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Manipulation and diversification of natural vegetation toward ecosystem services enhancement and restoration of sustainable farming systems

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1 Introduction

Achieving a balance between biodiversity and productivity in agroecosystems remains challenging (Sachs et al., 2010; Mitchell et al., 2014). Even though agriculture is pivotal in addressing environmental sustainability and food security (DeClerck et al., 2016), it is usually considered the primary driver of biodiversity loss and there is increasing concern about the impact of pesticides on human health and the environment (Dudley and Alexander, 2017). Due to the intensification of farming systems, the excessive use of agrochemicals, and the conversion of natural ecosystems into farms, agriculture is responsible for 31% of wild biodiversity loss globally (Tilman et al., 2001). The profound negative effects on biodiversity loss are further enhanced by the frequency and severity of climate change events (Rinawati et al., 2013; Guo et al., 2017). Since most biodiversity and ecosystem indicators abruptly decline (IPBES, 2019), significant agricultural production and economic threats are posed (Bosch, 2022).

Therefore, an eco-efficient strategy sustainably optimizing the balance of agricultural production against its negative feedback is necessary. Nowadays, it is crucial to address the challenges of land restoration, pest-smart production and biodiversity enhancement by adapting sustainable agronomic practices. The biodiversity of the existing spontaneous vegetation (i.e. weed flora) could play a vital role. Even if weeds have been considered undesirable for crops and the scientific community focused mostly on their control, several studies confirmed the beneficial effects of weed flora on the agroecosystem by providing multiple ecosystem services (Blaix et al., 2018; Gaba et al., 2020; Travlos et al., 2021). Recently, the term "service weeds" has been introduced for weed species with the potential to offer ecosystem services in agricultural and non-crop areas (Gazoulis et al., 2024).

The aim of this opinion letter is to discuss some perspectives and key-issues of exploiting the manipulation and diversification of natural vegetation as a practice for ecosystem services enhancement in the farming systems.

2 Manipulation and diversification of natural vegetation

2.1 Ecosystem services: spontaneous vegetation as a part of a dynamic ecosystem

The concept of natural vegetation manipulation could emerge as an effective strategy for enhancing sustainability by integrating non-crop plant diversity within agricultural fields. Several studies have demonstrated that spontaneous plants, referred to as natural vegetation and "service weeds", can deliver valuable benefits on ecosystem services under specific soil and climatic conditions across various agroecosystems. Among them, weed communities provide food and habitats for multiple organisms including beneficial insects, pollinators, and birds enhancing pollination and natural pest control (Bretagnolle and Gaba, 2015; Carpio et al., 2020; Blubaugh et al., 2021). Weeds also decrease the vulnerability of crops to pests by making them less appealing to the pests or by boosting crop defense mechanisms (Blaix et al., 2018). Previous study showed that the existing floor vegetation increased the beneficial nematodes, and organic matter of the up-soil level (Rahman et al., 2009). Furthermore, weed communities can improve soil health by increasing N uptake and fixation, reducing N leaching, and enriching the soil with organic matter, nutrients, and carbon (Garcia et al., 2018; Moreau et al., 2020; Mia et al., 2020). It has also been proven that several weed species enhance water acquisition and infiltration by preventing runoff and soil erosion (Power, 2010; Petit et al., 2011). These weed services are expected to probably become increasingly important, as modeling studies refer to climate change as likely to result in pollinator decline, resource depletion, and soil degradation (Martín-López et al., 2018). Given that diverse plant communities promote the potential of several plant species to thrive under various conditions (Visconti et al., 2018), "service weeds" could contribute to more resilient agroecosystems.

