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Dually-beneficial habitats serve as a practical biodiversity mainstreaming tool in European crop production

Zweifach-nützliche Habitate dienen als praktische Integrationsmaßnahme zur Förderung biologischer Vielfalt im europäischen Ackerbau.

Abstract

Semi-natural habitat creation in Europe is a tool to address habitat loss, caused by agricultural landscape simplification. Research on habitats is mostly conservation-centered, while studies on their delivery of multiple agro-ecosystem services are limited. However, knowledge about these habitats' suitability for production could make them a practical biodiversity mainstreaming tool. This paper identifies potential dually-beneficial (db) habitats for use in cereals, oilseed rape, and sunflowers, the three major EU arable field crops. They are often grown in simplified landscapes, where the need for improved biodiversity connectivity at landscape level is high and their integration expected to be most effective. The paper provides a qualitative survey of the db-habitats effects on agro-ecosystem services and disservices while addressing trade-offs and synergies thereby using an ecology-focused agro-ecosystem services and disservices framework. Four differently suitable db-habitat groups were identified: 1. Uncropped fields/subfield areas, 2. Managed fields/subfield areas, 3. Managed flower areas and 4. Managed margins.

Key words: agro-ecosystem services, disservices, agriculture, semi-natural habitats, mainstreaming biodiversity, landscape management, precision agriculture, precision conservation

Zusammenfassung

Die Schaffung semi-natürlicher Habitate in Europa ist eine Maßnahme, um dem Verlust von Habitaten entgegen zu wirken, die durch die Vereinfachung landwirtschaftlicher Landschaften entstanden sind. Die meisten wissenschaftlichen Arbeiten zu Habitaten fokussieren auf Artenschutz, während Untersuchungen zur Bereitstellung verschiedener Agrar-Ökosystem-Dienstleistungen begrenzt sind. Kenntnisse über den Nutzen derartiger Habitate für den Ackerbau, würden es jedoch ermöglichen, sie zur Standard-Maßnahme („mainstreaming“) für die Integration von Biodiversität im Ackerbau einzusetzen. Diese Arbeit zielt darauf ab, zweifach-nützliche Habitate zu identifizieren, die in Getreide, Raps und Sonnenblumenfeldern eingerichtet werden könnten, da diese die drei wichtigsten Ackerkulturen in Europa darstellen. Diese Kulturen werden oft in vereinfachten Agrarlandschaften angebaut, wo die Notwendigkeit zur verbesserten Konnektivität der biologischer Vielfalt auf Landschaftsebene hoch ist, und ihre Integration den größten Nutzen verspricht. Eine qualitative Beurteilung dieser Habitate erfolgt im Rahmen ökologisch fokussierter Agrar-Ökosystem-Dienstleistungen und -Undienste, erläutert Kompromisse (Vor- und Nachteile) für den Ackerbau sowie potentielle Synergien. Vier unterschiedlich geeignete Gruppen von Habitaten konnten identifiziert werden: 1. Brachfelder/Teilflächen, 2. Bewirtschaf-

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tete Felder/ Teilflächen, 3. Bewirtschaftete Blühflächen, 4. Bewirtschaftete Ackerrandstreifen.

Stichwörter: Agrar-Ökosystem-Dienstleistungen, -Undienste, Pflanzenproduktion, semi-natürliche Habitate, Integrationsmaßnahme, Biodiversität, Landschaftsmanagement, Präzisionslandwirtschaft, Präzisionsumweltschutz

Introduction

Agriculture occupies approx. 40% of total EU land. It is a crucial part when pursuing conservation goals, with respect to habitat connectivity that supports biodiversity. This paper focuses on arable land (Glossary), which constitutes 24% of total EU land, i.e., 61% of the utilized agricultural area (Eurostat, 2018a; Fig. 1). Current biodiversity challenges are mainly caused by intensification and related habitat loss (abandonment and expansion of cropland) even though cropland is an ecosystem in its own right, supporting a range of species (Shrubb, 2003; Ceaușu et al., 2015). Good agricultural practices (Glossary) and more efficient use of natural resources (e.g., land, water, energy) have been increasingly adapted by farmers in Europe over centuries. These practices sustainably use biodiversity and natural capital (Glossary), hereafter biodiversity, to maintain or enhance the delivery of agro-ecosystem services (Glossary) and contribute to productivity resilience (Glossary). They are indispensable for the ecological and socio-economic viability of agricultural operations irrespective of whether the cropping system is integrated (Glossary), or organic (EC, 2017; FAO, 2019). To more specifically reverse habitat loss, the creation of semi-natural habitats (Glossary) received increasing attention in Europe and has been recommended by various stakeholders, including ecologists, scientists, farmers, as well as national and EU authorities (e.g., EC, 2013; ELO, 2015). Their creation can also be an important element to improve landscape heterogeneity and connectivity (Weibull et al., 2003; Sayer et al., 2017). Their benefits to cropland associated biodiversity (Glossary), and to individual, iconic species such as corn bunting (*Emberiza calandra*), or small mammals such as hamsters (*Cricetus cricetus*) and hares (*Lepus lepus*) are well documented (e.g., Dicks et al., 2014; Wagner et al., 2014; Cole et al., 2019). However, research on their effects on multiple agro-ecosystem services delivery is limited, and few researchers focused on economics (e.g., Holland et al., 2017). Despite continued support for this recommendation, re-iterated by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), a key question remains: Which habitats are potentially suitable to be integrated into crop production as a biodiversity mainstreaming tool (Glossary), as called for by policy makers at international level, that will increase and more effectively contribute to the twin goals of biodiversity and production, while sup-

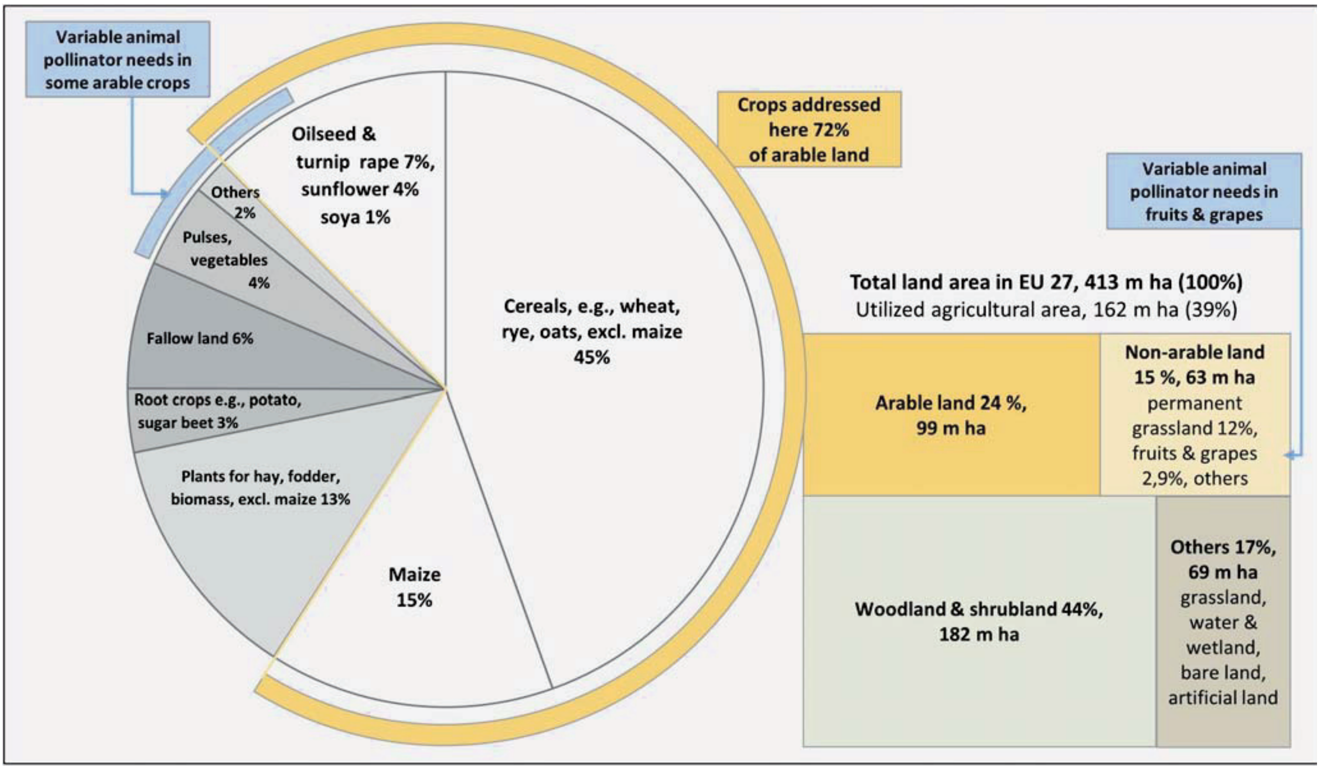


Fig. 1. Percentage of arable field crops in EU-27 (Eurostat, 2018a) and their pollination needs.

porting resilience building over time and scale (CBD, 2011)?

