but not on species richness, appear to be equally related to reduced pressure of farming practices on the rice field banks on flying and hunting habits. Ecosystem diversification does not seem to be connected with Odonata's species diversity. Common, generalist and more competitive species prevail anyway (Supplementary Materials, Table 2). Moreover, a "biodiversity derived effect" can be found in conventional control farms with its surroundings, hence farming practices and surface water availability (irrigation networks, water reservoirs, etc). In particular, those focused on field banks, can have direct and significant consequences on local entomological diversity (Fig. 4), especially in conventional farms with a generally high disturbance rate for biodiversity compared to organic ones (Onorati et al. 2022;

Hervè et al. 2020; Giuliano et al. 2019; Pianca 2019; Luppi et al. 2018; Ouvrand et al. 2017; Ernoult et al. 2013). Furthermore, superior soil cover (90-100%) and flora richness support a higher number of larvae, nectar resources, and hunting prey for dragonflies. These last are strongly exposed to heat waves and climatic shock, as during the 2022 field and monitoring season. Flora abundance and species richness are definitely crucial to support entomological butterfly and dragonfly biodiversity, even for dragonflies, even if their life cycle does not directly involve plants' presence (Fig. 4).

Environmental and Landscape Matrix Diversity

At the same time, first step cluster analysis indicates that for landscape quality indicators, organic and conventional farms belong to two well-separated groups, one high input and uniform inside and the other more diversified in terms of crops and landscape (Table 1, env 1 variables). Different clusters are also present considering farm pollution and climate change potential, which are levelled downwards in organic farms. Conversely, conventional farms situated on higher scales offer differentiated climate resilience performances. However, a different but partially overlapped cluster emerges from rice field bank-related indicators (Table 1, env2 variables). This illustrates similar internal conditions, with slightly different internal variability between the groups. In general terms, data analysis clearly shows how conventional rice farming practices and environmental context usually appear less variable in terms of species richness, with a high incidence of high mobility generalist species. Organic rice farming typically includes more diversified and complex landscape elements (e.g. hedges and rows) integrated with natural or semi-natural elements, such as regional, national, or European protected areas (Castellano et al. 2022; Magaudda et al. 2020; Luppi et al. 2018; Staley et al. 2016; Borshing et al. 2013; Rundlöf et al. 2008).

Specific Low-Impact Farming Practices Relevance

Within the second step of the analysis, it is revealed that farming practices that favour soil protection (e.g. soil cover, cover crops, flora variety, good edges, and row systems, etc.) are to be considered key for climate resilience. These environmental conditions also support biodiversity protection in wetlands areas of target, good environment-proxy, and Habitats Directive protected species (Fig. 4). Water management is the other crucial factor in determining local field banks-related environmental conditions, reducing environmental impacts, and supporting biodiversity (Giuliano et al. 2019; Mayer et al. 2019; Miniotti et al 2016). The same field-bank-based approach can, primarily, contribute to sustaining natural diurnal butterfly and dragonfly populations in highly productive farmland areas, including high-value and rare species, maintaining the potential of rice paddy wetland substitution (Fig. 3-4). Intensive and high impacts on biodiversity practices, such as chemical weeding, frequent mowing, and intensive soil tillage can severely deplete specific rice field bank conditions for butterflies (Tibi et al. 2024; Mallick et al. 2023; Pianca 2019). For example, reducing nectar sources and availability of host plants, and promotion of aggressive and low biodiverse weeds depletes natural entomological butterfly and dragonfly biodiversity. In addition, dragonflies are disturbed during hunting habits and due to reduced prey abundance. A positive role on insect communities of cheaper low-input field bank management and reduced frequency-farming practices is suggested (Fig. 3-4). Thus, reduced impact farming practice support is crucial to be strengthened in the CAP agro-schemes (Hervè et al. 2020; Giuliano et al. 2019; Pianca 2019; Luppi et al. 2018; Sybertz et al. 2017; Ernoult et al. 2013; Van Swaay et al. 2010).

Environmental and Landscape Matrix Diversity

At the same time, first step cluster analysis indicates that for landscape quality indicators, organic and conventional farms belong to two well-separated groups. One groups within high input and uniform farms; the other is diversified in terms of crops

and landscape (Table 1, env 1 variables). Different clusters are also present considering farm pollution and climate change potential, reduced in organic farms. Conversely, conventional farms situated on higher scales offer differentiated climate resilience performances. However, a different but partially overlapped cluster emerges from rice field bank-related indicators (Table 1, env2 variables). This illustrates similar internal conditions, with slightly different internal variability between the groups. Conventional rice farming practices and environmental context usually appear less variable in terms of species richness, with a high incidence of high mobility generalist species. Organic rice farming typically includes more diversified and complex landscape elements. They are also better integrated with natural or semi-natural elements, such as regional, national, or European protected areas (Castellano et al. 2022; Magaudda et al. 2020; Luppi et al. 2018; Staley et al. 2016; Borshing et al. 2013; Rundlöf et al. 2008).

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dragonfly biodiversity. In addition, dragonflies are disturbed during hunting habits and due to reduced prey abundance. A positive role on insect communities of cheaper low-input field bank management and reduced frequency-farming practices is suggested (Fig. 3-4). Thus, reduced impact farming practice support is crucial to be strengthened in the CAP agro-schemes (Hervè et al. 2020; Giuliano et al. 2019; Pianca 2019; Luppi et al. 2018; Sybertz et al. 2017; Ernoult et al. 2013; Van Swaay et al. 2010).

b) Field Scale

Butterflies Diversity

Data relevant to the butterflies collected during the 2022 field season were dominated by generalist low-mobile species (Supplementary Materials S2, Table 3). A significantly greater abundance of butterflies were found on less disturbed and more diversified field embankments. Generally lower inputs and conditions of farming practices are positive for biodiversity. They include major soil cover, flora, and diversity of nectar resources, and proximity of well-connected to semi-natural local landscape elements (Fig. 2 a). Severe drought conditions on rice fields affected butterfly abundance, the first counting months were marked by fewer clustered observations compared to a standard climatic season. The most abundant butterfly species such as *Pieris rapae*, *Coenonympha pamphilus* (Linnaeus, 1758), and *Colias croce*a (Geoffroy, 1785) are being favoured by the presence of very abundant cultivated cruciferous plants. No other crops were used as host plants by butterfly larvae. The abundance of species more closely related to herbaceous cover and wetlands is low (Gatti et al. 2021; Zing et al. 2018; Börschig et al. 2013).

Dragonflies Diversity

The lack of water supply up to late August 2022 severely reduced biodiversity in terms of species richness also for dragonflies. Dragonflies communities were similarly

dominated by generalist lowland-still water species with a clear unique mid-summer peak (Supplementary Materials S2, Tab. 4). The dominant species were the very common *Sympetrum fonscolombii*, *Calopteryx splendens* (Harris, 1780) and *Orthetrum albistylum* (Sélys-Longchamps, 1848). Beta diversity is much more clustered than that of butterflies. This bottleneck of species is much more pronounced. This probably indicates the major impact of uniformity of cultivation and landscape practices on this taxon. Dragonflies seem much more dependent on favourable agro-environmental conditions determined to low-impact practices and water management. They lack alternative habitats to rice fields and irrigation networks compared to butterflies (Onorati et al. 2022; Huynh et al. 2021). The specific richness of both butterflies and dragonflies is much less sensitive to environmental conditions. This condition is more closely dependent on the management practices of the embankments of the fields. In this case, a richer agro-environmental matrix is probably a key factor in explaining this phenomenon (Castellano et al. 2022; Labeyrie et al. 2021; Luppi et al. 2018; Vasseur et al. 2013).

Plants and Butterflies Diversity

Based on statistical regressions, major plant diversity can increase larval survival and development through a wider host plant range. At the same time, more individuals are sustained due to greater nectar availability, habitat diversification, and protection (Fig. 3-4). Regarding the second objective and analytical step, it is evident how the referred variables of rice field banks (env 2) are the most relevant to defining local environmental conditions. The latter determine abundance and specific diversity, both for butterflies and dragonflies. In particular butterflies (Fig. 3) are more exposed and sensitive to field management practices. Practices concerning water, soil cover, and botanical diversity management are far more sensitive for butterflies compared to Odonata (Fig. 4). This was apparently demonstrated to be less dependent on the

disturbance due to human activities. The control variable was not significant in any case, placing the focus on single practices more than general farming methods. For example Fig. 3 a and c, the percentage of flowered strips emerged to be key elements in promoting butterfly abundance. Probably flower and plant diversity seem to play reverse dynamics in terms of nectar and host plant availability (Fig. 3 a and b). Plants and non-flowering plant diversity seem to be the key to promoting butterfly alpha diversity. In fact they are more linked to the life cycle of butterflies in terms of food resources for larvae. Lower soil cover (<40%) simplified habitats, and ultimately less entomological-friendly habitats (Fig. 3 a, b, c). More precisely, the heterogeneity of rice bank flora was preferred by both taxa, particularly butterflies (Fig. 3 a,b, c). Conversely, high input and farming pressure on rice field banks offer more disturbed and environmental network-weakened habitats, less attractive for butterflies.

Plants and Dragonflies Diversity

Viceversa for dragonflies in Fig. 4 c, flower diversity is a very weak variable to explain the alpha-diversity of dragonflies. Due to their feeding habits, in Fig. 4 a and b, the percentage of flowered strips and plant diversity are consistently aligned in associating with a greater alpha-diversity. The latter is also connected with the presence of habitats less disturbed by intensive agricultural practices and richer in hunting and refuge microhabitats, particularly relevant for dragonflies. In synthesis, different variable clusters for regression essentially underline agronomic practices. In particular, those referring to the management of rice field banks (Fig. 4) are relevant, even if indirectly. As well as the indices of cultural-landscape diversity (Fig. 2-4) for biodiversity support and promotion. Dragonflies' individual abundance appears to be equally related to reduced pressure of farming practices on the rice field banks. This can be linked to flying and hunting habits. Ecosystem diversification does not seem to be connected with Odonata’s species diversity. Common, generalist and more competitive species prevail

anyway (Supplementary Materials, Table 2). Moreover, a “biodiversity derived effect” can be found in conventional control farms. This is particularly true in their surroundings for different farming practices and surface water availability. In particular, those focused on field banks, can have direct and significant consequences on local entomological diversity (Fig. 4), Conventional farms show a generally high disturbance rate for biodiversity compared to organic ones (Onorati et al. 2022; Hervè et al. 2020; Giuliano et al. 2019; Pianca 2019; Luppi et al. 2018; Ouvrand et al. 2017; Ernoult et al. 2013). Furthermore, superior soil cover (90-100%) and flora richness support a higher number of larvae, nectar resources, and hunting prey for dragonflies. These last are strongly exposed to heat waves and climatic shock, as during the 2022 field and monitoring season. Flora abundance and species richness are definitely crucial to support butterfly and dragonfly biodiversity. This is even more relevant for dragonflies, considering the fact that their life cycle does not directly involve plants’ presence (Fig. 4).

Future Research Topic

There are several open areas of investigation to explore in greater detail related to: a) farmers' role in promoting crop, landscape, and entomological diversity, starting from rice farming areas in a high biodiversity context, such as the Ticino River Regional Park; b) different farming and agro-environmental conditions in 2023 compared to 2022, including reduced rice surface, more diversified crops, and increase of grassland and leguminous crops; c) features of mutated rice farming contexts, due to crop diversification with relevant results in ecological terms, even in hyper-simplified areas. For example a subsequent research step could be to address farm-specific species richness for butterflies and dragonflies. In particular, agro-ecological practices and farm-specific context in-depth analysis can be performed following a scale approach. This starts from a local rice field bank (richness and management of bank flora,

essences, nectar, etc.), to a farm and field agro-system in terms of global sustainability. Further analyses should include water management timing, different rainfall regimes, water height, quality and availability, and management climatic and economic resilience measures. Moreover, surrounding agro-ecosystem elements, including hedges, rows, and channel networks, are crucial in a deep farm agro-ecological analysis. Including more detailed indices of landscape and cultural diversity could be useful. Notably, more specific indices that connect biodiversity and crop- or cultivar-specific farming practices diversification should be included. A subsequent step will include a short time series comparison, even with different wetlands-associated taxa (butterflies, dragonflies, amphibians, birds).