However, the adoption of weed-related ecosystem practices will be challenging due to the nudges toward weeds and the potentially negative impact on crop yield. Farmers and advisors are not familiar with the beneficial ecosystem functions that service weeds can provide. Since most spontaneous plant communities are effective competitors with crops for nutrients, water, and sunlight causing significant yield losses, the perception of growing weeds in cultivated or even abandoned fields remains negative (Zimdahl and Basinger, 2024; Mia et al., 2020). In addition, weeds are linked with disservices acting as hosts for harmful insects, pests, and diseases, degrading soil quality, and releasing dangerous toxins for livestock (Keeler et al., 2013; Thanou et al., 2021). Therefore, specific cultivation practices should be recommended to promote the adoption of weed management strategies among producers and keep them present in density, frequency, place and time that they do not cause major or irreversible problems. These practices should highlight their role in enhancing ecosystem services while maintaining high crop productivity.

2.2 Natural vegetation manipulations through cultural practices

Weed management methods are mainly focused on reducing potential weed-crop competition by effectively eradicating weed abundance (Lowry and Smith, 2018). As a result, many arable plants vanish, while a few more competitive species adapt to intensive management (Storkey et al., 2012). Common practices such as tillage and the application of herbicides, even if in some cases were temporally efficient against weeds, should be lowered due to their environmental consequences such as soil erosion, and fertility loss (Prosdocimi et al., 2016; Rodrigo-Comino, 2018). Therefore, alternative and more sustainable weed management methods should be proposed. The urgency of this necessity is further emphasized by the EU Natural Restoration Law (NRL) adopted by the European Union in 2024. According to NRL, biodiversity conservation in agricultural regions is outlined as a primary long-term restoration goal to be achieved by 2050 (European Parliament, Council of the European Union, 2024).

The current opinion letter addresses this need by highlighting the shift in focus from weed removal to biodiversity maintenance through manipulating weed communities. Given that resource availability (i.e. light, water, nutrients, and space) affects competition between crops and weeds, functional diversity will be used to increase resource utilization. This diversity can be achieved by introducing additional plant species or preferably by managing existing natural vegetation in agroecosystems. Newly entered plant species, referred to as cover crops, have been extensively studied, with considerable evidence demonstrating their effectiveness in suppressing weeds and providing ecosystem services like soil erosion prevention, nitrogen (N) fixation, and N leaching mitigation (Blanco-Canqui et al., 2015; Lemessa and Wakjira, 2015). Cover plants can be cultivated either before the main annual crops or during the growing season between primary crops as living mulch (Hartwig and Ammon, 2002). Previous studies showed that as cover crops grow more, they generate more residues, which in turn absorb greater amounts of soil resources and nutrients, thereby limiting their availability to weeds (Blanco-Canqui et al., 2015).

Given the beneficial effects of cover crops in weed suppression and ecosystem services, we propose that the strategic manipulation of the natural vegetation may result in analogous valuable outcomes. Compared to newly entered plant species, existing weed communities exhibit significant traits shaped by the evolutionary selection pressure. Their plasticity, adaptability, and short life cycles enable their adaptation to environments and improve their resilience to climate change (Bradshaw, 1965). Furthermore, weed species are self-seeded, facilitating their adequate ground cover and minimizing the financial and labor investments compared to the establishments of newly induced vegetation. Through the weed flora manipulation by means of practices like mowing, a less competitive environment could be created regarding resource availability. Ecological niche theory argues that a more diverse weed community, consisting of species with different resource requirements results in a greater variation in resource availability (Chesson, 2000; Storkey and Neve, 2018) and mitigates dominant competitive effects that could reduce crop yield (Borgy et al., 2012). Previous studies have demonstrated the ability of strips, fallow land, and field margins to promote biodiversity, and diversification, and provide multiple ecosystem services that contribute to improved conditions for crop growth and productivity (Gaba et al., 2020; Robinson et al., 2022). In this regard, service weeds present in arable crops or orchards could be transformed into "cover weeds" exploiting their ground floor cover and/or their mulches.