Glossary

Agro-ecosystem services = biotic (e.g., soil biota) and abiotic (e.g., soil organic matter) services that sustain crops/cultivars variably (Mace et al., 2011; Bommarco et al., 2013). They are a subset of all ecosystem services.

Associated biodiversity = the vast range of organisms that live in and around food and agricultural production systems, sustaining them and contributing to their output (FAO, 2019) e.g., predators, pollinators, soil biota.

Arable land = is land worked (ploughed or tilled) regularly, generally under a system of crop rotation (Eurostat, 2018b).

Biodiversity = short for biological diversity, 'life on earth', the variety of life at species, ecosystem and genetic levels. "Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (CBD, 1992).

Cultural services = are defined within a wider framework of ecosystem services as "non-material benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experience" (MA, 2005).

Disservices = are provided by nature to crop production. They include pests, diseases, weeds, climate related weather variations e.g., droughts, floods (Shackleton et al., 2016).

Dually-beneficial habitats (db-habitats) = semi-natural habitats created within fields to conserve biodiversity and support crop production goals. Benefits for biodiversity can be the provision of space for multiple species at local level and an improved habitat connectivity at landscape level. Benefits for farming can include the maintenance and enhancement of agro-ecosystem services delivery, which supports productivity resilience.

Ecosystem Services = "The benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth. The concept "ecosystem goods and services" is synonymous with ecosystem services" (MA, 2005).

Environmental enhancement measures in agriculture = include conservation of flora and fauna within fields via semi-natural habitat creation (e.g., fallow land, field margins); the application of various good agricultural practices: conservation, restoration or creation of agricultural habitats/landscape features beyond fields, e.g., stone walls hedgerows, tree lines, ditches and other water bodies; reduction of pollution/waste; reduction of risks from or quantity of inputs (e.g., of plant protection products, e.g., pesticides, herbicides, fungicides, and fertilizers); and the provision of incentives.

Good Agricultural Practices (GAP) = "address environmental, economic and social sustainability for on farm processes, and result in safe and quality food and non-food agricultural products" (FAO, 2019). In crop production they include broader crop/plant rotations, crop diversification (including cover crops, e.g., legumes), reduced tillage, Integrated Pest Management (IPM) [see details below] and integrated plant nutrient management (IPNM).

Integrated Crop/Farm Management, ICM/IF = as part of sustainable agriculture, ICM/IF is a holistic approach for the management of crops/plus livestock at farm level. It flexibly adapts good agricultural practices with modern technologies, while using natural resources efficiently depending on the field, environmental and local conditions.

Integrated Pest Management, IPM [called integrated crop protection here to emphasize that this term also encompasses weed and disease] = "means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms". IPM is a legal requirement in the EU (EC, 2009).

Mainstreaming Biodiversity = "means the integration of the conservation and sustainable use of biodiversity in … sector-specific plans such as agriculture … It implies changes in development models, strategies and paradigms. Mainstreaming is not about creating parallel … processes and systems, but about integrating biodiversity into existing … cross-sectoral structures, processes and systems." Mainstreaming biodiversity was pledged by the 196 parties to the UN Convention of Biological Diversity, the forum that develops global policy on biodiversity (CBD, 2011).

Monoculture = "The practice of cultivating the same crop in the same soil year after year" (Bullock, 1992; Shipton, 1977).

Natural capital = "The stock of renewable and non-renewable natural resources (e.g. plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits to people." The benefits provided by natural capital, such as ecosystem services, include clean air, food, water, energy, shelter, medicine, and the raw materials we use to create products. Natural capital also provides less obvious benefits such as natural hazard (e.g., flood) regulation, climate regulation, pollination (from e.g., wind) and recreation. (The Natural Capital Coalition, 2016).

Resilience = "The ability of a system to recover from, or adjust to, changes over time and scale" (Folke et al., 2010).

Semi-natural habitat = "an ecosystem with most of its processes and biodiversity intact, though altered by human activity in strength or abundance relative to the natural state" (IPBES, 2019). EU definition: "Semi-natural habitats have ecological assemblages that have been substantially modified in their composition, balance or function by human activities. They may have evolved through traditional agricultural, pastoral or other human activities and depend on their continuation to retain their characteristic composition, structure and function. Despite not being natural, these habitats and ecosystems often have high value in terms of biodiversity and the services they provide" (EIB, 2018).

Sustainable agriculture = "to be sustainable, agriculture must meet the needs of present and future generations for its products and services, while ensuring profitability, environmental health and social and economic equity. Sustainable agriculture contributes to the three pillars of sustainable development over time (FAO, 2019).

Objective

The paper describes a novel approach towards semi-natural habitats. First, it aims at identifying those habitats that are dually-beneficial to conservation and arable crop production (hereafter db-habitats; Glossary). Second, we will elaborate on the qualitative effects of db-habitats' on agro-ecosystem services and disservices, while addressing, trade-offs and synergies, thereby applying a mostly ecologically focused agro-ecosystem services and disservices framework defined in this paper. Our paper will also consider the constraints farmers face in terms of habitat creation, such as ease of manageability and cost-effectiveness. These informations will support farmers decision-making, which is based on the provision of ecosystem goods and services, plus typically a reaction to private use value of biodiversity, not to biodiversity-centered 'external' benefits that accrue to the wider society (Jackson et al., 2007). Considering that habitat loss is most severe in, e.g., simplified landscapes, defined as containing less than 20% of non-managed habitats, these landscapes were chosen as the priority areas for our work (Tscharntke et al., 2005). Arable field crops, typically grown in these simplified landscapes on large farms are cereal, oilseed rape and sunflower that constitute more than 70% of all EU arable land (Fig. 1). Precision agriculture, for instance spatial soil quality or plant health mapping based on global positioning systems (GPS) give impetus to advancements. These technologies can also serve the improved identification of db-habitat locations within fields thus may become more common, tailor-made precision conservation technologies (Berry, J. K. et al., 2005). These technologies can also lead to db-habitats' increased upscaling and better configuration as part of broader landscape planning efforts that address multi-use lands in addition to protected areas and assist the transformative change called upon in the context of the development of the Post-2020 Global Biodiversity Framework (Landis, 2016; Sayer et al., 2017; Früh- Müller et al., 2019; Gassner et al., 2020). Currently, farmers are entitled to payments for the creation of certain types of habitats under the EU Common Agricultural Policy (CAP) (EC, 2013). While this paper will refer to these habitat payments, it will not discuss the CAP's biodiversity quality outcomes as this has been exhaustively covered elsewhere (e.g., ECA, 2018; Pe'er et al., 2014; Früh-Müller et al., 2019; Cole et al., 2019; Mammola et al., 2020). The objective of this paper is to provide plausible rationales to assist farmers with the creation of cost efficient db-habitats as a concrete, practical management tool. This comes in addition to other tools, such as good agricultural practices, as mainstreaming requires the appropriate use of various solutions adapted to local conditions and landscape context irrespective of cropping systems (Schneider et al., 2014).