Conclusions

The current study suggests that a new multifunctional approach combining site-specific entomological and farming system characteristics can be implemented in rice farming contexts. In general, our study shows that information gathered from entomological monitoring, paired with vegetation community data, can be useful to provide crucial management indications for maintaining local biodiversity. It is particularly true within a wide but relatively homogeneous study area, such as with little variation in terms of soil, altitude, and surrounding farming context. It is noteworthy that the trial was performed in a real intensively farmed rice production context, both conventional and organic. More specifically, the present study of farming demonstrates how farming practices can affect entomological butterfly and dragonfly biodiversity, especially on very site-specific environmental indicators, despite formal cultivation methods. In particular, crop and farm landscape diversification, low input, promotion of low environmentally impactful farming practices, and surrounding field flora community integration can sustain biodiversity. The most local scale farming practices are the most

relevant for explaining the richness and diversity of the taxa considered. In fact, in the rice sector, farming practices are important for natural wetlands-related biodiversity, even more than the official classification of the farms. A subsequent research step could be to address farm-specific species richness for butterflies and dragonflies. In particular, agro-ecological practices and farm-specific context in-depth analysis can be performed following a scale approach. This starts from a local rice field bank (richness and management of bank flora, essences, nectar, etc.), to a farm and field agro-system in terms of global sustainability. Further analyses should include water management timing, different rainfall regimes, water height, quality and availability, and management climatic and economic resilience measures. Moreover, surrounding agro-ecosystem elements, including hedges, rows, and channel networks, are crucial in a deep farm agro-ecological analysis. Including more detailed indices of landscape and cultural diversity could be useful. Notably, more specific indices that connect biodiversity and crop- or cultivar-specific farming practices diversification should be included. A subsequent step will include a short time series comparison, even with different wetlands-associated taxa (butterflies, dragonflies, amphibians, birds). Current research findings suggest that maintenance and promotion of wetlands-associated biodiversity in areas of intensive agriculture is possible. This can be even more successful and scalable if properly supported by clear analysis indices and protocols. Consequently, this could also promote coexistence through land sharing between biodiversity species on wetlands and intensive farm production. There are several open areas of investigation to explore in greater detail related to: a) farmers' role in promoting crop, landscape, and entomological diversity, starting from rice farming areas in a high biodiversity context, such as the Ticino River Regional Park; b) different farming and agro-environmental conditions in 2023 compared to 2022, including reduced rice surface, more diversified crops, and increase of grassland and leguminous crops; c)

features of mutated rice farming contexts, due to crop diversification with relevant results in ecological terms, even in hyper-simplified areas.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

Supplementary Materials

- Supplementary Materials S1:
  - Table 1: Farms transects description and features (authors' elaboration 2025).
  - Table 2: Farms' environmental indicators clusters: Env1= Farm Agro-System, Env2= Local field Bank, Env3= Environmental Impacts (Bacenetti et al. 2016; Santoro 2016; Mancinelli et al. 2015; Schleuter et al. 2010; Bechini and Bastoldi 2009; Bockstaller et al. 2008; Gozdowski et al. 2008).
  - Table 3-4: Lepidoptera and Odonata species and abundance in monitored farms in 2022 (authors elaboration 2025).
  - Table 5: Lepidoptera Abundance in monitored farms in 2022 (authors elaboration 2025).
  - Table 6: Odonata Abundance in monitored farms in 2022 (authors elaboration 2025).
- Supplementary Materials S2: Supplementary Materials 2 - Figures 4-5 (Original Version)

Supplementary Materials are available to the author upon request in the repository: https://github.com/michelesalvan/Supplementary-Materials---Michele-Salvan-Ph.D.-

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Chapter IV

Community Seed Banks in Europe: their role between ex situ and on farm conservation

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Abstract

This article enlightens the role of community seedbanks (CSBs) in Europe within the plant genetic resources for food and agriculture community and their role in the conservation and sustainable use of agrobiodiversity in complementarity with the ex situ management system. For more than 40 years, CSBs around the world have emerged as part of the so-called informal seed system to counteract the loss of locally adapted varieties through the development of collective seed systems. Most of the studies and articles refer to experiences from the Global South, whereas a comprehensive analysis of the impact and role of CSBs on seed systems in industrialized countries is still missing. This paper provides three case studies describing the community seed banking experience of different European organizations: Pro Specie Rara (Switzerland), Arche Noah (Austria) and Rete Semi Rurali (Italy). These organizations exemplify the diversity among European CSBs and their efforts to engage with genebanks and the formal seed system.

Keywords: community seedbanks, agrobiodiversity, participatory plant breeding, on-farm conservation, seed networks

1. Introduction

This article describes the role of community seedbanks (CSBs) in Europe in the plant genetic resources for food and agriculture (PGRFA) community and their contribution to the conservation and sustainable use of agrobiodiversity in complementarity with the *ex situ* management system. Recently, two EU Horizon projects (DYNAVERSITY: www.dynaversity.eu and Farmers' Pride: https://more.bham.ac.uk/farmerspride/) have worked on this complementarity promoting the emergence of a European network of actors involved in PGRFA conservation and use. Both projects have involved CSBs in

their activities and developed manuals and guidelines for the management of CSBs in connection with public genebanks. But what are the main differences between CSBs and genebanks? If the complementarity between *ex situ* and on-farm conservation of PGRFA has been accepted by the scientific community in the last 20 years, less attention has been given to investigating the role of CSBs in relation to these two systems. Only a few scholars have studied such collective endeavours (e.g. Vernooy *et al.*, 2015) while national seed policies hardly include CSBs among the relevant institutions for conservation and sustainable use of PGRFA. A quantitative study on the impact of CSBs and civil society organizations (CSOs) in the European conservation system of PGRFA is still lacking. Many questions about their role can be addressed. How can they act as an intermediate between genebanks and farmers/gardeners? How can they increase the awareness of citizens on biodiversity conservation? How can they work with public research centres to support participatory plant breeding programmes? How can they diversify European seed systems and, subsequently, food systems? It becomes important to better understand the functions as well as the practical and collective actions of CSBs, based on concrete experiences. This article aims to fill this gap, presenting three case studies from Italy, Switzerland and Austria, based on the personal experiences of the authors, who work with the three organizations, and on the results of surveys and workshops organized within the framework of four EU-funded research projects – DIVERSIFOOD (https://diversifood.eu/), DYNAVERSITY, Farmers' Pride and PRO-GRACE (https://www.grace-ri.eu/pro-grace). Genebanks and CSBs should not be considered as competitors but as complementary actors, each having specific objectives, targets and rules as summarized in Table 1 (data from the Farmers' Pride project see Bartha *et al.,* 2021). Perhaps the most relevant difference is that genebanks are committed to the long-term conservation of PGRFA and to granting facilitated access to a wide range of users, while CSBs aim at short-term conservation

and easy availability of seed for the aims of the community managing the CSB. This complementarity means that together, they can contribute to creating inclusive and integrated conservation strategies at national and regional levels.

Table 1: The main conceptual framework of community seedbanks (CSBs) and genebanks (from Bartha et al., 2021).

Main topics	**Genebank**	**Community Seedbank**
Organizational structure	Public Institution	From single-person initiatives to community-based organizations (association, foundation, network without legal status, etc.).
	Centralized structure	Partly decentralized (network structure)
Actors	Employees (scientists, practitioners), occasionally farmers and breeders (if project available)	Network member volunteers (gardeners, farmers, horticulturists, etc.), employees (scientists, practitioners).
Funding structure	State, public–private partnerships (PPP), projects	Private (members, sponsors, foundations, etc.), public (European, state, region, municipality), commercial activities, non-profit organizations (NPO)
Communication strategy –	Towards scientific and breeder	Broad public (sponsors, donors), practitioners (farmers, gardeners,

Know-how transfer	community. Case by case policymakers too. Specific and science-focused communication. Specific communication to farmers.	horticulturists), governmental decision-makers and politicians. Integrative and comprehensive communication.
Quality management for plant genetic resources	Aiming at a common and internationally agreed certification system based on protocols and standardized procedures. Monitoring only internal genebank activities.	Aiming at quality systems that are best adapted to the needs and actual situation (financial and structural) of the CSB. Monitoring is based on the control of the whole network.
Choice of plant material	Based on national breeding programmes, genebank managers' interest, national agrobiodiversity strategy (if existent). Only recently international coordination and	Based on CSB strategy developed by network members based on public or founder's interests as well as financial and network capacity. Often local, national

	sharing of responsibilities (e.g. AEGIS, A European Genebank Integrated System).	or regional focus.
Breeding	Providing PGR for breeders for targeted breeding activities mostly for resistance. Aiming at specific and homogenous varieties. Varieties adapted to industrial agriculture.	Evolutionary breeding mostly aims for tolerance. Varieties with a less homogenous calibration spectrum. Aiming at varieties that keep their adaptation capacity to different agricultural systems.
Governance	Public mission based on national and international law/agreements/protocols	Based on common agreed values, shared visions and missions and agreed statutes and bylaws. Social aspects are key.
	Hierarchic, top-down	From hierarchic to democratic structures, bottom-up
	Bound to governmental obligations	Civil society organizations, representing the interests of the community
Access to materials	Mainly through the easy standard material transfer agreement (SMTA) and the rules of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA)	It could vary from one CSB to another. There are CSBs fully compliant with ITPGRA, others that have specific mutually agreed terms

Type of materials	Mainly old varieties and landraces in the public domain. Some conserve also breeding lines or commercial varieties with dedicated access rules	From old varieties and landraces in the public domain to new heterogeneous materials bred through participatory breeding programmes

1.1 Community seedbanks in Europe

For more than 40 years, CSBs around the world have emerged as part of the so-called informal seed system to counteract the loss of locally adapted varieties through the development of collective seed systems (Vernooy *et al*., 2015). Most of the studies and articles on the subject refer to experiences from the Global South. However, a comprehensive analysis of the impact and role of CSBs on seed systems in industrialized countries is still missing. In 2017, within the framework of the European project DIVERSIFOOD, a group of seed networks including Arche Noah, Rete Semi Rurali (RSR), ProSpecieRara (PSR), Réseau Semences Paysannes (RSP) and Red de Semillas (RdS) organized a regional survey on CSBs in Europe, to start understanding their distinctive features. The results of the survey, briefly presented in this paper, showed the great diversity of initiatives in terms of age, size and internal structures. Differences emerged also in their approaches to PGRFA management, with some leaning towards a more 'dynamic management' approach. Since 2005, the number of CSBs in Europe seems to be rapidly growing, at least in some regions (Koller and Bocci, 2018). The first CSBs in Europe were established in Northern and Central European countries (Austria, Denmark, Germany, the Netherlands, Sweden, Switzerland, United Kingdom), mainly by seed saver organizations and managed by gardeners. The US-based Seed Savers Exchange inspired the birth of many of these

organizations. The UK Garden Organic's Heritage Seed Library, known at the time as Henry Doubleday Research Association, was founded in 1975. ProSpecieRara (Switzerland) was founded in 1982 and Arche Noah (Austria) in 1990. Since then, other organizations have sprung up in European countries, with an accelerated increase occurring since the mid-2000s, especially in France and Spain. The DIVERSIFOOD survey was able to map only a few experiences from south-eastern Europe. The survey revealed that there is not one type of CSB that fits all. This diversity is related to the fact that CSBs in Europe have followed two different pathways. In the older CBSs in Europe, mainly from central and northern Europe, private gardeners had a key role, following the example of the seed savers in Australia and the USA. On the contrary, in southern Europe small farmers played a major role, adapting the experiences of social movements in the Global South, where CSBs emerged to provide seeds to farmers in marginal areas or after conflict. However, most experiences converge around the key ideas of diversity, conservation, exchange, community and sovereignty. Regardless of the crop, most of the accessions they conserve are landraces, farmers' varieties, old commercial varieties (open-pollinated varieties) or breeding populations. What is important to note is that many initiatives have moved from just conservation to more dynamic approaches, where participatory and decentralized plant breeding plays an increasing role. This change was achieved through dedicated training activities for all the members of the CSBs, which raised awareness of breeding for diversity and local adaptation. Many CSBs have also been able to create strong links with citizens, often using public campaigns focused on the importance of plant and seed diversity, and protecting local varieties. Through these activities, they have promoted more diversified, sustainable and resilient food systems that are better suited to face climate challenges. The main obstacles raised by the participants to the survey have been the lack of financial resources and an enabling legal environment. In fact, seed and food

policies have often promoted uniform and formal seed systems, through regulations on seed marketing. For example, the interpretation of seed exchanged by farmers varies across countries in Europe: some countries allow it, while others consider it as commercialization following the rules of seed marketing. Only recently more diversity entered this picture with the concept of Conservation Varieties (EU Commission directives 62/2008 (EU, 2008), 145/2009 (EU, 2009) and 60/2010 (EU, 2010)), even if its impact is still questioned (Didonna, *et al.*, 2024). Networking and cooperation as well as mutual support and social learning have been indicated as strategies to overcome these barriers. Within this large and diversified movement of seed conservation, sharing and breeding, the idea of creating a European umbrella organization emerged as members of different CSBs started connecting through European meetings. In 2005, European seed networks organized the first European meeting – 'Let's Liberate Diversity' – in Poitiers, France. After that meeting, RSP, RSR and RdS started the process of formalizing a regional-wide organization which would group the different associations involved in seed saving, on-farm conservation and agrobiodiversity management. After seven years of negotiations and meetings, the European Coordination Let's Liberate Diversity (ECLLD) was formally registered in 2012 as a non-profit organization in Belgium, and as of 2024, it brings together 22 organizations from 21 countries, encompassing over 170 national organizations. ECLLD is dedicated to promoting the dynamic management of cultivated biodiversity and farmer-led seed systems across Europe and aims to bring diversity back into our food systems. By connecting CSBs, researchers, civil society groups, seed savers, and farmers, ECLLD operates through three core focus areas: policy, community seedbanks, and communities. As a platform for policy engagement, ECLLD supports capacity-building initiatives and fosters exchanges among its members to enhance their advocacy efforts toward policies and regulations that promote and sustain agrobiodiversity. In the area of