From a practical perspective, two manners are proposed for the manipulation of natural vegetation as cover weeds; before the crop is grown (fallow cover weeds) or alongside the crop (ground floor covered by weeds). Both practices are focused on the decrease of weed emergence and weed biomass, but their implementation is highly dependent on the crop. In arable crops, a short-term fallow before the crop establishment would be a suitable tactic and reduce the potential yield losses due to a long-term fallow (Lin et al., 2023). Previous studies demonstrated the significant role of fallow in the agroecosystem since it reduces soil erosion and improves several soil chemical properties (Wortman et al., 2016). Moreover, it reduces nitrogen losses, enhances soil organic matter and limit the dispersal of noxious or invasive species (Ando et al., 2014; Wortman, 2016; Gu et al., 2019). Therefore, a short-term fallow lasting a few months (Petit et al., 2011) is proposed as part of the rotation to simultaneously target weed communities that could emerge in the next crop, exploit the fallow benefits, and allow farmers to manage the land more successfully (Lin et al., 2023). Fallow is proposed to be managed with 1–2 cuttings at different height, depending on weed density, biology and ecology (e.g. presence of invasive species or ecosystem services prioritized). Accordingly, the weed cover is suggested to be mechanically terminated by roller crimping or mowing before crop establishment (Wallace et al., 2017). Weed mulches can also persist on the soil surface to restrict weed emergence in the subsequent crops (Teasdale and Mohler, 2000).

Concerning permanent crops, the exploitation of natural vegetation concerns the weeds that appear directly contiguous to the planting row, and between row spaces of woody perennial fruits. In these cases, spontaneous vegetation in orchards and vineyards can be managed by mowing at different heights and times to achieve suitable biomass growth and to prevent further weed seeding (Baumgartner et al., 2008). At the same time, cut weeds as mulching material will remain in the orchard or vineyard ensuring soil coverage (Travlos et al., 2024). Among the several ecosystem services provided, maintenance and mowing of ground floor can improve water retention and control of erosion, contribute to pest control, and increase soil organic carbon and biodiversity (Muscas et al., 2017; Daane et al., 2018; Guzmán et al., 2019; Hall et al., 2020).

2.3 Steps to be taken for cultural practices implementation

The above-mentioned practices, although immediately applicable, they depend on many parameters that must be