Identifying db-habitats

The creation of many different habitats on cropland is usually recommended along with a broader mix of other environmental enhancement measures (Glossary) of which habitats, or the CAP's agri-environmental or greening measures are only a subset (EC, 2013). The Web of Science core collection 2015–2020 listed 31 publications for environmental enhancement measures, 130 for semi-natural habitats, 67 for agri-environmental measures, and 335 for greening measures in the context of EU agriculture. As this paper focuses on the identification of db-habitats, the 31 publications on environmental enhancement measures and the 130 for semi-natural habitats were surveyed irrespective of the year of publication and publication platform. Out of those 161 publications, six key ones were selected and further investigated. They included: A European review by Dicks et al. (2014) and studies or guidelines by Thomas et al., 2009, Jenny et al., 2011, IlöK, 2012, Jahn et al., 2014, and INSPIA, 2015. These publications were chosen as they contain a broad variety of perspectives across cropping systems (integrated, organic), European geographies and target various purposes and stakeholder groups (e.g., policy recommendations, farmers). 204 environmental enhancement measures were found in these publications. They included 96 habitats of which 42 (Table S1) qualified as db-habitats, based on criteria defined by the authors: a) broadly beneficial to multiple species, b) potentially beneficial to agro-ecosystem services delivery in arable field crops and c) ease of manageability, cost effectiveness (Table 1).

After closer inspection, the 42 db-habitats (Table S1) contained duplications, different terms used synonymously for the same habitat (e.g., fallow or set-aside land), various subcategories (e.g., entire fields, subfield areas, extensively cropped areas, cover crops), dual strategic intents (e.g., buffer for biodiversity sensitive areas, crop production/biodiversity services delivery) or durations (annual, perennial). We clustered them into four

Table 1. Criteria that identified 42 db-habitats out of the total 96 recommended habitats.

a) Included: Habitats providing space, refuge, foraging, and nesting opportunities to multiple species (flora and fauna) within arable field crop areas.
Excluded: Habitats addressing the protection of individual species beyond fields/on farms, e.g., hedgerows, tree lines, ditches, and other water bodies and agricultural landscape features, e.g., stone walls

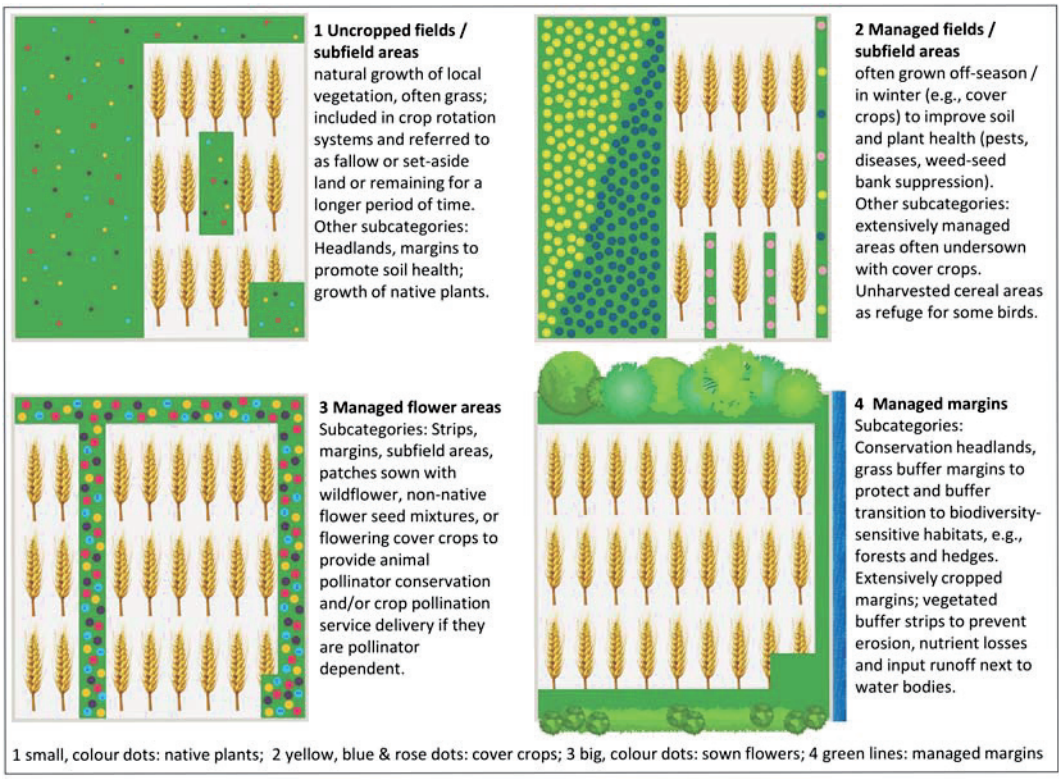
b) Included: Habitats potentially providing agro-ecosystem services beneficial to arable field crops
Excluded: other crops (e.g., perennials, permanent grassland).

c) Included: Habitats providing benefits in terms of e.g., time, cost, and labor savings; productivity; easily integrable as part of commonly applied arable crop management practices.
Excluded: Habitat creation requiring the purchase/rent of specific, not commonly available machinery and/or unacceptable high costs or labor efforts.

groups indicating various sensible options for farmers to choose from depending on local conditions and needs. For instance, managed margins particularly serve as useful transition habitats to conserve various wildlife species, prevent erosion or run-off of inputs (details see Fig. 2).

Establishing a framework for agro-ecosystem services and disservices for arable crop production

Ecosystem services (Glossary) frameworks provide multiple disciplinary perspectives for evaluating human well-being, i.e., the value of nature to people to inform decisions. For instance, frameworks can be used to measure the delivery of ecosystem services, to determine their [monetary or qualitative] value or to define their management (Power, 2010). Here, to practically connect the db-habitats with the addressed crops and elucidate their potential suitability, i.e., value in terms of agro-ecosystem services and disservices delivery, a mostly ecology-focused ecosystem services and disservices framework was used (Bremmer et al., 2020). To evaluate ecosystem services, first *all* services potentially affecting a decision and in a second step the *priority* services relevant to the particular context, here db-habitat creation in the three addressed crops, have to be identified (Geneletti, 2015). All potentially relevant agro-ecosystem services were identified by consulting the key ecosystem services'



1 Uncropped fields / subfield areas
natural growth of local vegetation, often grass; included in crop rotation systems and referred to as fallow or set-aside land or remaining for a longer period of time. Other subcategories: Headlands, margins to promote soil health; growth of native plants.

2 Managed fields / subfield areas
often grown off-season / in winter (e.g., cover crops) to improve soil and plant health (pests, diseases, weed-seed bank suppression). Other subcategories: extensively managed areas often undersown with cover crops. Unharvested cereal areas as refuge for some birds.

3 Managed flower areas
Subcategories: Strips, margins, subfield areas, patches sown with wildflower, non-native flower seed mixtures, or flowering cover crops to provide animal pollinator conservation and/or crop pollination service delivery if they are pollinator dependent.

4 Managed margins
Subcategories: Conservation headlands, grass buffer margins to protect and buffer transition to biodiversity-sensitive habitats, e.g., forests and hedges. Extensively cropped margins; vegetated buffer strips to prevent erosion, nutrient losses and input runoff next to water bodies.

1 small, colour dots: native plants; 2 yellow, blue & rose dots: cover crops; 3 big, colour dots: sown flowers; 4 green lines: managed margins

Fig. 2. Graphic visualization of the four db-habitat groups. Each group consists of various subcategories and indicates sensible implementation options for farmers to choose from according to the local conditions.

frameworks (MA, 2005; TEEB, 2010; CICES, version 5.1 by Haines-Young & Potschin, 2018) and publications on the subject (Lin, 2011; Dale & Polasky, 2007; Power, 2010; Finisdore et al., 2020). In crop production, disservices (Glossary) such as weeds, pests, and diseases present significant production constraints, yet are rarely considered in evaluations. Here the disservices are considered to achieve a more balanced and meaningful system approach (Schaubroeck, 2017). Table 2 summarizes all potentially relevant agro-ecosystem services and disservices as they were defined here.

Prioritizing agro-ecosystems services and disservices by connecting the db-habitats and the crops addressed here

In the following we will elucidate, with respect to the four db-habitats categories, which of the services and disservices summarized in Table 2 are priority ones, i.e., add ecological value, disservices, i.e., hamper production or are possibly not relevant for the crops focused on here. This elucidation will determine the db-habitats overall suitability, although suitability is subject to significant variability. For instance, soil type, climatic conditions, crop protection and topographic needs will in practice influence the db-habitats targeted deployment. When crop and cultivar specific know-how is available it will be included. For other services, e.g., those relating to soil, common agricultural knowledge and publications are used. The potential monetary value of db-habitats cannot be addressed as it goes beyond the scope of this paper and only limited specific data are available (Dale & Polasky, 2007). As profitability aspects are key to farmers, the costs for the creation and ease of management of the db-habitats, loss of yield and production area and disservices are qualitatively evaluated.