CSBs, ECLLD empowers local groups by facilitating knowledge sharing, supporting exchanges on practices, and the integration of participatory plant breeding (see as reference the three Technical Manuals on CSBs, Galluzzi, G., *et al.*, 2021a, b, c https://liberatediversity.org/knowledge/readings/). Finally, through its work on communities, ECLLD fosters peer-to-peer learning, enabling stakeholders to share practices, exchange experiences, innovate, build connections and collectively drive action on cultivated diversity. Events like the Let's Liberate Diversity and Let's Cultivate Diversity forums, are central to these community-building efforts (for further details visit www.liberatediversity.org).

2. Three case studies

Our case studies describe the CSB experience of three different European organizations which are ECLLD members: Pro Specie Rara (PSR, Switzerland), Arche Noah (Austria) and Rete Semi Rurali (RSR, Italy). They were chosen since they exemplify the diversity among European CSBs and are well connected to their respective national systems for PGRFA conservation. Moreover, the three organizations have all made efforts, although in different ways, to engage with the so-called formal seed systems, with activities such as seed marketing, registration of local varieties/populations, characterization of the accessions conserved and traceability of the work of the CSBs through dedicated databases. For each organization, we will describe the history, turning points, PGRFA managing system, the networks they are involved in and their perspectives. A brief summary of the main characteristics of the three organizations is presented in Table 2. They have different members (single persons in the case of PSR and Arche Noah, and other organizations for RSR), activities (PSR is working also on animal breeds), facilities and access rules. PSR and RSR have integrated the easy standard material transfer agreement (SMTA) of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) for providing accessions for

research and breeding, meanwhile Arche Noah has its own access rules with an obligatory compliance check: if companies or organizations work with GMOs or patents, they are excluded from seed access.

Table 2: Main features of Rete Semi Rurali, ProSpecieRara and Arche Noah

Name	**Rete Semi Rurali**	**ProSpecieRara**	**Arche Noah**
Date of founding	2007	1982	1990
Website	https://rsr.bio	www.prospecierara.ch	www.arche-noah.at
Legal structure	Non-profit organization – Umbrella org.	Foundation	Association
Board, staff	5 board members, 2 employees, 15 consultants	7 board members, 35 employees	9 board members, 57 employees (approx. 39 full-time equivalents)
Members	35 entities (profit and non-profit)	13,000 donors and 4,400 active seed savers and rare-breed holders. Farmers, breeders, gardeners, researchers, etc.	10,000 members + 7,000 extra donors
Mission	Diversification of farming and seed systems	Maintain and promote the genetic and cultural diversity of plants and animals.	Conservation and development of crop diversity in regional and Europe-wide

			networks and advocacy for an enabling policy framework
Main collections	3,487 accessions. Crops: soft and durum wheat, barley, rye, oat, other cereals, rice, maize, tomato, sunflower, soybean, chickpea, bean and lupine.	5,600 cultivated plants and 32 rare breeds	5,500 seed accessions and 550 fruit cultivars
Main facilities	Central seed storage (climatic chamber and freezer). Database: DIVERSITAS.	Central seed storage (climatic chamber and freezer), tuber storage facility (climatic chamber), nursery and greenhouse and tunnel. Webpage for seed and breeds exchange. Database for dynamic on-farm management	Central seed storage (climatic chamber and freezer), one visitor's garden and one multiplication garden incl. tunnels. Online shop and shop in the visitor's garden. Internal and external database.
Main network activities	Seed saving, knowledge exchange, courses, markets, collection	Seed saving, knowledge exchange, courses, markets, collection holders, data	Seed saving and regular multiplication incl. data collection, educational

	holders, data collection, breeding	collection,	programme with approx. 50 courses per year, political campaigning, participatory vegetable breeding networks, Arche Noah Diversity Farms
Main projects (2024 status)	Implementing the ITPGRFA in Italy, ECPGR EVA Network, 5 Horizon Europe projects	72 different projects; Label for PSR products; Horizon 2020 projects; Projects within the frame of the national action plan for PGRFA	No patent on seeds-campaign, Participatory vegetable breeding, Fruit Monitoring Austria, Supporting community biodiversity management in South-Eastern Europe via Small-Scale Grants. Online seed savers index

2.2 Rete Semi Rurali

2.2.1 History

Rete Semi Rurali (RSR) is the Italian seed network, an umbrella non-profit association grouping organizations involved in the sustainable use of agrobiodiversity, within an agroecological framework. RSR was set up in 2007 by seven founders; in 2024 it consisted of 36 profit and non-profit members. RSR's mission is to diversify our food systems, starting from seeds and varieties. Its projects are directed primarily towards increasing diversity in agricultural systems, starting with the management of diversified seed systems in organic farming. RSR's strategy aims to recognize the role of farmers and other actors in breeding and seed production and enable a legal framework for the dynamic management of agrobiodiversity (Bocci & Galluzzi, 2015). RSR activities cover four different work areas:

a) Action research: this area supports the diversification of agricultural systems, by promoting a different model of agricultural research which brings research back to farmers' fields (decentralization) and involves different food system actors (participation).

b) Community seedbanking: this area supports diversified seed systems by promoting CSB development at a local level (see Figure 1).

c) Communities: working on seeds means working with the communities that grow them, process and consume their products. RSR works to build and support vibrant communities in which food system actors interact with each other, being aware of their complexity and diversity.

d) Policies: to promote changes in agricultural systems, it is necessary to build a political, legal, economic and social environment that makes these possible. RSR is active in fostering this enabling environment at local, regional, national and European levels.



Figure 1: Community seed bank at Rete Semi Rurali

In 2013, after the ECLLD meeting Let's Cultivate Diversity in Tuscany, RSR started to create its own CSB dedicated to different cereal species. Subsequently, the CSB expanded its structures and functions, engaging new members, opening hubs in new regions, establishing field trials for different crops, and engaging the communities in the evaluation of varieties and sensory analysis of the products (Petitti et al., 2022). Great emphasis was placed on participatory approaches to bottom-up seed system innovation, focused on the development and dissemination of dynamic crop populations and their management within organic farming systems (De Santis, *et al*., 2022). The concept of Community Biodiversity Management (CBM – De Boeuf, *et al.*, 2013) was adopted, believing in its great potential for change and adaptation, and for making agricultural systems the places where site-specific innovation takes place. Each year, RSR's CSB organizes two seed distribution campaigns, one for winter and one for spring crops,

through which a catalogue of landraces and populations is released and from which farmers or gardeners can ask for small seed samples. RSR has developed a dedicated material transfer agreement to trace the exchange of the materials and keep track of the flows from the CSB. The samples distributed are small, but generally larger than the ones of formal genebanks. For more uniform varieties, RSR provides around 200 or 300 gr and for populations up to 2 kg, to avoid reducing the diversity by sampling a small amount of seeds. In 2019, RSR inaugurated its new headquarters, called the House of Agrobiodiversity, a multifunctional space, which includes the first agrobiodiversity library in Italy, a fully operational seedbank and a training centre. In 2022 RSR launched DIVERSITAS – the Digital Ecosystem of RSR. It collects and manages all the accessions in the CSB and the data from the experimental fields. DIVERSITAS is designed to track the flow of seeds in and out of the CSB.

2.2.2 Turning points

From 2010–2019, thanks to EU projects SOLIBAM (www.solibam.eu) and DIVERSIFOOD, RSR moved from the mere preservation of local varieties and landraces to actively breeding for diversity, developing evolutionary populations of soft and durum wheat (*Triticum aestivum* L. and *T. turgidum* subsp. *durum* (Desf.) Husn.), and barley (*Hordeum vulgare* L.). This work on participatory and decentralized plant breeding, and in particular on evolutionary populations, was done in collaboration with Dr Salvatore Ceccarelli, a breeder who worked at the International Center for Agricultural Research in the Dry Areas (ICARDA), one of the SOLIBAM partners, and then directly with RSR. ICARDA's evolutionary populations of soft and durum wheat and barley were evaluated and tested in different and contrasting farming environments (Bocci *et al*., 2020; Ceccarelli and Grando, 2020). This move from agrobiodiversity conservation to breeding for diversity was the first important turning point in the history

of RSR. Over time, the work on wheat and barley was expanded to other crops: rice (*Oryza sativa* L.), tomato (*Solanum lycopersicum* L.), oat (*Avena sativa* L.), lupin (*Lupinus albus* L.), sunflower (*Helianthus annuus* L.) and recently other legumes, following the increasing interest among farmers in crop populations for organic farming systems. In the beginning, the populations remained within RSR's network and were exchanged during the seed campaigns, since marketing this kind of seed was not legally possible. In 2014, a second relevant turning point occurred: thanks to the lobbying done by SOLIBAM partners, mainly the Organic Research Centre (UK), Fibl (Switzerland), Itab (France) and RSR, the European Commission opened the space for marketing the seeds of these populations by an experimental derogation (EU commission implementing decision 150/2014 (EU, 2014)). Using this derogation, RSR supported farmers to engage in the process of seed production, multiplication and marketing of the populations they were growing and adapting, by registering as small seed companies. In 2017, the first soft wheat population was officially certified by public authorities and two farmers (one in Tuscany and one in Sicily) started marketing its seeds. At the same time, RSR developed its label for the seed packages using and adapting the open-source pledge promoted by the Open Source Seed Initiative in the US (https://osseeds.org). The last relevant turning point was the approval of the new EU regulation 848/2018 (EU, 2018) on organic production and labelling of organic products that entered into application in January 2022. This regulation created a new varietal category, the Organic Heterogeneous Material (OHM), which took up the concept of populations contained in the Decision of 2014. Since then, RSR has worked to support the implementation of OHM in Italy, notifying one rice, one sunflower and one soft wheat OHM.

2.2.3 Collaboration with institutions

Since its foundation, RSR has collaborated with the Ministry of Agriculture, being one

of three partners of the national programme for the implementation of the ITPGRFA. This programme involves 29 research facilities of the Council for Agricultural Research and Agricultural Economics Analysis (CREA), the Institute of Plant Genetics of the National Research Council (CNR) in Bari and RSR. Thanks to the programme, RSR supports its CSB as well as the Italian delegation within the ITPGRFA framework on negotiations related to the sustainable use of agricultural biodiversity and Farmers' Rights. Thanks to the above national programme and its involvement in Horizon projects, RSR has developed dedicated agreements with a range of European organizations, including one with the CNR genebank in Bari for the multiplication and regeneration of some of the accessions conserved there. Other agreements on participatory and decentralized plant breeding have been signed with the Universities of Florence, Bari, Turin, Milano Bicocca, Viterbo and the Sant'Anna School of Advanced Studies in Pisa. The aim of these agreements is to place RSR as an intermediary organization between the public research system and farmers.