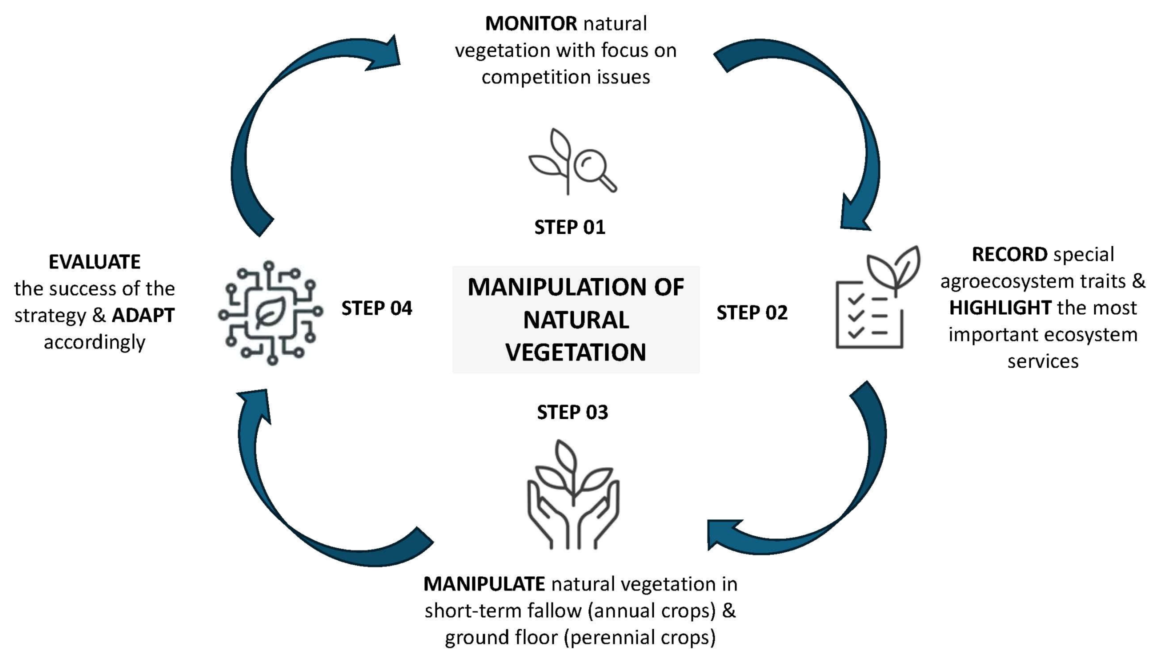

FIGURE 1
Steps to be taken toward a systematic natural vegetation manipulation.

considered before their implementation. We hereby propose a structured sequence of steps to enhance the effectiveness of these practices and evaluate the performance in the growing season (Figure 1). First, it is crucial to observe the weed flora composition (with particular attention to their competitiveness, the presence of invasive or perennial species in the wider area) and record their density, and potential fluctuations, as they depict the overall field history and the specific growing conditions (step 1). In case there are present considerable populations of perennial, noxious and/or invasive species, then ploughing or site-specific control of such species is necessary (Travlos et al., 2019; Kanatas et al., 2019). After recording the existing weed species, special characteristics of agroecosystems such as sloppy fields, soils of low fertility or bad structure and pest infestations must be recorded to adapt the cultivation practices and prioritize the ecosystem services in the short, medium and long term as previous proposed by Gazoulis et al. (2024) (step 2). The next step includes weed flora manipulation either as fallow in arable crops or ground floor in permanent crops with the adjustments made based on the agroecosystem special needs (step 3). In the end, an evaluation of the performance of these practices should follow up since it will determine the success of the proposed strategy and whether any adaptations and modifications are needed or not (step 4). The assessment of the ecosystem services of natural vegetation can be accomplished by means of field trials across various soil and climatic conditions (Gaba et al., 2020). In all cases, any evaluation should also consider the impact of these practices on crop productivity and biodiversity indices (Robinson et al., 2022). Recently, Feng et al. (2025) evaluated the long-term effectiveness of soil reconstruction and ecological restoration techniques in a non-agricultural area through the assessment of different parameters such as vegetation coverage, species diversity, biomass, and soil stability. Another issue to be taken into account is that diversification should be enhanced at different scales, both between fields (large scale) and within fields (small scale). Therefore, this manipulation of the natural vegetation that we propose here can be also extended in the areas between the fields to ensure a higher biodiversity and ecosystem services provision in a wider area.

3 Conclusions and challenges

One of the primary challenges of the balance between productivity and biodiversity in farming land is addressing the biases and nudges of farmers and agronomists related to weeds and natural vegetation in general. Moreover, even if there are encouraging findings about weed flora manipulation and weed related services, there is a lack of systematic field research across different regions, sites and pedoclimatic conditions. Similarly, the knowledge about the competitive effect of weeds in complex communities, their interaction with pests and diseases, and the influence of weed diversity on crop productivity, is still in its infancy. Therefore, further research should be conducted to valorize the potential of natural vegetation, its services, disservices and interactions, and the prospects and obstacles derived by management methods. In all cases, if it is to restore and regenerate our farming systems, we ought to shift the paradigm and redesign them to rationally exploit natural vegetation in a beneficial way both for the productivity and the environment.

Author contributions

IT: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. IG: Investigation, Writing – original draft, Writing – review & editing. NA: Writing – original draft. AK: Visualization, Writing – original draft. MK: Investigation, Writing – original draft. DP: Investigation, Writing – original draft. PK: Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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