Soil-related agro-ecosystem services

Soil related agro-ecosystem services are indispensable to all crops and have been the focus of farmers' attention for centuries. Ancient examples include the so-called Plaggenesch soils (plaggic anthrosols). They demonstrate how the continuous application of grass and heather 'plaggen' improved soil fertility, including by adding organic matter content over time (Giani et al., 2014). In the context of habitat creation, soil services have been the least assessed for effects on crop production, although soil erosion by water is one of the major threats to soils in Europe (Panagos et al., 2015; Holland et al., 2017). All db-habitats provide erosion prevention while its extent depends on the field's topography e.g., inclination of slopes, soil texture, and root depth of the plants grown in habitats (Schulte Moore et al., 2017). Uncropped, naturally vegetated entire fields or smaller, subfield areas (db-habitat-1) are easily integrable into crop rotation systems. They can provide an increase in organic matter and soil fertility, while simultaneously support ecological benefits such as bird nesting opportunities, flowering plants (forage sources), refuge and connectivity for multiple species.

In the EU, cover crops are traditionally part of crop rotation and diversification to manage in-field soil fertility, maintain physical soil properties (e.g., amelioration of soil compaction), and to suppress diseases, pests and weeds as part of preventive, integrated crop protection management (Shipton, 1977; Ball et al., 2005). The effects of cover crops on carbon sequestration and climate change adaptation needs are being increasingly researched together with sustainable management practices such as reduced tillage. These soil attentive approaches have been referred to as climate-smart agriculture in the EU and crop rotation of three to four crops are practiced on 80% of arable European land (EC, 2017). In Table S1, cover crops are only highlighted as part of undersowing (Table S1 line 14, 17, 22), yet their ecological value cannot be over-emphasized with respect to climate change, biodiversity and food provision resilience (Harrison & Gassner, 2020). For instance, in the US (corn belt) and Canada (Ontario) monoculture (Glossary) production has been more widely replaced by 2-year rotation of maize and soybean, with cover crop deployment as a third crop limited below 5% (Bullock,

Table 2. All potentially relevant agro-ecosystem services for the crops addressed (cereals, oilseed rape, sunflower) here and categorized according to the MA (2005); disservices added.

Supporting services:
Soil fertility related services:
Nutrient cycling
Soil texture and structure
Organic matter formation
Carbon sequestration
Soil physico-chemical composition
Soil water storage etc.

Provisioning services/goods:
Food, feed (e.g., yield, biomass)

Regulating services:
Natural pest/weeds/disease control
Pollination
Water quality (nitrate, input runoff)
Soil-water regime (retention/regulation)
Soil erosion prevention (regulation)
Carbon sequestration (climate regulation)

Cultural services:
Aesthetic values, recreation, ecotourism

Disservices: Pests, weeds, diseases

1992; Landis, 2016; Zulauf & Brown, 2019). Because of the ecological benefits of cover crops' and their potential to create additional farm revenues (through economic value capturing mechanism, e.g., carbon credits), current research increasingly investigates their deployment: New and more integrated-outcome related plant based-technologies are being developed, including perennials, new cover crops, winter annual cash crops, such as e.g., winter camelina (*Camelina sativa*), in addition to reduced tillage to regenerate soil services (recently referred to as regenerative agriculture in the US) (Berti et al., 2017; Corry, 2018; Moore et al., 2019). Thus, uncropped, vegetated land (db-habitat-1) is an alternative to cover crop use and similarly a means to enhance agro-ecosystem services delivery (Brandes et al., 2016).

Water related agro-ecosystem services

All four db-habitats have the potential to positively influence the maintenance of the soil water regime (retention, regulation) including in neighboring fields and landscapes (Brandes et al., 2016; Capmourteres et al., 2018). Depending on the location of the db-habitat in the field (topography and vicinity to water bodies) water quality is protected by reducing run-off and/or leaching of nutrients and pesticides (Finger et al., 2019). The subcategory, vegetated buffers (under db-habitat-4) have thus a long tradition as part of pesticide risk mitigation approaches under the EU Plant Protection Products Regulation and complements biodiversity protection goals (EC, 2009; MAgPIE, 2017) by providing habitat.

Pollination (crop pollination needs and pollinator conservation)

This ecosystem service is complex, and knowledge is steadily evolving. Together with natural pest control, this service received the highest attention regarding habitat creation, pollinator-centered conservation goals and pollination needs of crops (e.g., Wagner et al., 2014; Holland et al., 2017; Dainese et al., 2019; Table S1). With some exceptions, investigations into pollination effectiveness regarding crop and cultivar specific parameters such as yield, fruit set and quality are rare (e.g., Bommarco et al., 2013; Garibaldi et al., 2014; Holland et al., 2017; Cole et al., 2019; Albrecht et al., 2020). The four identified db-habitats provide different amounts of floral resources, reaching from residual flowering plants on uncropped, naturally vegetated land to seeded wildflowers, aesthetically attractive, hereafter 'artificial', flowering plants or cover crops providing bee forage, such as phacelia *(Phacelia tanacetifolia)* or clover (*Trifolium sp.*). Habitat characteristics (annual, perennial), their spatial configuration and the need for cross seasonal (especially late season) bee forage provision require thorough consideration to provide stable pollinator conservation over scale and time that achieve abundance and diversity benefits (Kleijn et al., 2015; Hofmann et al., 2019).

Pollination conservation-centered papers indicate that approx. 84% of European crops depend on animal pollinators and relate this to the importance of food security (EC, 2018). This forged a strong public perception that overall crop production pollinator-dependency is high. However, pollinator-dependent crops cover a small area of EU land and are only required for producing 15 to 30% of global human food supply (Greenleaf & Kremen, 2006; Fig. 1). In Europe mostly vegetables or permanent crops e.g., fruits and grapes are pollinator-dependent, although some e.g., apple cultivars are self-pollinated hence do not rely on pollinators for pollination provision (Ramirez & Davenport, 2013). Pollinator-dependency is thus more important for food diversity than security and the provision of flower habitats for the majority of arable field crops is mostly irrelevant. When evaluating agro-ecosystem services in the context of db-habitat creation, biotic (pollinator) or abiotic (e.g., wind) pollination needs of single crops and cultivars need to be differentiated similarly as the type of pollinator required. For instance, high value crops such as almond and hybrid canola seed production are pollinated by honeybees (*Apis mellifera*). As increase in productivity has been substantiated, honeybee hive provision is the preferred technical solution over floral habitat provision (Ghazoul, 2005; Ovinge & Hoover, 2018). The popularity of the iconic domestic animal, the honeybee, resulted in floral habitats being promoted under the CAP and today are the most widely applied habitat internationally (FAO, 2019). In the light of the heightened creation of 'artificial' flower habitats, their ecological function is increasingly questioned and an area of further research. 'Artificial' flower habitats have the potential to provide disservices for wild bees as their forage-needs differ from those of the honeybee and increased hive deployment in some areas may provide forage competition (e.g., Isaacs et al., 2009; Kleijn et al., 2015; Wojcik et al., 2018; Buch & Jägel, 2019). Thus, diverse residual flowering plants of uncropped, naturally vegetated fields (subcategory of db-habitat-1) remaining in integrated and organic crop fields are better db-habitats as they provide diverse local floral resources and correspondingly some wild bee pollinator forage. An additionally useful, wild bee conservation-centered habitat are those seeded with perennial wild flower mixes adapted to the specific region. These mixes have shown to enhance species abundance and diversity in a landscape over time and scale (Buhk et al., 2018).