2.2.4 Networks

RSR is a member of several Italian alliances and networks including Azione TerrAE, the Coalition for Agroecological Transition (https://azioneterrae.com). This coalition is made up of 7 international cooperation associations (ACRA, CISV, COSPE, DEAFAL, LVIA, Mani Tese, Terra Nuova) and two Italian and European civil society networks (RSR and Agroecology Europe), engaged in experimentation, promotion, training and dissemination of different aspects of agroecology, involving both research and farmers' organizations. Azione TerrAE plays a crucial role in the promotion of agroecology in Italy and West Africa, while the role of RSR is to strengthen the link between good farming practices and seed systems, putting the development of diversified seed systems at the core of activities of the Coalition. At the national level, RSR has also been involved in the campaign *Cambiamo Agricoltura*, which unites over 70 organizations

actively engaged in the negotiations of the Common Agricultural Policy (CAP). At the European level, RSR is a full member of the European Consortium for Organic Plant Breeding (ECO-PB, https://www.eco-pb.org/), which aims at facilitating knowledge exchange and supporting breeding programmes for organic farming. As mentioned, RSR is one of the founding associations of the European Coordination Let's Liberate Diversity. At the international level, RSR is a member of the Global Coalition of Open Source Seed Initiatives (GOSSI, https://www.opensourceseeds.org/en/gossi), an international coalition of organizations, individuals (farmers, seed keepers, plant breeders, activists) working to ensure that seeds can be freely used and shared in perpetuity. RSR contributes actively to the debate and negotiations on the European regulatory framework and is involved within the ITPGRFA in the development of policies on the sustainable use of PGRFA and Farmers' Rights.

2.2.5 Perspectives

RSR has become a complex, inclusive and dynamic network dealing with local field experimentations as well as international processes. It aims to maintain a fruitful dialogue among practitioners, researchers and policymakers. Its work demonstrates that we must enlarge the vision of agrobiodiversity, focusing not only on mere conservation but on innovation and breeding for diversity, i.e. delivering new varieties that are sufficiently diverse (rather than narrowly responding to the standard criteria of distinctness, uniformity and stability (DUS) of modern varieties) to be able to adapt to climate change and low-input farming systems. The belief in the importance of diversifying seed, farming and food systems is the reason why RSR has recently moved towards projects and research activities that involve not only seed diversification and breeding but also intercropping, rotations and soil microbiome. These will be the challenges for RSR in the coming years. Regarding the CSB and its database DIVERSITAS, the next steps will be the possibility of implementing the ITPGRFA easy

SMTA directly from its website for the accessions distributed from the CSB and the digital object identifier (DOI) for some of the conserved accessions.

2.3 ProSpecieRara

2.3.1 History

PSR was founded in 1982 in St. Gallen (Switzerland) and its first activities were related to safeguarding rare breeds. In 1985, collecting activities for fruits, field crops and vegetables started. In 1988, the first employee was hired with a fixed salary. Around the same time, the network of seed savers was established and the seedbank (called 'seed library') was founded. Very successful TV broadcasts and some national exhibitions about rare breeds and fruit varieties organized by PSR and its partners and volunteers helped to raise awareness among the broader public. In the 1990s, the first private foundations started funding the projects of PSR and private donors supported the organization as well as many volunteers who helped to propagate seeds as seed savers. In addition, many breeders joined the different breeding associations created by PSR to coordinate the conservation of the different endangered breeds. After 15 years of existence, PSR encountered about 2,000 donors, 250 seed savers and over 2,000 breeders organized in 15 different breeding associations.

2.3.2 Turning points

The first important turning point for PSR's activities was the ratification of the Convention of Biological Diversity by Switzerland in 1995, followed by the development of the National Plan of Action for the Conservation of Plant Genetic Resources for Food and Agriculture (NAP-PGRFA) in 1998. The Department of Agriculture decided to create the Swiss Commission for the Conservation of Cultivated Plants (SKEK/CPC) in which PSR became a leading member of the governing body to implement the NAP-PGRFA. This mandate was and still is accompanied by some funds

(3.2 million CHF per year). At the time, the Commission developed a conservation strategy with conservation standards for various crops and a national database that relates to the European Search Catalogue for Plant Genetic Resources (EURISCO). PSR's own database has an interface with the national database to transfer and exchange passport and characterization data. Today about 15% of the turnover of PSR is covered by these public funds. A second important turning point was the collaboration with COOP, the biggest supermarket chain in Switzerland. Together with this impactful partner, PSR participated in one of the biggest national exhibitions called EXPO02, which attracted millions of people over six months. The interest of the visitors in the topic was so big that COOP decided to fix the collaboration through a contract. This collaboration has lasted until today. Accordingly, PSR's focus shifted more and more from pure conservation towards the sustainable use and development of PGRFA. PSR developed a label for the promotion of traditional and endangered varieties to keep or reintroduce them in the value chain. Aside from the COOP outlet, farmers and horticulturists who are part of the PSR conservation network use this label for their own marketing activities, helping them showcase the added value of their products to consumers. In 2023, PSR's database revealed that about 600 people use the PSR label and surveys reported that around 30% of the Swiss population know this label. Another important turning point in the Swiss PGRFA conservation activities occurred when the Government implemented article 147a in the agriculture law (SR 910_1 Art. 147a LwG):

The Confederation may promote the conservation and sustainable use of genetic resources. It may manage genebanks and conservation collections or have them managed and support measures such as in situ conservation, in particular with financial contributions.

Under this provision, PSR and other stakeholders in this field could apply for funding

for activities going beyond pure conservation such as on-farm development and improvement of PGRFA. Thanks to the development of a suitable legal framework (e.g. the national long-term strategy for PGRFA and its accompanying measures) as well as through adequate funding opportunities, PSR was able to grow further, engaging new stakeholders for on-farm management of PGRFA. Today governmental financial support constitutes only about 20% of their total turnover but is still crucial because it guarantees the financing of conservation activities that depend on a long-term financing source (e.g. on-farm fruit and berry collections).

2.3.3 Development and monitoring

ProSpecieRara went on to develop its network of seed savers (for vegetable species) and collection holders (for fruits and berries). Today, 400 seed savers maintain 1,208 vegetable varieties, 270 people care for 1,012 ornamentals, 1,000 people host 2,436 fruit and 422 berries varieties all over the country. The PSR staff is responsible for managing the network and monitoring conservation activities. For seeds, this work is facilitated by the central seed library, located in Wildegg (AG) and consisting of a climatized room with 2,000 accessions stored as seeds. This repository functions as a backup of the *in situ* collection, with seed savers regularly sending back a reference seed lot of the variety/accession they maintain and regenerate. The reference lots are sown in PSR's different demonstration gardens, where quality and varietal identity are verified. All the exchanges between the seed savers and PSR are registered in a specific database for on-farm conservation and can be traced back. Every year, the 1,653 label holders (i.e. registered and validated seed savers) receive a request to fill in a checklist to describe the status of the genetic resources they are maintaining. This checklist is provided by PSR on its portal (https://www.prospecierara.ch/it.html). Based on the results of this monitoring activity, PSR delivers a report about the status of each of the 5,600 accessions maintained by the people of the network. This report also allows the seed

library manager to establish how many seed lots are in the genebank and their storage time. The manager will also know how many seed savers are maintaining the accession, how many are marketing seeds, fresh and processed products and how many of them are offering seeds on the variety finder portal of PSR. By compiling all this information, facilitated by the database, the manager can judge the conservation status of an accession and decide if an accession is endangered and must be propagated quickly or not. In addition, different training courses are organized for beginners and advanced seed savers to improve their knowledge and skills.

2.3.4 Sustainable use

Over time, PSR's activities shifted more and more from pure conservation to sustainable use of PGRFA and the development and improvement of varieties, e.g. for niche markets and with niche varieties. The shift of PSR's activities towards sustainable use was backed by a national law (SR 916.151.1 Art. 2.4 - 2.7, 27, 29) for the marketing of seeds brought into force in 2010: besides registered and certified varieties, a new category called 'niche varieties' was created to include varieties that don't fulfil the DUS criteria. The government considered that certain varieties could be very interesting for niche markets or small-scale farmers or private gardeners (see Figure 2).



Figure 2: Carrot variety "Gniff" from Ticino from Pro Specie Rara collections being commercialized

Allowing to register these varieties and being able to place them on the market would enrich the diversity of vegetables and field crops in the fields and on consumers' tables. This positive legal environment led to breeding activities to improve landraces, minor or 'opportunity' crops, or develop populations, with the support of government and private (e.g. COOP) funds. Some of the breeding activities included participatory methods and, in some cases, citizen participation when a broader range of information about plant growth and development in different agricultural and horticultural contexts had to be collected and compiled. While often breeding activities take the form of mass selection to advance a population variety, in some cases, cross-breeding is the only way to make a variety fit for on-farm utilization (see table 3).

Table 3: Cross-breeding activities initiated by ProSpecieRara (PSR) for new niche varieties

Species	Varieties	Origin	Breeding
Daucus carota	‘Gniffola’	Landrace ‘Gniff’ x ‘Purple Haze’	Sativa Rheinau, 2012–ongoing
Solanum lycopersicum	‘Cuore di Bue’	‘Cuore di Bue’ x resistant varieties against *Cladosporium sp.*	Sativa Rheinau, 2012–ongoing
Brassica rapa subsp. *rapa*	‘Albedo Viola’ (rejected name) ‘Guringa’	Several old varieties of PSR, the Swiss Genebank and from commerce landrace ‘Bosco Gurin’ x several varieties of the same type	Sativa Rheinau, 2016–2024
Allium cepa	‘Piri’	Old variety ‘Birnenförmige’ x (‘Yankee F1’ x (‘Rijnsburger’ x ‘Yankee F1’))	Sativa Rheinau, 2012–2022
Tragopogon porrifolius	Salsify populations	11 salsify lines from PSR, the Swiss Genebank and from commerce	PSR & Sativa Rheinau together with PSR network (participatory breeding), 2024–ongoing
Cucurbita pepo var. cylindrica	Striped zucchini	Old variety ‘De Gênes Striée Vert-Jaune’ x other striped zucchini	Sativa Rheinau, 2024–ongoing

2.3.5 Further development as a CSB

In the future, open-pollinated crops will become even more important for alternative, independent, locally adapted and innovative agricultural systems, a grassroots alternative to hybrids that are taking over more and more intensive and industrial agricultural production of food (IPES-Food, 2016). On the other hand, citizens are increasingly interested in agroecological food production systems that foster biodiversity, protect the environment and provide healthy food for them. This is one of the reasons why urban farming and gardening movements are popping up all over the country in and around cities. Well-educated young people are applying new and better-adapted farming systems to local conditions. Several community-supported agriculture systems around cities like Geneva, Basel or Zurich have contacted PSR to get access to bigger amounts of seeds to be able to start their trials on a bigger scale and select those varieties that fit best to their local and specific needs and establish production plots for the marketing of produce. For PSR this development causes different challenges: first, quantities of seeds requested are greater than those normally distributed for purely experimental purposes; second, these new actors require training in order to acquire the ability to produce and regenerate their own seed each year. Finally, these users demand more detailed information about the PGRFA stored in PSR's seed library. To face these challenges, PSR is considering a series of new developments. To produce and distribute greater quantities of seed to growers, it could become a small seed company or start collaborating with local seed companies. In general, PSR would like to act as a knowledge hub or be part of a knowledge platform that provides information to growers and helps them to make decisions tailored to the specific environmental and/or economic and social conditions they operate in – a kind of one-stop shop for farmers.

2.3.6 Networks

Since the early 2000s, PSR has entered several partnerships with research institutions, whether within the framework of the NAP-PGRFA for the inventory, description and conservation of PGRFA, or within the framework of production and distribution with COOP. An important factor in the success of many of these collaborations was the clear definition of partners' roles. The typical collaboration between PSR and research institutions covers three steps along the continuum from conservation to the sustainable use of PGRFA:

1. Conservation: *ex situ*, i.e. *in vitro* and genebank conservation by research institutions (e.g. Agroscope) linked with the *in situ* and on-farm conservation by PSR and its partners. The research institutions use their scientific expertise to carry out *ex situ* conservation measures. On the other hand, PSR has an interest in testing PGRFA in on-farm conditions to possibly promote them among farmers, while network partners can use their PGRFA collections as sources of material for the multiplication and commercialization of seeds.

2. Evaluation: genetic and morphological characterization by research institutions (e.g. Agroscope) linked with the quality assessment, value description (e.g. cultural history, or market value), and determination of the utilization potential by PSR. While research institutions provide the expertise and technical infrastructure for characterization, PSR and its network can evaluate the PGRFA in terms of their socio-economic impact.

3. Environmental adaptation for agricultural use: selection of PGRFA, breeding activities and marketing activities by PSR and partners linked with agronomic evaluation and case studies by research institutions with a strong link to farmers (e.g. Fibl). PSR initiates breeding activities to recover the varieties and bring them to the market. The 'ProSpecieRara' label provides a tool to enhance the product's credibility with consumers. On the other hand, it is important for farmers to know the expected quality and quantity of the PGRFA available before accepting it for large-scale

cultivation on their farms. Research organizations advise farmers about the agronomic and quality features of the PGRFA available through PSR enabling them to make informed choices depending on their context and needs.

2.3.7 Perspectives

PSR is dedicated to further developing the plant and animal genetic resources it maintains in its broad network. As this example shows, there are strong incentives for collaboration between CSBs, research institutions and genebanks. There is a great need for research on the characterization and evaluation of PGRFA, and the role of research institutions and genebanks is undeniable. At the same time, PSR experience shows that successful promotion of PGRFA is only possible with many dedicated actors, which come together in the CSB network. This collaboration will not only enable better integration of PGRFA into society through innovative agroecological farming systems but will also return a wealth of real-world data and experiences about PGRFA to the research institutions.

2.4 Arche Noah

2.4.1 History

The development of Arche Noah can be divided into four phases:

Pioneer phase. Emerging from predecessor organizations, Arche Noah was founded in 1990 by farmers and gardeners who had formed a network among crop collectors and seed savers. Early on, the organization issued a *Seeds Handbook* (not published, for members only) to stimulate the exchange of seed and other plant reproductive materials and began compiling a collection of rare and endangered varieties. The 1990s were a time of rapid growth of the collection, stimulated by collecting missions (Austria, Croatia, Romania) but also by research into commercial open-pollinated and heirloom varieties. Eventually, in 1994, the organization opened

a garden for crop multiplication that was also open to the public for educational purposes. Seed production was organically certified which gave it a unique position among seed savers organizations as well as in the agricultural scene. Arche Noah was a pioneer in the then-emerging Austrian organic farming scene.

Differentiation phase. Around 2000, the organization had become well-known and grew to 6,000 members. The annual plant market attracted many visitors and became a meeting point for the organic gardening community. Arche Noah took up the direct marketing of transplants. To manage risks from commercial activities and to clearly separate commercial from non-profit activities, a company with limited liability was founded. Along with these developments, the number of employees at the organization rose and departments developed, specializing in plant collections (seed archive, fruit collection), gardening, seed savers activities, sales and event management. An early act of policy advocacy was to secure exemptions for unregistered PGRFA under the Austrian National Seed Legislation. This was achieved through persistence, as well as a rare window of opportunity for alternative farming approaches at that time. Since then, the legal exemptions have allowed for marketing small quantities of seeds, making Austria a unique environment for heirloom varieties in the EU. Beyond that, Arche Noah advocated for lighter registration procedures for Conservation Varieties. The demand for seeds was growing and it became necessary to open the registration process for plant materials not conforming to industrial standards and feasible for small seed companies. In the educational sector, a series of books was launched, setting off with a handbook about seed gardening (Heistinger, 2013). In 2008, the education programme on organic gardening and crop diversity was expanded, comprising nowadays up to 80 courses per year, training people in seed-saving techniques, crop diversity and gardening skills.

Integration phase. In the late 2000s, a bundle of new strategic targets pushed the enlargement of the organization. With the slogan 'Eating up what we want to save', Arche Noah built a wider network with home gardeners and farmers, incentivizing access and marketing of rare varieties in the form of seeds, plantlets and products through different channels (plant markets, Arche Noah shop, farmers markets). The focus shifted from 'home gardeners' to the urban consumer as a new target group. This was accompanied by systematic on-farm research – also within EU projects – to evaluate varieties and their potential uses. The cooperation with the organic seed company Reinsaat led to an ever-increasing demand from consumers and retailers. Since then, Arche Noah has been registering several heirloom varieties in the EU catalogue per year and offering seeds via the Arche Noah webshop.

Association phase. As of 2010, the political and international cooperation expanded: Arche Noah hosted several international policy workshops and advocated for seed law issues, in some cases directly in Brussels. In 2015, the cooperation with the campaign 'No patents on seeds' started. At the same time, Arche Noah started to coordinate the Austrian participatory tomato breeding network. The financing structure was expanded thanks to Austrian and European research funds and new fundraising models, first targeted sponsorships for on-farm breeding and multi-location fruit conservation. Since then, the number of employees and supporters of Arche Noah has remained stable, while noticing a shift from association members to sole financial donors.

2.4.2 Multiplying accessions and making accessions available

In comparison to public genebanks, the association focuses more on cooperation with farmers and gardeners in terms of conserving, describing, spreading and further developing PGRFA. The activities of Arche Noah centre on the seed archive and the

gardens which are responsible for maintenance, variety descriptions and seed quality testing. Documentation of each variety or accession is supported by a database of text descriptions and photos for each variety or accession, complemented by data about the origin, plant health status, quantity and germination performance of harvested or stored seed lots. Recently, the database was enforced with crop-specific descriptors, mainly based on UPOV and IPGRI standards, but supplemented by more user-related descriptors such as taste, utilization class, yield or lodging. Distribution of plant material (mainly seeds) is done via various production lines (Table 4). Seed surplus of non-registered varieties from the multiplication garden are offered as 'Treasures from the Seed Archive' in strictly limited quantities in accordance with the Austrian Seed Regulation revised in 2006 (RIS 2025). Two additional production lines pursue the aim to provide seeds of registered varieties and varieties of non-regulated species on a regular basis to a wider audience, having the Arche Noah webshop and local sale points as main channels, but also serving major retailers such as a supermarket chain. These marketing activities are carried out by the associated company *Vielfalt Erleben*, which is fully owned by the non-profit Arche Noah. Most of the offered varieties are registered in the EU variety catalogue as "varieties with no intrinsic value for commercial crop production but developed for growing under particular conditions" and are multiplied by contracted farmers. The main target group for Arche Noah seeds are amateur gardeners in Austria and neighbouring countries (see figure 3). Accessibility of rare fruit varieties is limited to a set that is managed by certified organic nurseries cooperating with Arche Noah. Due to plant health restrictions and the complexity of handling planting material (seasonality, storage, shipping), the assortment of available varieties is less dynamic compared to seed crops.

Table 4: Seed marketing lines of ARCHE NOAH (2024 status)

Marketing line	**Proven for home garden**	**Rare Vegetables**	**Treasures from the Seed Archive**
Since when	2009	2014	1998
Main target group	Beginner and advanced home gardeners	Advanced home gardeners	Advanced and professional home gardeners
Criteria for taking into the collection	Robust varieties of well-known vegetable crops, with reliable yield and good taste	Lesser-known vegetable crops, underutilized	History, traits, utilization and/or special usage properties
Flexibility	Consistent collection, 1–3 varieties change per year	Consistent collection, 1–3 varieties change per year	Annually or biennially changing collection
Variety registration	Registration usually as "varieties bred for cultivation under special conditions”	Usually, no registration necessary if species are not listed	No registration necessary subject to restrictions and quantity limit set out in the Austrian Seed Regulation 2006
Number of varieties	53	18	approx. 100
Varieties also	31	12	0

sold to retailers			limited quantities due to legal restrictions



Figure 3: Sale of Arche Noah seeds at the annual seed fair in Wien (Austria).

2.4.3 Conserving and managing PGRFA

In Austria, there are approximately 150 active seed savers in the network of Arche Noah, contributing through growing, multiplying and collecting varieties. Some of them manage their private collection of varieties (with or without links to the Arche Noah seed archive), but many engage in coordinated conservation activities of the organization. As 'guardians', they test varieties of the seed archive in their location and collect data. Depending on season, location and personal preferences, they contribute new or confirm previous observations, and thus, add to the wealth of knowledge and

perspectives regarding crop diversity. These seed-saver programmes cover both seeds and tubers as well as fruit crops. Seed guardianship can be permanent or temporary (alternating varieties annually). Fruit guardians are designated permanently with a minimum number of ten trees per location. To facilitate the exchange of plant material and contacts among seed savers and the broader public, Arche Noah digitalized the former*Seeds Handbook* to an online private database where seed and fruit tree savers can indicate their varieties via text and photos. Farmers multiply seeds in larger quantities for Arche Noah's seed sale. Some of them run farms specialized in vegetable seed production, and others are biodiverse farms selling vegetables or other produce. Together with Arche Noah, they carry out maintenance breeding of seed archive materials by positive or negative mass selection and selection of elite plants. The aims are to maintain the phenotype and to maintain or improve plant health and sensory quality. In addition to this partnership for seed multiplication, Arche Noah licences a label to organic farms which produce and sell rare varieties. In 2024, 32 farms registered for this label, the so-called Arche Noah Diversity Farms. Some of the partner farmers of Arche Noah not only multiply, produce and sell rare varieties, but actively engage in further developing varieties by cross-breeding and selection. In 2010, the working group *Bauernparadeiser*, a participatory breeding group on tomatoes, was founded on the initiative of farmers due to a lack of organically bred tomato varieties to suit the needs of direct marketing. Conventional tomato breeding mainly breeds hybrids which neither can be reproduced on the farm nor adapted to local conditions, and sensory quality is often neglected. Currently, the group consists of 12 organic Austrian farmers, three research institutions and Arche Noah. The goal is the development of tasty and reproducible (open-pollinating) tomato varieties, featuring resistance to plant pathogens, by means of crossing heirloom and modern varieties. The group works, first, on varieties for greenhouse cultivation, resistant to the fungal pathogen *Cladosporium*

fulvum, to Tobacco Mosaic Viruses and common root diseases and, second, on varieties for outdoor production, resistant to the fungal pathogens *Phytophthora infestans*, Early Blight (*Alternaria* spp.) and Septoria leaf spot (*Septoria lycopersici*), and less susceptible to fruit cracking. Since 2020, Arche Noah has coordinated participatory screening and breeding activities within other vegetable crops, such as sugar pea and winter radish.

2.4.4 Networks

Apart from previously mentioned partners in the multiplication and marketing of plant material, Arche Noah is a partner in various research projects, being well-connected with national universities and research stations. The latter are permanent partners in screening and breeding activities. There is loose contact with several other vegetable breeders, mainly in Austria and Germany. Further, Arche Noah is an active member of the Balkan Seed Network Association. The organization was founded in 2021 by 16 organizations and institutions active throughout Southeastern Europe. The purpose of the network is to increase the conservation and sustainable use of PGRFA in agriculture. Activities aim at stimulating resilient food systems and establishing a paradigm of collaboration within the wider Balkan region, which has historically been shaped by conflict. The network consists of seed savers, breeders, scientists, farmers, gardeners, associations, organizations, research institutes and educational institutions. In addition, being an active member of the Balkan Seed Network Association, Arche Noah has been supporting seed savers organizations in Southeastern Europe by awarding small-scale grants, provided by foundations.

2.4.5 Perspectives

Arche Noah calls itself ‘The Association for Preserving and Developing the Diversity of Cultivated Plants’ and cooperation with diverse network partners is extremely relevant. Arche Noah considers both preserving and developing as equally important activities.

Regarding conservation, Arche Noah makes increased use of long-term conservation at sub-zero temperatures of accessions, to enhance the capacities to study and distribute the most valuable accessions for use. The participatory breeding activities account for the necessity to let the accessions adapt and improve according to the needs of home gardeners and farmers. Arche Noah does not intend to be a sole breeding organization by any means, but rather a motivator and catalyst for organic breeding in Austria. Since breeding and cultivating diversity also require suitable frameworks, Arche Noah wants to create the appropriate awareness and the political foundations so that the development and marketing of diverse seeds does not only happen in niches but can also be economically successful on a broader scale. Under the prevailing market economy conditions, diversity is a massive business disadvantage. It would therefore be naive to expect private and for-profit companies to do this work. However, since the preservation and further development of diverse seeds represent an indispensable basis for humanity's livelihood, it cannot be left solely to the dynamics of the market. Arche Noah therefore claims that conserving and breeding for diversity should become part of public services and corresponding programmes should largely be publicly financed.