Insect pollination needs of the crops addressed here, are either irrelevant (cereals are self- or wind-pollinated) or of limited value (oilseed rape is mainly self-pollinated). Many sunflower genotypes are self-pollinated, yet others show variable insect dependency. They often benefit from honeybee-pollination, hence from honeybee hive deployment, less so from habitat provision (Greenleaf & Kremen, 2006; Kleijn et al., 2015). Oilseed rape also benefits from wind-pollination and a few cultivars benefit from a variety of pollinators, including honeybees, as pollen-transporting mechanisms. This explains the inconsistent yield increase or seed set, reported in pollination assessments (Hudewenz et al., 2014; EC, 2019). It should be noted that oilseed rape needs a sufficient supply of sulfur to be identified by honeybees as a source of pollen (Schnug & Haneklaus, 2005). The EU-27 acreage of oilseed rape expanded from 1 to 6 million hectares between 1970 and 2018, thus provides forage for many insect species similar to other floral resources and habitats and can be considered a temporary habitat in its own right (FAO, 2020).

Natural pest control

Natural pest control also attracts significant attention, yet it is complex and depends on many variables (Holland et al., 2017; Albrecht et al., 2020). If natural enemies of pests (predators, parasitoids) exist and are available in a landscape matrix, the four db-habitats may potentially contribute to natural pest control as they provide space for a broad spectrum of insects. Positive impacts of habitats to support natural pest control, especially in arable field crops, have been difficult to substantiate because of the many variables involved, e.g., landscape matrix that may or may not hold the required natural enemy of pests in the sufficient quantity to be effective. (Cardinale et al., 2012; Scheper et al., 2013). A few examples of floral resources, e.g., buckwheat (*Fagopyrum esculentum*) or oilseed radish exist as attractive forage sources that support parasitoids in natural pest control. These resources are often overlooked in natural pest control, yet, could be further screened for their specific suitability as part of seeded floral db-habitats, similarly as pollinator supporting plants (Garibaldi et al., 2014; Araj et al., 2019). Natural pest control may be easier to verify in perennial crops. For instance, in fruit orchards, vegetated strips are grown between the rows of the trees for integrated pest management and erosion prevention purposes (Pfiffner et al., 2018). Here natural enemies of the crop may build up over time. However, in these crops a limited number of positive yield effects have been recorded as a result of reduced pest pressure and the presence of a specific natural enemy of the pest (Albrecht et al., 2020). Abundance and occurrence of a specific natural enemy at the right time remains an effectiveness challenge for natural pest control in dynamic arable field crop rotation systems, yet natural pest control has shown to be enhanced in complex landscapes (Bianchi et al., 2006; Tscharntke et al., 2016; Holland et al., 2017). Crops are also often threatened by different pests occurring at the same time, adding complexity for this service's effectiveness and reliable provision. While all four db-habitats potentially increase natural pest control, they may equally enhance disservices such as weed, pest, and disease pressures for some crops. For example, cereal farmers biggest constraints are weed pressures (see disservices).

Potential disservices created by all db-habitats

All four db-habitats potentially increase weed and pest pressure at different extents over time. Cover crops or mixtures thereof are an exception. They are used as a key preventive measure to manage weeds and pests as part of integrated crop protection management (Glossary). Weed pressure particularly affects cereal crops. Here, the control of monocotyledonous weeds such as couch grass (*Elymus repens*), and black grass (*Alopecurus myosuroides*) in a monocot cereal crop is particularly challenging (Critchley & Fowbert, 2000; Buhler, 2002). This grass weed disservice has been substantiated through practical experience made in integrated and organic cropping systems and remains the most difficult, expensive, and time-consuming challenge, negatively affecting yield, quality, and economic viability (farm income) (Berry, P., et al., 2005; McErlich & Boydston, 2013). Thus, integrated weed management practices using multiple control strategies need to be available to counter weed seed build-up. These integrated management approaches are very well established and include, e.g., preventive crop rotation and diversification including cover crops, mechanical weeding (harrowing), as well as the targeted use of chemical control measures (herbicides) that integrate weed biology knowledge (Buhler, 2002). Seeding flowers, which become (invasive) weeds, or seeding wildflowers that are attractive to herbivory slugs, should be avoided (Frank, 2003). Disease pressures depend on local conditions and are less important in the crops addressed here, yet various pests, such as slugs in winter wheat (Eggenschwiler et al., 2013) and soil diseases, for instance take-all (*Gaeumannomyces graminis* var. tritici), may spread and cause disservices through db-habitat creation (Dulout et al., 1997). Accordingly, it is important to adapt site-specific strategies when creating db-habitats that take account of specific disservices. Disservices are commonly omitted from ecosystem services framework evaluations as focus is given to benefits to people (MA, 2005). However, to properly address all nature contributions to people, negative and positives ones, both services (benefits) and disservices need consideration. Otherwise evaluations lack practical real-world realism and remain conceptual approaches (Shackleton et al., 2016; Schaubroeck, 2017; Kenter, 2018).

Cultural services

The importance of cultural services (Glossary) has been emphasized with respect to human wellbeing in the Millennium Ecosystem Approach, MA, 2005. However, there is still a lack of clarity on how they can be integrated into management models among the ecosystem services research community and policy makers (Jones et al., 2016; Torralba et al., 2020). Here these services are addressed in the following way: 'Artificial' flower areas are appreciated in more densely populated areas by the public at large and may provide societal acceptance or image benefits for farmers in nearby, local communities (COPA-COGECA, 2010). They have, however, less value in remote, simplified arable crop landscapes where tourism or recreation activities are limited. This cultural service does not directly translate into dual, direct ecological and economic benefits unless it is turned into new business models, e.g., sales of wildflowers (Delphia et al., 2019). Another unpaid aspect of a cultural service provided by farmers is the large-scale cropping of e.g., oilseed rape in Schleswig-Holstein, northern Germany. It attracts thousands of tourists each year to view the bloom (Haase, 2020). However, unless a farmer provides ecotourism services (accommodation, farm shop, cafés) during the flowering season the beneficiary of this service is appropriated by the community (Stallman, 2011). The consequences of higher disturbance by human activity, e.g., through presence and moving, including hiking and driving has shown to have stronger negative impact on animal movement than habitat modification, such as logging and agriculture itself (Doherty et al., 2021). Therefore, from a conservation point of view, recreation activities in cropland are questionable, especially, as an increasing number of visitors and selfie-takers cause damage to private crop land and production (Fu, 2019).

Synergies

Synergies relate to the combined benefits for biodiversity and agro-ecosystem services in this paper. Enhancing soil-related services on less productive entire fields for a longer time, benefits certain birds, e.g., skylarks, which need larger fields (Meichtry-Stier et al., 2014). Similarly, these fields also provide benefits for insects and small mammals, although many insects are better off with smaller, connected subfield areas for better orientation within the landscape (Hass et al., 2018). The benefits to these species can be additional to the soil erosion prevention benefits of all db-habitats (Briner et al., 2005; Albrecht et al., 2020). Synergies also occur when flowering cover crops such as phacelia, or clover, are grown as they provide pollinator forage in addition to their well-known benefits to crop production. For example, phacelia's deep roots are good to loosen soil compaction, thus improve soil structure, they are annual, non-winter-hardy, and non-invasive plants that will not become a weed; oilseed radish (*Raphanus sp.*), another cover crop, attracts predatory hoverflies that feed on aphids and other pests, thus providing pest control benefits as part of integrated pest management (Glossary) (Garibaldi et al., 2014). Synergies could potentially also accrue when entire fields of db-habitats and cover crops are harnessed as new value chains for biomass, feed, flower production, or carbon sequestration, which enhances ecological services such as soil and plant health.

Trade-offs

As there is a lack of quantitative data for measuring the monetary value of ago-ecosystem services per field, crop, and cultivar (with the exception of food, or feed provision as traded goods), their financial implications cannot be calculated and are not the focus of this paper. All four db-habitats can potentially maintain or enhance agro-ecosystem services, which provide a feedback loop over time in terms of soil related services (Schulte Moore et al., 2017). Potential yield losses are often seen as the major trade-off. They can be minimized when db-habitats are created in chronically unproductive fields and especially subfield areas that are e.g., nutrient-deficient, dry, wet, shaded, erosion-prone (topography: contours and slopes), compaction-prone (e.g., headlands, field margins) (Capmourteres et al., 2018). These areas can increasingly be better mapped through precision technologies and exist in all landscape types including in simplified, intensively cropped landscapes, although homogeneous soils usually dominate in productive land (Corry, 2018). Additionally, costs for db-habitat creation can be reduced in areas where access with machinery is difficult or which support "squaring up" edges. Trade-offs of habitats also include disservices (weeds, pests, diseases) as all db-habitats can add to the disservices enhanced reproduction or spread.