3. Conclusions

The three cases presented here show that CSBs in Europe can maintain and manage thousands of varieties, landraces and populations within broad networks of different actors such as private gardeners, farmers and horticulturists. They operate in diverse, decentralized agricultural and climatic environments. Their activities can be framed as Community Biodiversity Management, and they focus not only on mere conservation but also on the dynamic management of PGRFA. This allows evolutionary and adaptive processes to happen. All the described CSBs are well connected to the local/regional communities they are operating in. Because they provide facilitated access to PGRFA, mostly open-pollinated varieties free of intellectual property rights, they are an excellent

partner for agricultural movements that advocate for the enhancement of diversity in farming systems. They can be an excellent partner for researchers too, because they can act as bridges between scientific and tacit knowledge and help scale up interesting and crucial ideas for the future of our seed and food system. Moreover, CSBs can play an important and complementary role with regard to the *ex situ* system. In fact, they can be considered as an intermediary between farmers and the genebanks, receiving small samples from the banks and multiplying them before distributing them to farmers. Propagation activities of the CSBs, in collaboration with their networks, offer the opportunity to provide a larger quantity of seeds to the final users. Very often the small quantities of seed coming from genebanks are considered as an obstacle by farmers, who do not necessarily know that providing larger quantities is not the mandate of these institutions. The multiplication and regeneration done by CSBs can provide useful information about the agronomic value of PGRFA, which leads to a better understanding and knowledge of the variety or landrace itself. These processes, done by the CSB members, operate in very diverse agricultural and horticultural systems, under different climatic conditions and within different social and economic contexts. This opens opportunities to collect site-specific information on how PGRFA perform and could help in coping with climate change and other challenges in the future, providing knowledge that is also useful for future breeding for diversity efforts. As described by the three case studies, the turning points for CSBs are at least partially related to a change in the legal system. These changes allowed RSR to market the seeds of populations, PSR to market the seeds of niche varieties and Arche Noah the ones of conservation varieties. This means that the operativity of such organizations is concretely impacted by the legal and political environment in which they are embedded, and which has historically been conceived to promote DUS varieties while leaving diversity outside of the picture. As of the time of writing this article, the EU is

reforming the rules on seed marketing, with a proposal released by the European Commission in July 2023, voted by the Parliament in April 2024 and revised by the Council during 2025, before the final approval by the Trilogue involving all three bodies. The proposal contains a series of derogations to the conventional system to allow more diversity and actors in the seed sector. For the first time, the concept of "dynamic management of diversity" by farmers is mentioned in a legal text and participatory plant breeding is defined as an activity which develops locally adapted varieties. Moreover, an article is dedicated to the exchange between farmers, with the aim of creating a harmonized rule across Europe with less space for different national interpretations. All these points need to be maintained in the final regulation, if an enabling environment is to be created in Europe. Only in this way can the development of CBSs, a relatively new and highly relevant actor in the PGRFA community, can be supported and the space for more diversity be created in our seed and food systems.

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Chapter V: General Conclusions

5.1 Assessing the Impact of Rice Farming Practices on biodiversity: Findings from Ph.D. articles and field research

The overall set of current Ph.D.-related publications represent one of the first comprehensive efforts to map the environmental impact of rice production on biodiversity, through key taxa evaluations, including butterflies, dragonflies, and amphibians across their entire crop cycle. **Chapter II** highlights how different agronomic practices either support or hinder biodiversity, with particular emphasis on water and weed management, soil interventions, and varietal selection in Italian rice farming systems. Specifically, butterflies are particularly sensitive to herbicide applications, late-season soil disturbances (such as chemical fields-banks weeding), and mechanical shredding. Conversely, practices like sowing on green mulch, crop rotation with legumes, and autumn soaking can have positive effects. Butterflies thrive in environments with diversified field margins, abundant floral resources, and reduced chemical inputs, also according to previous literature evidence (Van Swaay et al. 2022; Ferrero et al., 2021; Sybertz et al. 2017; Haaland et al., 2011;). However, as outlined in **Chapter III**, severe drought can significantly reduce butterfly abundance, with only generalist species remaining prevalent, underscoring the additional stress imposed by climatic extremes. Conversely, dragonflies, which are highly dependent on aquatic habitats, were most affected by early-season tillage, dry seeding, insecticidal treatments, and harvesting. Their populations benefit from continuous water availability, autumn submersion, and high water tolerance in rice fields. Severe drought events can drastically limit dragonfly diversity, with only resilient species persisting in rice agrosystems. The reliance of this taxon on stable wetland conditions makes it particularly vulnerable to farming practices that disrupt water regimes, reinforcing the need for careful irrigation management (Huyn et al, 2020; Giuliano and Bogliani, 2019;

Giuliano et al., 2018). Finally, amphibians are severely impacted by practices that alter hydrological conditions, such as repeated drainage and herbicide use. Maintaining water-logged fields, avoiding early drying, and implementing winter flooding tend to be crucial for their survival. Studies also noted that amphibian populations responded positively to rice varieties with longer growth cycles and lodging tendencies, which provide more stable aquatic microhabitats, as already demonstrated in the literature (Giuliano and Bogliani, 2019; Giuliano al., 2018). The analysis identified critical agronomic bottlenecks where farming practices most heavily influence biodiversity. Soil tillage, particularly when conducted early in the season, have medium-to-high negative impacts, though these could be mitigated by delaying operations to avoid peak spring biodiversity activity. Herbicides and phytosanitary treatments are among the most damaging interventions, particularly for Lepidoptera and Odonata (Mallick et al., 2023; D'Antoni et al., 2020; Santovito et al., 2020). Harvesting operations also pose significant threats, as they often destroy aquatic habitats, emphasizing the need for compensatory measures like post-harvest flooding. Water management emerges as a decisive factor for biodiversity, as previously documented in the literature (Giuliano and Bogliani, 2019; Giuliano et al., 2018). While practices such as winter flooding and prolonged submersion support multiple taxa, recurrent drainage and early-season drying had severe negative consequences. The study also highlighted the role of varietal selection, noting that modern, short-cycle, herbicide-resistant varieties, dominant in Italian rice farming, often conflict with biodiversity conservation (ENR, 2025; De Santis et al., 2022; Orlando et al., 2020). Traditional, long-cycle varieties, though less common today, are more compatible with wetland-dependent species due to their extended water requirements and taller growth, which provided better habitat structure (Ibidem). As detailed in **Chapter III**, landscape and farming system comparisons reveal that organic farms generally support higher biodiversity due to diversified field margins,

reduced chemical inputs, and a greater presence of semi-natural habitats (Mallet et al., 2022; Giuliano and Bogliani, 2019; Angelini et al., 2008). Conventional farms, while more uniform in high-impact practices, still have the potential for improvement through adjusted water management and reduced tillage intensity (Yun et al., 2022). Field margins play a particularly important role, with floral diversity enhancing nectar and host plant availability for butterflies, while structurally complex banks provide hunting and refuge habitats for dragonflies (Ibidem). The 2022 drought introduced significant biases in the study, reducing overall species richness and abundance, particularly for water-dependent taxa. This climatic stressor exacerbates existing pressures from intensive farming, highlighting the need for adaptive strategies that enhance resilience. For instance, maintaining high soil cover, minimizing disturbances, and ensuring water continuity are key measures for buffering biodiversity against extreme weather (Mayer et al., 2019; Zampieri et al., 2019; Azar et al., 2016). To reconcile rice production with biodiversity conservation, current research parties recommend several adjustments in farming practices, namely delaying tillage to reduce spring disturbance, adopting shallow and non-rotating tillage equipment, minimizing herbicide use, and maintaining waterlogged conditions where possible. Landscape diversification, through flower strips, hedgerows, and preserved field margins, can further enhance habitat quality, as documented in **Chapters II** and **III** and deeply supported by the literature (Tscharntke et al., 2021; Ganser et al., 2019; Van Swaay et al. 2022; Robinson et al, 2012). Policy measures, such as CAP agro-schemes, should incentivize biodiversity-friendly practices, while varietal development should prioritize traits that support ecological functions, such as longer growth cycles and lodging tolerance (Hervè et al. 2020; Giuliano et al. 2019; Pianca 2019). In conclusion, rice paddies can function as surrogate wetlands for biodiversity, but current intensification trends, particularly dry seeding and herbicide-resistant varieties, threaten this potential. A systemic shift toward

agroecological practices, informed by multi-criteria decision analysis (MCDA) and integrated into policy frameworks, is essential for balancing agricultural productivity with biodiversity conservation. Future research should focus on long-term monitoring under varying climatic conditions, economic assessments of sustainable practices, and scaling successful interventions across different rice-growing regions (Tibi et al., 2024; Vaglia et al., 2022; Tscharntke et al., 2021). This study highlights the importance of aligning agronomic choices with ecological resilience to ensure the sustainability of rice production systems, also integrating good farming proposals within the framework of CAP agro-schemes (Salvan et al., 2022; Van Swaay et al. 2022; Hervè et al. 2020; Giuliano et al. 2019; Luppi et al. 2018). As outlined in **Chapters II** and **III**, the impacts of farming inputs' on biodiversity are mainly related to the use of mechanical processes as a source of fuel consumption and emissions as well as a source of disturbance for the soil, in addition to water consumption and emissions of greenhouse gases related to the use of irrigation techniques that involve the complete submersion of the rice paddy. Some components, in particular those related to soil tillage techniques and the management of clippings are particularly problematic for biodiversity. The hydro period is certainly one of the most studied crucial elements, as it can modulate the agrosystem from wet to dry, and therefore either promote or damage the biodiversity. In particular, as a result of the reduction of water quantities and the spread of dry methods, it has become increasingly urgent to assess the costs and impacts of different water management options (Martinez-Eixarch et al. 2024, Gilardi et al., 2023; Gharsallah et al., 2023). Specifically, attention has been paid to the methodology of round irrigation and alternating dry with dipping, calibrated according to the plant physiology, without analysing the impacts on the overall ecological network of biodiversity in paddy fields. From this perspective submersion is positive in the initial phases and positive in terms of increased water supply and the creation of replacement wetlands in agricultural areas

and therefore anthropogenic. The use of discrete water blades has the advantage of combating the infesting flora associated with dry areas, as well as an easier metabolism of nutrients. The persistence of anoxic conditions, however, results in the accumulation of heavy metals inside the plant, as well as increasing emissions of reduced compounds (methane and nitrous oxide on all), with potential climate-altering possibilities (Vinci et al., 2024; Vaglia et al., 2022; Bacenetti et al., 2016).

5.2 Scale approach and the role of the surrounding matrix

The use of a scale approach has been fundamental for understanding and valuing biodiversity at different levels. The agrosystem does not place itself as an isolated element inside no empty space, but interacts with the surrounding elements. Knowledge and assessment of ecological matrix elements is also important to detect possible "biodiversity drift effect" within paddies. Among the most relevant elements observed, we can certainly include: a) The scale of landscape-district-farm, which is particularly relevant for determining the presence of key elements, such as the system of edges and rows, the presence of a surface irrigated system integrated with semi-native elements, the presence of non-man-made river courses and semi-natural wetlands, with "drift effect", in terms of local source and refuge for biodiversity ; b) The farm scale is an important proxy of rice farms' environmental impacts, being linked to scale operations, farms' selected rice varieties and agricultural practices, and overall economic costs to the community in terms of ecosystem services. The LCA estimation is a methodology, limited to this level of territorial scale and unit ownership, adapted to understand the level of indirect impact; c) The field scale, in its various central levels and interfaces with other company networks and with local interfaces, represents the most precise and relevant level for determining individual practices, with their different specific adaptations according to the context and the business direction, in particular with

reference to soil management practices, spontaneous plant cover, crop and water management (Ali et al., 2023; Habel et al., 2022 a-b; Luppi et al., 2018). Their degree of interaction with biodiversity is the highest, and most statistically relevant. At each level, results can be achieved in reducing impacts and supporting biodiversity. On a wider perspective, the role of surrounding landscape elements is not to be underestimated and is still crucial. The surrounding matrix is a complex amalgam of different responsibilities such as landscape structure, cultivation system, water availability, water supply modality, land construction, adherence to eco-schemes and low impact practices, the quality of systems of hedges and rows, the presence of semi-natural areas and the farm structure (Savoini et al., 2025, a-b; Mallet et al 2022; Hervè et al., 2020). This is a combination of crop and farm key elements and others determined by the surrounding environmental and territorial characteristics, and as such difficult to accurately map. The influence of the surrounding matrix is relevant in terms of the drift effect (Mallet et al 2022; Hervè et al., 2020; Topping et al., 2019). Key elements are those involving the diversification of the landscape, determined by pre-existing features and business practices. This is particularly valid in the field of crop diversification, the presence of semi-natural elms, the presence of riparian areas, and the quality of the system of hedges and rows (Mallet et al 2022; Topping et al., 2019; Naito et al., 2012). Good ecological conditions of the surrounding environmental matrix can maintain and attract biodiversity, in particular for taxa that are very related to the water component, such as dragonflies, also positively integrating agrobiodiversity and low environmental impact farming practices. Daily butterflies benefit in part from landscape and botanical diversification at the territorial level (Ali et al., 2023; Huynh et al., 2020; Naito et al., 2012). The matrix component is very relevant, in particular as it overrides the role of business choices and methodologies, is able to level and integrate results at different spatial scales, and lends itself to a characterization and zoning and district level

production (Mallet et al 2022; Hervè et al., 2020; Angelini et al., 2008). The land use detailed approach can be important even if it is to consider the importance of the farm choices in coherence with the CAP, in terms of reduction of environmental impacts. Therefore, the nature of this boundary competition should not be overlooked in defining conservation practices at the farm and district level (Tibi et al., 2024; Savoini et al., 2025, a-b; Salvan et al., 2022).