Effects and effectiveness of db-habitats on biodiversity at local and landscape level

Positive effects of the four db-habitat groups are expected for multiple species at field level as per the survey of the six publications undertaken. For instance, Table S1 highlights in more details the number of research studies that substantiate biodiversity benefits. For example, Dicks et al. (2014), report that the db-habitat subcategory 'provide or retain set-aside areas' demonstrated benefits in 23 out of 44 studies, and the subcategory 'take field corners out of management' showed benefits in 17 out of 21 studies. In addition, the positive effects of the db-habitats in terms of biodiversity connectivity at landscape level is expected to be greatest if their spatial configuration in priority areas and e.g., forage provision across seasons is taken into account (Hofmann et al., 2019; Früh-Müller et al., 2019). However, their overall effect, is unequivocally, dependent of the landscape matrix, environmental, climatic and geophysical conditions and indirect drivers of change, e.g., population growth and wealth (more protein-based diets) increase. Figure 3 visualizes the interlinkages between cropland and other EU land areas such as non-arable land, woodland and shrubs and others.

Concerns over habitat loss, generated many efforts across the landscape in Europe. Although this paper focuses on db-habitat creation within fields, e.g., 6% fallow land (Fig. 1), beyond-fields i.e., on farm activities are also underway, for instance via the CAP, and are referred to as Ecological Focus Areas. The target is to reach 5% on farmland. In addition, under the EU Nature Directives (Birds and Habitat Directives), Natura 2000 protected area-networks have been established. They cover 18% of EU land and comprise extensively cropped land and High Nature Value Farming (HNVF) areas that conserve traditional farming types such as semi-natural pastures, meadows, and orchards (EC, 2018). The EU Biodiversity Strategy 2030 contains various targets, including for agriculture, to adopt more sustainable practices and committed to legally protect a minimum of 30% of the EU's land by 2030 (EC, 2020b). Creating db-habitats in productive land would thus come in addition to species protection in Nature Reserves or in protected areas that are maintained through multiple projects (e.g., EU LIFE projects) (Mammola et al., 2020). The latter target the protection of specific species listed under e.g., the Nature

Directives or the European Red List of Species (EC, 2020a). These species are different compared to those thriving in agricultural landscapes, which provide characteristic habitats and typical farmland diversity (Tscharntke et al., 2005). Thus, upscaling db-habitat creation and enhancing agro-ecosystem services delivery through good agricultural practices within fields complement efforts to conserve biodiversity across the landscape and add biodiversity benefits at scale, via e.g., improved connectivity.

Identifying suitable areas for db-habitat creation through new precision technologies

To avoid yield loss, habitats have preferentially been created on less fertile subfield areas such as headlands, field margins, cropland bordering forests or tramlines, as these are often less productive as a result of limited access to water, light, nutrients, or soil compaction or lack of easy access. Extended long-term studies showed that the variability of soil parameters within a single field can easily be as high as the variability of the same parameters within the surrounding landscape. A meta-data analysis by Rogasik et al., (1999) showed that the variability of grain yield within fields may exceed the variability between years (Haneklaus & Schnug, 2006). This influences the effectiveness of fertilizer input that interferes with soil parameters in different ways and to different degrees, leading to unsatisfying side by side of nutrient deficiency and surplus. This in turn results in not achieving the potential yield, or having negative impacts on local ecosystems, and thus the sustainability of crop production. It is estimated that for instance nutrient input only matches the demand on about 70% of a field while variable rates of fertilizers promise a 100% match (Haneklaus & Schnug, 1998). Betteridge et al. (2008) pointed out that soil texture and structure are the common limitation to yield as they reflect the soil water holding capacity and aeration state. In New Zealand, unproductive areas are mostly not planted, because the cost of production in these areas can exceed the value of the crop grown. These subfield areas are ideal for db-habitats creation.

New precision agriculture technologies, such as remote sensing, and increased availability of combined geo-referenced and field-specific data, such as yield/biomass, plant health, topography, climate and soil maps, will also allow for improved spatial analysis of fields (Berry J. K., et al., 2005). Perhaps the biggest advantage of precision agriculture is that it scientifically substantiates farmers' local knowledge in delineating subfield areas that enables the verification of their crop management practices by single field yield mapping (Haneklaus & Schnug, 2006). The customized analysis of their own fields will be more convincing to farmers than scientific investigations of other fields, as parameters vary significantly between fields. These technologies will enable farmer's decision-making based on soil and plant health parameters, or profitability and more independently of incentive provision (Muth, 2014; Capmourteres et al., 2018; McConnell, 2019). They will allow a more targeted, science-based identification of the most suitable locations for the creation of db-habitats within fields. Since 2005 they have also been referred to as precision conservation by Berry, J. K., et al. (2005).

Size of db-habitats

Another key aspect regarding biodiversity conservation is the minimum size of a habitat. Aljmli (2007) studied the impact of different nitrogen and sulfur rates to oilseed rape on the inventory of pests and beneficial insects in soil and plants. As a result, plot sizes of 60 and 135 m^2 proved to be suitable to assess input related differences in the insect inventory and are used here as an indication for a meaningful plot size. This is in line with Bianchi et al. (2006) and Albrecht et al., (2020) findings that a dense spatial network of relatively small habitats across the landscape is more effective for natural pest control, i.e., beneficial insects build up. Briner et al. (2005) made a similar observation for the movement pattern of voles, which stayed in a confined area of 125 m^2. Some birds e.g., skylarks (*Alauda arvensis*), corn bunting, lapwing (*Vanellus vanellus*), linnet (*Carduelis cannabina*) and partridges (*Perdix perdix*) require larger open cropland, as part of their wider use of different habitat types to thrive. Other birds and bees benefit from smaller connected patches (Fuller et al., 2004; EC, 2017; Meichtry-Stier et al., 2014, Hass et al., 2018). Therefore, it seems appropriate to combine several smaller subfield areas with larger open areas.

An aspect often debated is the necessary quantitative proportion of native habitats in different landscapes (e.g., Garibaldi et al., 2020). It is in so far addressed here as it depends on the landscape matrix (Fig. 3) and needs differentiation. What constitutes a native habitat in South America (e.g., rainforest) or North America (e.g., prairies) varies significantly and what Europe would consider to be native is unclear, e.g., historical agricultural landscapes or remnant beech/oak forests, in predominantly man-made landscapes where almost no native land remains (Glossary: semi-natural habitat, EU definition) (Shrubb, 2003; Schulte Moore et al., 2017; Helm et al., 2018). Thus, translation of a recommendation from one part of the world to another is not possible and area alone is an ineffective metric for ensuring biodiversity outcomes (Strassburg et al., 2020).

Overview of the four db-habitats' effects on biodiversity, agro-ecosystem services and disservices, synergies and trade-offs

The qualitative evaluation of the db-habitats identified priority services for the addressed crops: All crops rely on soil health related services and all db-habitats provide at least erosion prevention benefits and differing extents of benefits to soil health. Grass weed control is a priority disservice in monocot cereal production. This disservice is difficult to manage through natural weed control and can be enhanced through some db-habitats. Hence it

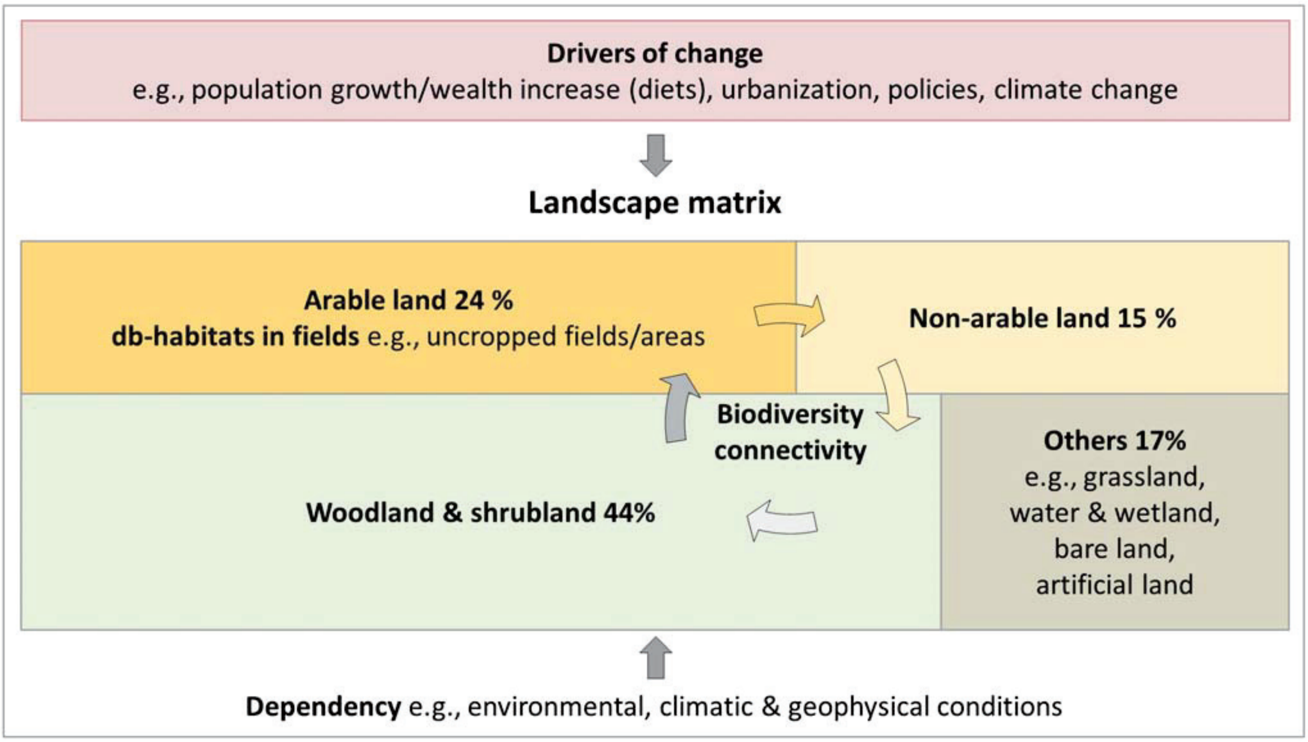


Fig. 3. db-habitats as part of the broader landscape matrix, dependencies and drivers of change.

requires special attention as to the choice of the db-habitat. Here, cover crop inclusion in crop rotation are indispensable preventive tools to manage weed and other plant health needs. Wild pollinator dependency, with the exception of some oilseed rape cultivars, is not a priority agro-ecosystem service in the arable crops addressed, yet sunflowers benefit from honeybee pollination for which they serve as forage. Likewise, cultural services are not considered a priority service in the addressed crops. Creation of db-habitats at local level translates to improved biodiversity connectivity gains at landscape level, if their spatial configuration would be improved in priority areas (e.g., simplified landscapes) and their creation upscaled, while fitting the surrounding landscape matrix needs.

Table 3 presents a summary of the analysis of the four db-habitat groups' effect on agro-ecosystem services and disservices, synergies, and trade-offs for the addressed crops. All four db-habitat groups can locally be dually-beneficial and can potentially provide disservices, while their agro-ecosystem services delivery occurs to a differing extent and requires differentiation by crop and cultivar, local environmental conditions (e.g., topography, landscape matrix) and implementation option (duration, spatial location and size of the db-habitat).

Discussion

The four identified db-habitat groups can provide services/benefits and disservices/disadvantages simultaneously, although their benefits for conservation or production purposes vary. db-habitat-1, subcategory 'entire uncropped, naturally vegetated fields' (fallow land) is the easiest to integrate as part of common crop management and has been deployed on 6% of EU arable land (Fig. 1). These 'ecological production' areas are entitled to incentives under the CAP, however, their ecological value depends much on their longer term deployment (EC, 2013). Fallow land has a well-established track record as being more beneficial to various bird species than integrated and organic farming and it also supports pollinator conservation (Berg & Pärt, 1994; Poschold, 2015). In Europe, fallow land (formerly called set-aside) was introduced in the 1980s to reduce overproduction. Some of that land later lost its status as cropland in some countries (EC, 1988; COPA-COGECA, 2010). This negative experience still resonates with farmers and requires clear policy and legal framework responses to reassure farmers. Cover crops as part of good agricultural practices are traditionally well-established in the EU. They provide indispensable soil and plant health services and reduce the use of crop production products and fertilizers. While some pollination conservation-centered research criticizes the CAP incentivized uptake of some specific cover crops as biased towards agriculture, these crops' integrated, multiple ecosystem services delivery benefits are being increasingly researched (Berti et al., 2017; Cole et al., 2019). This research combines ecological, biological, pollination, soil sciences, crop health and crop production knowledge. It attempts to link biodiversity, climate change and food production needs and points to ever more system-based solutions thinking. The creation of

Table 3. Summary of the effects of the four db-habitat groups on biodiversity, agro-ecosystem services and disservices (weeds, pests, or diseases), synergies, and trade-offs relating to the addressed crops.*

db-habitat	Effects on biodiversity	Agro-ecosystem services & disservices provision		Synergies	Trade-offs	
1 **Uncropped fields/ subfield areas**	Larger areas better for some birds; small mammals & insects, pollinators require smaller areas; increased plant biodiversity	Soil fertility	+(+)	Increase of soil fertility on entire field & higher biodiversity gains over time; potential profitability benefits	Loss of yield & production area	+
		Erosion prevention	+(+)			
		Soil water regime	++(+)			
		Pollination: crop need/conservation	N/A /++		Profitability	+/-
		Natural pest control	+(+)			
		Disservices	+++		Costs to control weeds, pest, diseases	+
		Cultural services	N/A			
2 **Managed fields/subfield areas**	Larger areas are better for some birds; small mammals & insects require smaller areas; increased crop & plant diversity	Soil fertility	+(++)	Soil fertility increase on entire field over time; landscape pollination & biodiversity benefits; potential profitability benefits	Loss of yield & production area	+
		Erosion prevention	+(+)			
		Soil water regime	++			
		Pollination: crop need/conservation	N/A /++		Profitability	+/-
		Natural pest control	+(+)			
		Disservices	- (+)		Costs to control weeds, pest, diseases	+
		Cultural services	N/A			
3 **Managed flower areas**	Attractive to insects & pollinators; habitat for birds, & small mammals	Soil fertility	+	Conservation pollination benefits; yield, seed set & quality increase limited to some oilseed rape cultivars	Profitability	-
		Erosion prevention	++(+)		Higher costs for seed and management	++
		Soil water regime	++			
		Pollination: crop need/conservation	N/A /+++		Loss of yield & production area	+
		Natural pest control	+(+)			
		Disservices	+ + +		Costs to control weeds, pest, diseases	+
		Cultural services	N/A			
4 **Managed margins**	Transition habitats for various wildlife: birds, small mammals, insects, pollinators	Soil fertility	+	Easily applicable, facilitating work; conservation of biodiversity sensitive areas; potential profitability increase; risk mitigation from input runoff	Loss of yield & production area	+
		Erosion prevention	++(+)			
		Soil water regime & water quality	++		Profitability	+/-
		Pollination: crop need/conservation	N/A /++			
		Natural pest control	+			
		Disservices	+ + +		Costs to control weeds, pest, diseases	+
		Cultural services	N/A			

* +/- signs indicate the extent of the qualitative effect on agro-ecosystem services and disservices and trade-offs; brackets indicate the effects' variability, whereby habitat duration/quality is not reflected. N/A: not applicable. Under Pollination we differentiate between crop pollinator-dependency/and pollinator conservation. N/A means irrelevant or of limited benefit for the addressed crops/pollinator conservation relates to common wild bee benefits. Profitability: includes qualitative cost evaluation for the creation and management/time of db-habitats.

db-habitats on margins has the benefit that they occupy unproductive, compacted soils on the one hand and protect adjacent biodiversity-sensitive habitats on the other hand. With regard to pollination conservation through seeded flower areas a balance must to be struck between pollinator conservation and crop pollinator dependency.