5.3 Impacts and limits of cultivation practices

Farms involved in trials generally show low to medium concern for climate resilient practices and varietal choice, despite the changing weather conditions of 2022-2023 (Graskemper and Feil, 2021; Hervé et al., 2020; Fabian et al., 2019). Farmers seem to be more interested in short-term economic gains, being stuck on a farming "technological plateau" (Vaglia et al., 2022; Fusi et al., 2014). The preferred farming practices are, in fact, focused on reducing water consumption, especially in the early stages (e.g. dry seeding techniques with recurrent irrigation). More diversified and climate resilient agricultural practices are still needed, also focusing on the surrounding environmental elements (Vaglia et al., 2022; Mainini and Baici, 2021; Miniotti et al., 2016). However, interest in low-input rice cultivars and rice HOM is increasing and gradually adapting to the specific context of farms (De Santis et al., 2022; Orlando et al., 2020). In the "Resilient Rice" project, the development of rice HOM by farmers and consumer acceptance were tested as generally positive. Further years of scale-up trade can pave the way for a stable, renewed sustainable rice supply chain. Only rice crops and rice HOM in field trials under organic farming conditions in the period 2022-2023 has been the subject of scientific papers within the doctoral structure. Concerning entomological monitoring, based on farmers' surveys carried out in form of interviews during Ph.D. project, the low concern for ecological and biodiversity-friendly practices

for Lepidoptera, Odonata and amphibians persists, despite the changing weather conditions of 2022-2023. According to the data analysis, traditional high input rice cultivation contexts and related practices are usually associated with critical areas for biodiversity (eBMS, 2024; Huynh et al., 2021; Labeyrie et al., 2021; Staley et al., 2016) in terms of: a) low prevalence of environmentally resilient agricultural practices; b) Modulation, in particular with water and grass management measures, is one of the weakest features of wetlands covered by paddy fields; c) A wider range of agricultural practices in terms of impact on the taxa concerned. Odonata and Amphibia are usually more exposed to biodiversity issues related to "agricultural bottlenecks". At the same time, weed control practices are relevant for maintaining a suitable ecosystem for the taxa considered. Frequent chemical weeding and mowing, in particular, and intensive tillage can seriously impair the conditions of specific rice fields, affecting key elements of the life cycle of taxa such as nectar sources, host plants, protected areas and availability of prey. Phytosanitary treatments and crop rotation can also indirectly interfere with the life cycle of taxa and affect biodiversity (Whipple and Bowser, 2023; Gemmill-Herren et al., 2021; Sybertz et al., 2017; Staley et al., 2016). Farmers' choices can be considered just trade-off solutions for different taxa, and any crop cycle can match each taxa requirement. Specific farmers' choice must consider local biodiversity consistency and structure. However a more concerned and biodiversity respectful rice farming calendar can be adapted to specific rice farmed agro-systems, for specific biodiversity needs (Tibi et al., 2024; Labeyrie et al., 2021; Vasseur et al., 2023). Thus regarding the thrive of vegetation, the level of anthropization and entomological adaptability on field banks are mutually related. Moreover, irrigation practices are crucial because water management is vital to maintain paddies as ecologically functional wetlands. The water source is also difficult to control because of the nature of the field, for capacity, degree of levelling and position, also of the nozzles of water

drainage, determining different water supplies (Gilardi et al., 2023; Huynh et al., 2021; Tang and Visconti, 2021). The overall amount of water in the field is fundamental at the physical-chemical level in defining partial or total lack of oxygenation and related "reduced" chemical conditions. This determines the selection of adventitious plants that are exquisitely aquatic. On the other hand, the higher parts of the soil, such as field banks, benefit from water availability for the botanical diversification, being positive for the winter entomofauna, and life cycle of butterflies too. Hence the margin areas of the fields acquire a pivotal role, comparable to proper rice fields. This interface is crucial for sustaining and promoting biodiversity, despite its limited consideration in terms of management systems (Giuliano and Bogliani, 2019; Giuliano, 2018).

5.4 The importance of multi-criteria analysis and crop trade-offs: crop bottlenecks for biodiversity

Multi-criteria analysis lends itself to numerous crop and environmental implications. The assessment of choices should be carried out through an evaluation of criteria, namely a) economic-organizational; b) environmental-climatic; and c) protection of biodiversity. Among the most important crop-growing pastures, we can identify: 1) The use of synthetic inputs such as herbicides, plant protection products and fertilisers; 2) The management of the clippings is doubly crucial since it is not only a factor of destruction for agrosystems of rice and ecosystems of wetlands, but it is also a real destruction of the food sources (plants and nectar) for important taxa (like those of the pollinator insects, including butterflies); 3) Irrigation practices are important as they determine the creation, maintenance or destruction of the area of substitution. The role of the dry land is a breakdown of the habitat and in this sense it must be used carefully, including through the use of compensatory practices or transitions, such as winter submersion; 4) Soil cultivation has a more circumstantial impact in terms of time, but it

can also be reduced or altered. The same is true of the temporal organization, as in the case of other cultivation practices with significant environmental impacts (e.g. emissions of GHGs and accumulation of heavy metals related to the hydroperiod), which are crucial in determining the higher or lower impacts of cultivation practices. Therefore, this analysis is the attempt to carry out an agro-environmental analysis through its main components, and secondly to create a perspective that is able to consider the dual economic-productive vision of farmers with respect to the conservation and ecological nature of the research. The assessment of biodiversity should also be carried out on the basis of the preferences and precedence of the specific biodiversity of the farms and the territorial realities involved. As already remarked in the literature, good agronomic practices are within the reach of both organic and conventional rice farming (Singh and Singh, 2023; Giuliano and Bogliani, 2019; Giuliano et al., 208; Fusi et al., 2014). This is a corollary issue, even if it is of relevance and impact, not least socio-economic, but it is also represented by the fact that often the agricultural companies are rarely interested in or engaged in biodiversity and agrobiodiversity. They are less inclined to adapt their systems and crop choices to the needs imposed on biodiversity, also as a result of a dedicated economic compensation. In summary, the good practices associated with rice farming include: a) Management of fertilisers; b) Combating acidification, eutrophication and synthesis phytosanitary treatments; c) Reduced mechanical disturbance from soil tillage, sowing and weeding practices; d) Wetland conditions extension from late ripening varieties to winter flooding. In order to combat the very competitive weeds, the proliferation of algae and the decrease of oxygenation in the paddy fields, some practices are particularly delayed in an increasingly problematic picture for water quantity and quality, not only for the selection of weeds resistant to changing climatic conditions. For example, rice farmers who want to sow in water should avoid phosphatic fertilizers, for the control of algae,

rice must be sown 1-3 days, sowing according to the availability of water at the time to have the paddy with the correct water level, seed soaking for 24-48 h, keeping water 7-10 days before rooting dry, quickly draining the paddy after the first root crop to promote good rooting and emergence in a regular way. This should always proceed steadily and gradually in the water management, for example, lengthening times of emptying of the rice paddy, reducing the speed of flow of the paddy (Savoini et al., 2025, a-b; Butterfly Conservation, 2024; Mallet et al 2022; Topping et al., 2019).

5.5 The economic dimension of sustainable rice farming practices

The economic dimension of biodiversity and environment management is largely not included in the evaluation of business models in the rice farming sector. A comprehensive analysis of the economic sustainability of different business models (organic and conventional) requires an analysis of on-farm revenues. However, the availability of accurate and complete economic data is critical. Consequently, for overall thematic consistency with the thesis project, and for the availability and overall certainty of the data, it was decided to carry out a targeted analysis of the economic sustainability of cultivation practices in rice farming, rather than conducting comparative economic analyses in a broader but less precise context. In fact economic studies in the sector usually focus mainly on cultivation practices efficiency, both in the conventional and organic methodology of productions and possible economic savings related to sustainable practices. Not much attention is paid to the profitability of the possible internal agorecological reorganisation of farming operations (Mouratiadou et al., 2024; Ahmad et al., 2023; Bacenetti et al., 2016). Most of the specific economic data comes from reports produced by industry organisations or expert-based panels (Order Dr. Agronomists and Dr. Forestry of Biella and Vercelli, 1015, 2021, 2023, 2024). This issue is crucial, also considering that for conventional rice farming in North

Western Italy, farms below 300 ha have a negative profitability, without a CAP aid per hectare of around 700 €/ha (Order Dr. Agronomists and Dr. Forestry of Biella and Vercelli, 1015, 2021, 2023, 2024). Organic or agro-ecological farms are able to reduce some of their costs through self-production or by implementing more extensive farming choices aimed at distributing the costs over more agricultural years (e.g. crop rotations or agroforestry). Regarding conventional rice management, it should be pointed out that this refers to a farming system which is now of medium-large size with proportionally few irrigation surface channels per area, about 60 ha on average, typically monocultural and with few semi-natural areas within the farmland, which makes the total agricultural area typically close to the total farmland area (Order of Dr. Agronomists and Foresters of Biella and Vercelli, 2015, 2021, 2023, 2024). Considering operational costs, conventional rice farming management costs are on average 1434 €/ha. The number of hours is approximately 18.55 h/ha, with an average hourly labour cost of 23 €/ha. Analysis of the key costs associated with conventional rice farming can indicate the following as main farming activities: a) ploughing (from 150 to 300 €/ha according to farming conditions); b) sowing by broadcasting (supplanted by sowing on green mulch in most of the organic farms): around 50 €/ha; c) weeding interventions: up to 750 €/ha in the whole farming season; d) distribution of inorganic fertilizers (on crops, typically, II and III intervention): up to 400 €/ha. In the case of total outsourcing (a rare occurrence) the estimated cost is 1500 €/ha, which is slightly higher than the operating cost of a direct company. However these amounts can definitely climb up to higher amounts, in less favourable areas and agrarian years of high prices, even exceeding 3000 €/ha. Conversely, the costs of organic rice management are approximately estimated to be higher, in less favourable conditions, but in any case stabler (due to minor purchase of external inputs), with an amount of 1883 €/ha (Data from Una Garlanda Farm (Rovasenda (VC), 2024). Agro-ecological, and usually get at the end of

the productive process higher total revenues, due to higher paddy rice price, stabler yield, flexible costs reduction, and usually stronger provision to voluntary CAP measure implementation. From organic farms costs should be subtracted hours and financial resources used for traditional processing, herbicides, treatments of pesticides, estimating a number 17.85 hours/ ha of operations, balanced by operations related to sowing and rolling of green mulch (typically fast, considering that soft ground is being worked). In particular an analysis of the key costs associated with organic rice farming can indicate: a) a simplified soil tillage, typically by trimming and possible digging: 150 €/ha; b) autumn sowing of grass: 52 €/ha; c) sowing on green mulch in spring: 52 €/ha (Personal Communication Una Garlanda Farm, Rovasenda (VC), 2024). Spreading of organic fertilisers is often optional, and avoided in closed cycle farms without direct livestock integration, due to high transport costs. Organic rice farming systems, moreover, refer to typically multifunctional, multi-cultural agricultural systems in which the area occupied by rice as a crop does not monopolize the entire farm (as it is subject to crop rotation). This certainly determines the greater difficulty of implementing economies of scale in these agricultural systems, an increased relevance on budget of input purchases, and the need to adopt a system with reduced input use and cost, and typically a more extensive farming methodology (Segre et al., 2022; Rosa-Schleich et al., 2019). This approach is aimed at exploiting the resources and technical means produced on the farm, namely seed, especially if we are referring to non-commercial varieties (classical, conserved, local or generally suitable for low-input systems, often with self-produced seed) and crop rotations, the use of phytosanitary treatments is reduced with the use of resistant cv, crop rotations and the use of a few organic products, usually cheaper than those of synthesis. This approach certainly requires more knowledge and business organization, but it is particularly relevant because the only technical means of production (seeds, fertilizers and plant protection products) if