Seeded flower areas bear a higher risk of sheltering potential pest and invasive weed species. They incur higher costs for seeds and management (seeding, mowing, workhours in busy times). These habitats are not expected to become farmers' preferred options with most arable crops and are only marginally relevant for the addressed crops in terms of pollination, although they may prevent soil erosion like all other db-habitats (Briner et al., 2005). It is noteworthy that in cases where additional pollination is needed and has shown to significantly increase productivity of crop production, the provision of bee hives is already part of the technological tool box farmers draw upon. Examples include the high-value crops and cultivars, almond, and canola and sunflower for hybrid seed production (Ghazoul, 2005; Greenleaf & Kremen, 2006; Ovinge & Hoover, 2018). This is a good example that plausible rationales resonate with farmers. The subcategory "leaving stubble fields over winter" (under uncropped fields/areas) relates to the full replacement of spring cereals (e.g., wheat, barley) by more productive (longer vegetation period), winter-hard cultivars in the 1960s (Chamberlain et al., 2000; Statistisches Bundesamt, 1955-2014). This change is considered a key reason for the decline in the numbers of some farmland birds, as it led to a decrease of larger habitats and food sources for birds (EC, 2017). However, according to the German fertilizer ordinance it is not permitted to leave fields unvegetated over winter to avoid nitrate leaching thus this subcategory's dual suitability is not supported (BMJV, 2017). Partly re-introducing spring cereals, e.g., on non-erosion prone land, could benefit some species, despite productivity reduction that some farmers may want to accept (Dicks et al., 2014).

The conflicting situations described above indicate the narrow balance between trade-offs and synergies and exemplify the many influencing variables that challenge the establishment of coherent and conducive policies, regulations and incentives that presently do not always embrace the flexibility needed to address interdisciplinary sciences' considerations. In the future, precision agriculture, coupled with precision conservation technologies, will provide increasingly higher quality of geo-spatial data and field-specific, customized data. This will increase farmers' confidence to identifying the most suitable habitat locations within fields from a profitability perspective, and equally assist science-based decision-making for conservation purposes. While customized data address farmers' interests and needs, which in turn drive voluntary creation of db-habitats, they may be less inclined to take action as long as they have access to unconditional area payments. Therefore, to support twin goals more adapted and flexible incentive models, such as agglomeration payments, or biodiversity discretionary fiscal incentives could be more conducive and cost-effective while also being more socially efficient (Pascual & Perrings, 2007; Drechsler et al., 2010). These models' benefits can be their collective management at landscape level and better configuration and spatial targeting in priority areas, such as simplified landscapes. Given current private property rights arrangements, new cooperation platforms need to be forged between state and non-state cross-sectoral actors such as farmers, ecologists, and local landscape planning authorities. They are as crucial as the availability of practical biodiversity mainstreaming tools, such as the db-habitats, to accelerate their upscaling into crop production at landscape level and thus lever transformative change.

Conclusions

The analysis of the db-habitats' effects on agro-ecosystem services and disservices generated a wealth of interconnected knowledge. It showed that there is not only a need for improved interdisciplinary and complementary knowledge integration: A systems approach that considers disservices, trade-offs and synergies, and addresses multiple services, are equally important to meet the twin goals of conservation and production. Dynamic, annually changing crop production and biodiversity patterns that are constantly occuring, will be amplified as a result of climate change and thus remain a complex challenge. Here, precision technologies will enable more effective and targeted decision-making for db-habitat location at field and landscape level and enhance the confidence of both conservationists and farmers to inform decisions irrespective of the cropping systems applied. From a crop production perspective, the greatest benefits of precision technologies would be the gain in scientific data that indicate plausible rationales in terms of the delivery of priority agro-ecosystem services per crop while minimizing disservices, and related customized profitability evaluation in terms of cost efficient db-habitat creation. These gains usually convince and motivate farmers to integrate db-habitats in their fields irrespective of financial incentives as the example of cover crops for the provision of soil and plant health services demonstrate. Targeting the creation of varying db-habitats in priority cropland areas through these technologies as part of broader landscape management efforts also assist in building multifunctional landscapes that are more environmentally and economically sustainable and which benefit biodiversity connectivity. The habitats' effectiveness, however, also crucially relies on coherent policies, regulations and conducive incentives, as well as on novel partnerships and cooperative approaches consisting of state and non-state actors. Together with these, db-habitats have a great potential to become a concrete, practical biodiversity mainstreaming tool for crop production. They can be deployed across groups of multiple local farms for better biodiversity outcomes through connectivity at scale, thus advance transformative change in arable crop production.

The quote of U.S. President Dwight D. Eisenhower "Farming looks mighty easy when your plow is a pencil, and you're a thousand miles from the corn field" may best summarize the complexity and demands towards agriculture and is a humble recognition to their vital work (Eisenhower, 1956).

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Conflicts of interest Statement

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Supplement

Table S1. List of 42 db-habitat aggregated by groups for application within arable field crops

	db-habitat group	db-habitat description (partly translated into English), subcategory	Authors (Dicks et al., 2014, includes total No of studies reviewed/No with positive result +)
	db-habitat-1	**Uncropped fields/subfield areas (naturally vegetated)**	
1		Provide or retain set-aside areas	Dicks et al., 2014 44/23 +
2		Take field corners out of management	Dicks et al., 2014 21/17 +
3		Leave cultivated, uncropped margins or plots	Dicks et al., 2014 1/1 +
4		Fallow land/set-aside for one year	Jahn et al., 2014
5		Fallow land/set-aside for a couple of years	Jahn et al., 2014
6		Leave parts of arable land fallow for birds breeding within fields, and for residual weeds	Thomas et al., 2009
7		Annual fallow land	ILöK, 2012
8		Permanent fallow land	ILöK, 2012
9		Rotational fallow land	ILöK, 2012
10		Leave stubble fields over winter	Dicks et al., 2014 16/16+
11		Keep stubble fields until following spring seeding	Jahn et al., 2014
12		Overwintering stubbles	Thomas et al., 2009
13		Keep stubble fields until late autumn/spring	ILöK, 2012
	db-habitat-2	**Managed fields/subfield areas (including extensively cropped areas, cover crops)**	
14		Undersowing spring cereals, e.g., with clover	Dicks et al., 2014 16/11 +
15		Leave unharvested cereal headlands in fields	Dicks et al., 2014
16		Plant cereals in wide-spaced rows	Dicks et al., 2014 2/0 +
17		Clover-grass-undersowing in cereal fields	Jenny et al., 2011
18		Create sparsely sown field crop areas or strips with reduced fertilization (in wide rows)	Jahn et al., 2014
19		Wide-spaced rows in cereals	Jenny et al., 2011
20		Double-spaced rows in cereals	ILöK, 2012
21		Light stand arable crop strips or fields (a different name for sparsely sown fields)	ILöK, 2012
22		Undersowing cover crops to suppress weeds	ILöK, 2012
	db-habitat-3	**Managed flower areas**	
23		Plant wild bird seed or flowering cover crop mixture	Dicks et al., 2014 50/35 +
24		Plant nectar flower mixture/wildflower strips	Dicks et al., 2014 97/68 +
25		Create flowering areas or strips	Jahn et al., 2014
26		Create flowering strips	Thomas et al., 2009
27		Wildflower strip management	Jenny et al., 2011
28		Flower strips	ILöK, 2012

Table S1.Continued

	db-habitat group	db-habitat description (partly translated into English), subcategory	Authors (Dicks et al., 2014, includes total No of studies reviewed/No with positive result +)
	db-habitat-4	**Managed margins**	
29		Conservation headlands (unsprayed)	Dicks et al., 2014 80/49 +
30		Plant grass buffer strips/margins around arable fields	Dicks et al., 2014 47/41+
31		Create uncultivated margins around arable fields	Dicks et al., 2014 45/24 +
32		Provide buffer strips alongside water bodies (e.g., rivers, streams)	Dicks et al., 2014 5/3 +
33		Buffer in-field ponds	Dicks et al., 2014
34		Fallow strips on crop edges (could also fall under habitat-1) for residual flowering weeds	Jahn et al., 2014
35		Spatially restricted, unsprayed field edges and headlands	Jahn et al., 2014
36		Leave uncropped field margins	Jenny et al., 2011
37		Margin strips	ILöK, 2012
38		Leave arable field margins	ILöK, 2012
39		Create riparian buffer strips	ILöK, 2012
40		Implement field margins and buffer strips with diversity of plant species	INSPIA, 2015
41		Build retention structures across slopes to reduce plot length	INSPIA, 2015
42		Establish and maintain riparian buffers	INSPIA, 2015