purchased amounted to about 25% of the costs of a conventional farm, down from more than 30% in 2023 but still higher levels than the previous decade (Order Dr. Agronomists and Dr. Forestry of Biella and Vercelli, 1015, 2021, 2023, 2024). Other savings in organic rice farms include the zero-use of inorganic fertilisers and plant protection costs. Another key item of savings is the lowered operational costs linked to reduced soil tillage, for example, by reducing levelling costs from 130 to 40 €/ha, due to less frequent interventions. Diesel consumption remains a critical and relevant issue: 50% of the consumption is related to drying costs (12-18 l/t of paddy rice), and only the remaining part for proper crop operations. The average cost of diesel is estimated at 252 €/ha. More specifically the consumption of diesel remains significant and hardly compressible, for average amounts from the literature between 240 and 260 €/ha. By 2024, it amounted to just over 5% of total company costs (compared with low agricultural fuel prices of 0.75 €/l), below the almost 7% reached in 2022-2023 but still well above the 3% that accumulated before 2021. Medium-large sized farms (about 120 ha, with reduced farm sizes, and a substantially monocultural agricultural system), very intensive and integrating chemical processes with the mechanics, arrive at considerable fuel consumption, of up to 45,000 l/ year (375 l/ ha, 357 €/ ha). On the other hand, an agroecological management with reduced use of inputs (including less frequent and more superficial soil tillage can, therefore, lead to substantial reductions of up to 15,000 l/year (125 l/ha, i.e. 119 €/ha), clearly below the cost threshold of both the most intensive and the average value. These economic costs are, however, definitely higher considering that the estimates of agricultural diesel in the last half-year have recorded higher averages (0.95 €/l) (Order Dott. Agronomists and Dr. Forestali di Biella e Vercelli, 1015, 2021, 2023, 2024). Considering common organic-conventional fixed costs, it must be noticed that these expenditure items are relevant for farms, but only a small part is directly related to farming and land tenure activities. However different

farmers' choices and agro-ecological approaches can be redirected and also reduce fixed costs. For example the irrigation contribution for Corsorzio Ovest Sesia corresponds to an average of 286 €/ha, but with significant differences (even double) dependent on the unfavourable location conditions and conditions of the surface irrigation network. The water consumption between the two business models is not equivalent, nor equally distributed. The three main rice farming operation types are: a) Seed-spreading: b) Dry seeding; c) Sowing on grass, ranging from 15,000 to 40,000 mc/ha, also considering irrigation network efficiency and soil texture (Vaglia et al., 2022; Fusi et al., 2014; Altobelli et al. 2011). The dominant conventional model of dry sowing distributes the irrigation consumption substantially in the second part of the season, determining an initial saving at the beginning of the season, and a peak of the water demand is therefore delayed and concomitant to the vast majority of farmers' requests. However, it should also be noted that the use of green mulch makes the soil very porous, covered and protected by soil erosion, significantly slowing down soil drainage and evapotranspiration, resulting in less water loss (Vaglia et al., 2022; Orlando et al., 2020). Another important expenditure that is "fixed" for many farms and not depending on the crop system is represented by agricultural rents, of about 800 €/ha. This, on the one hand, rewards owner farms (which often also benefit from CAP titles linked to rice cultivation), and on the other hand favours intensive approaches aimed at increasing the profit margin against increased expenses. The opposite strategy is to grow rice with a rotational model, with the aim of reducing crop costs linked to the much more expensive rice crop, diversifying farm incomes, enhancing productivity with bio-intensive methods on proprietary land (Order Dott. Agronomists and Dr. Forestali di Biella e Vercelli, 2015, 2021, 2023, 2024). In addition, there is a high purchase cost for machinery, with depreciation costs, consisting in the whole mechanization sector of around 15% of farm annual expenses. This is typical in many intensively and high

mechanized farms, both conventional and organic, in particular in Italy, due to a high rate of property owned machineries, with an hour/utilisation usually far below rapid, partially compensated by the long-term use of old-equipped machineries for non-proprietary and lighter operations, such as transport or powering irrigation pumps. In general these costs should be assessed in relation to the average price of rice and the profitability of the farm itself, largely dependent on the average price of paddy rice. In the first months of 2024, the price was around 550 €/t, with differences in prices for round and long rice A similar to the main varieties placed between around 350 €/t and 450 €/t, and classic and organic rice attested to figures even higher than 1000 €/t (in this way compensating the production losses) (Order Dott. Agronomi and Dott. Forestali di Biella e Vercelli, 2015, 2021, 2023, 2024). It is clear that a series of agricultural practices in the rice sector with reduced environmental impact is currently available, which would require greater support in the context of regional development policies and the CAP (Vaglia et al., 2022; Vitalini et al., 2020; Bacenetti et al., 2016). The current situation shows the possible modulation of good agricultural practices on different scales, and at the same time indicates how the agroecological transition requires a greater possible commitment at a financial level (Pimbert, 2015; Lamine and Marsden, 2023; Wynberg et al., 2023).

5.6 Potential and limits of participatory methodologies

In order for the process of adaptation of the current agrosystem to move from a system based on fossil resources and impacting biodiversity to a truly sustainable one, it is necessary to strengthen the active involvement of farmers. In this sense, communication, training, involvement, operational cooperation and co-creation in the field of research with farmers should be strengthened. Reflecting on the results in connection with methodological approaches to research work, the importance of

participatory methods should be stressed. Participatory methodologies included: a) participatory varietal selection of HOMs within the Resilient Rice project, at the end of which the PhD project was implemented; b) definition of monitoring transects according to standard procedures, implementable by volunteers (Pollard transects), and based on farms characteristics and needs; c) the use of expert panels including the various stakeholders in rice production (farmers, agronomists and researchers).. These processes have provided important components and resources for project development, namely a) relying on a monitoring and operational network to carry out monitoring and testing; b) being aware of an adequate and functional breakdown of the vitality of the project; c) the enhanced role in the III Mission, ensuring greater knowledge, scalability of good practices within social context around project activities; d) they are linked to open access methods both in terms of the tools used and the type of project deliverables. However, the limits and problems of participatory methods are different: a) they must be based on strong and organized social networks, characterized by a high level of trust and organizations as democratic as possible; b) they need time and attention to the specific aspects and internal dynamics; c) if operational chains are not clearly organised, there is a greater chance of errors being made and remedied in a timely manner, as well as the collection and processing of good quality data; d) soft skills such as open-mindedness and scientific creativity and multidisciplinary are required, as well as collaborative attitude inside and outside the working group; e) they lend themselves to tampering and conflicts of interest if there are divergent agendas within the research group, especially if there is defamation in the weight of the actors. In the case of this project, the participatory approach concerned: 1) the structuring, management and final phases of the Rice Resilient project (2018-2023); 2) collecting information and data of verification activities, methodological comparison with working groups of experts and volunteers in the field of entomological monitoring; 3) involvement in dissemination

activities and third mission, which took the form of poster presentations, bioblitz and field visits. The potential of participatory methodologies needs to improve knowledge and creativity, and a creative and transformative approach must be enhanced and cultivated by actions if the activities themselves are to be brought to a long-term development (RSR, 2025).

5.7 Social and Economic Agroecology Components

Based on numerous recent reviews, addressing future food and agricultural needs will require a transition to regenerative systems that effectively enhance ecosystem services, minimize negative impacts, and build natural and social capital (Fiore et al., 2024; Mouratiodou et al, 2024; Wezel et al., 2020). Agroecological approaches are central to this transition, integrating ecological principles with social and economic concerns to reduce dependency on external inputs and increase the productive capacity of natural systems. The fact should be considered that poverty is mainly concentrated in rural areas that rely on agriculture for income and employment. Agroecology is a knowledge-intensive process that optimizes ecological functions and biodiversity to improve agricultural performance and farmers' livelihoods, with impacts including enhanced food security, poverty reduction, and increased income (Fiore et al., 2024; Wezel et al., 2020). A consolidation of evidence from previous publications indicates that agroecological practices are associated with positive socio-economic outcomes in most cases. Unsuccessful elements pertained to financial capital, outcomes on income, revenues, productivity, and efficiency. This is supported by quantitative evidence suggesting that agroecological practices enhance financial capital, with results for yield, farm and product valorisation profitability showing similar positive patterns, though with high variability and uncertainty (Vinci et al., 2023; Vaglia et al. 2022; Mameno et al., 2021). Human capital metrics can match negative outcomes with higher labour

productivity. The results, due to combined agroecological farming practices such as agroforestry, diversified cropping system and biodiversity-integration, indicate an overall favourable potential for farms to benefit socio-economically from agroecology (Mouratiodou et al, 2024; Henke and Vaquero-Piñeiro, 2023). Furthermore, studies on EU certified food organic and geographical indications, found that these products outperformed their conventional counterparts on most economic and social indicators (Savoini et al., 2025; De Santis et al., 2022; Vaglia et al., 2022; Dara Guccione et al., 2021). At the same time they perform similarly on major environmental indicators like carbon and water footprints (Vinci et al., 2023; Vaglia et al., 2022). Although certified food is more expensive, its extra performance per euro is similar to classical policy interventions such as subsidies or taxes, legitimizing recent initiatives by standards to cover broader sustainability aspects (Ibidem). Despite this promising evidence, significant limitations remain. Few studies have quantitatively identified the social and economic benefits at the farm level, and the available data are largely confined to peer-reviewed studies that often fail to address holistic approaches or real farm conditions (Yasin, 2023; D'Annolfo et al., 2017). Data for indicators such as income stability are lacking, and future analyses must consider other co-variables like rainfall levels for a more exhaustive explanation. Additional attributes, such as practices with cultural values or those that build natural assets like watershed services, contribute to overall outcomes but are often excluded from evaluations. There is also a lack of evidence on interactive effects across practices, and their combinations deserve further analysis to explore the full potential of future agroecological systems (Vinci et al., 2023; Vaglia et al., 2022; Ceriotti, 2015). Finally, integrating qualitative methods is essential to capture farmer perspectives. The magnitude, temporal aspects, success factors, trade-offs, and system-level effects of an agroecological transition require further

assessment to fully understand their influence on individual farm performance (Vinci et al., 2023; Vaglia et al., 2022; Dara Guccione et al., 2021).

5.8 Conclusions

In an overall summary, the current doctoral research project has demonstrated how it is possible to integrate a transdisciplinary and multi-scale approach into the analysis of the impacts on biodiversity of rice agrosystems in North Western Italy. This modular approach allows the analysis of individual practice options, and can provide a flexible programming tool for farmers, decision makers and sector technicians. It is equally integrable within field research, including monitoring biodiversity associated with wetlands and paddies, as demonstrated in publications related to this research project. More generally, the work has underlined the complex link between agro-biodiversity, cultivation practices applied in the field and biodiversity, just as the genetic diversity of agro-biodiversity represents a piece and a lever within a more complex system of protection and promotion of biodiversity. In this sense, the specific institutions responsible for managing agrobiodiversity should carefully evaluate their role by considering in greater detail the "field" factors, practices and associated cultivation systems, in order to achieve multiple objectives such as the protection of biodiversity according to a systemic logic, climate resilience and global health, according to the One Health paradigm. Likewise, numerous research topics remain open and to be investigated as the most detailed impact of continuing the analysis of multi-criteria and multi-scale rice agrosystems, including both specific practices in the field on biodiversity and the role of landscape elements and medium-extended area. The socio-economic, innovation adoption and effective integration aspects of the CAP must also be explored in depth to promote sustainability in a broader perspective. Essentially, this doctoral thesis has provided an important methodological contribution of field

results, while at the same time indicating relevant future research areas to be investigated to achieve greater sustainability of rice production, especially in the field of biodiversity and climate resilience. More specifically in this sense the work carried out within the doctoral project will have an operational continuation in future projects resulting from the collaboration of academic institutions (University of Turin, University of Milan, University of Pavia) and non-academic institutions (Rete Semi Rurali, Piedmont Rice Biodistrict). Among these projects, the main ones are the PRIMA, CEREA+CONNECT and PEI-AGRI Piemonte projects.

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