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TOPICAL REVIEW

Ecosystem services of tree windbreaks in rural landscapes—a systematic review

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Supplementary material for this article is available online

Abstract

Windbreaks are key structural elements in the rural environment and affect the functionality of landscapes in multiple ways. A broad interdisciplinary view on these functions lacks in scientific literature and common knowledge. This led to under informed management decisions, a decrease in the number of windbreaks in wide areas, and a subsequent loss of landscape functionality. Therefore, the knowledge on windbreaks and associated ecosystem services (ES) was systematically reviewed to guide the way for a holistic comprehension of such structural landscape elements. We defined eight bundles of ES on the basis of the Common International Classification of ES scheme. Search terms that allowed to include only vegetative windbreaks consisting of at least one tree row were combined with appropriate search terms for the eight ES bundles in individual searches resulting in a total of 6094 hits. We considered only publications that provided quantitative data and allowed to derive a clear effect of windbreaks on ES so that 222 publications from all over the world were quantitatively and qualitatively analyzed. The outcomes provide information about the dimension of effort, scientific consensus or dissensus, and knowledge gaps in the different research disciplines involved. It was shown that windbreaks bring predominantly positive effects to landscapes in the course of all investigated ES bundles. Apparent positive effects were found for soil protection, biodiversity and pest control, whereas for biomass production, nutrient and water balance, also adverse or indifferent effects were reported. The present review reveals an intense need for further interdisciplinary research using indicators, ES approaches or similar instruments that enable quantitative and comparable statements about the functionality of windbreaks in rural landscapes.

1. Background

Agricultural intensification throughout the last century led to uniform landscapes, meaning larger field sizes and elimination of structural elements, and a corresponding loss of functionality (Emmerson *et al* 2016). While the growing need for food drives this development, it causes severe disservices for human society like erosion of fertile soil, loss of biodiversity, and greenhouse gas emissions (Stoate *et al* 2001, van Zanten *et al* 2014, Zambon *et al* 2017, Devaty *et al* 2019). Windbreaks, wind shelter belts or hedgerows are commonly considered to reduce such disservices and fulfill multiple crucial roles in rural landscapes (Baudry *et al* 2000). However, their presence is steadily decreasing to facilitate agricultural operations with large machinery and optimize large-scale production (McCann *et al* 2017). Such economic considerations still yield the most striking arguments for land managers, mainly farmers, which shape the landscape by their management decisions. An economically based decision, nevertheless, ignores a great part of the potential multi-functionality of the agricultural ecosystem (Cord *et al* 2017). Incentives to promote a change towards systems like climate-smart agriculture, ecological or sustainable intensification are increasingly launched all over the planet (Garnett *et al* 2013, Carter *et al* 2018). They often include windbreaks or similar elements, often called semi-natural habitats or nature-based solutions (Martin *et al* 2019).

The concept of ecosystem services (ES) has been developed to link the functioning of ecosystems to human welfare (Costanza *et al* 1997, MEA 2005). This concept is also considered an appropriate instrument for supporting landscape forming decisions (O'Farrell and Anderson 2010). For the consideration of ES, the value of a particular service is systematically quantified in different steps, potentially ending in a numeric or monetary value. To formulate the different ES, standardized procedures exist and their use ensures comparability and appreciation of applied studies (Finisdore *et al* 2020). Multiple applications of ES based on such standardized procedures have been carried out for different types of agricultural landscapes, for instance for vineyards (Winkler *et al* 2017), orchards (Demestihas *et al* 2017), or reed wetlands (Karstens *et al* 2019). A framework to valuate external economic values of tree-based intercropping systems classified by ES was presented by Alam *et al* (2014). They proposed an annual monetary value of CAD 2645 per hectare and year (average of 40 years) for the conditions of southern Québec, Canada.

Several reviews and syntheses have been carried out to summarize available knowledge about ES of vegetative windbreaks in different ways. Haddaway *et al* (2018) performed an extensive systematic review and quantified the available literature dealing with the multifunctional roles of vegetated strips in agricultural areas. A step further into the quantification of effects of hedgerows and grass strips was presented by Van Vooren *et al* (2017). They calculated mixed models using multiple study results and obtained a numerical value for the effect of hedgerows on several ES. The included characteristics focused on soil properties, crop yield and pest control. Similarly, other related reviews concentrated on a narrow selection of ES, for instance on soil functioning (Holden *et al* 2019), or set the focus on a slightly wider or narrower selection of landscape elements (Ferrarini *et al* 2017, Holland *et al* 2017, Bentrup *et al* 2019).

Consequently, a complete comprehension of the role of vegetative windbreaks for the functionality of rural landscapes is currently lacking. Such information, however, is relevant for decisions in farming practice, science communication, policy and land administration, as well as for the advance of research instruments like scenario modeling of landscape functionality and related trade-offs (Rallings *et al* 2019). The present work aims to review the knowledge on windbreaks and associated ES to (a) draw a holistic picture of the role of vegetative windbreaks for the functionality of rural landscapes, (b) find topics with scientific consensus or dissensus, and (c) identify existing knowledge gaps. For this, we conducted a systematic literature review followed by qualitative and quantitative analyses of all usable sources found.

2. Design and methods

2.1. Delineation of study subject

A precise differentiation is necessary regarding the character of the described landscape structures. There is a wide range of such elements which have been installed or maintained for different reasons. Examples are windbreaks, terrace ridges, agroforestry systems, and grass or flower strips for erosion control or pollinator support. Herein, we concentrate on vegetative windbreaks in rural landscapes consisting of at least one row of trees. Such elements are commonly present in many regions of the world, and their major function is the reduction of harmful wind effects (Baer 1989, Chendev *et al* 2015). Hence, the term windbreaks was used throughout the rest of the manuscript as a surrogate for all different expressions except for formulations where a repetition of the cited author's terminology was necessary (see search terms in supplementary S1 (available online at stacks.iop.org/ERL/16/103002/mmedia) for a full list of synonyms). The decision if a study fits the scope of this review had to be done individually based on information about the spatial arrangement of the trees. Land management systems where the areal effect of trees outreached the linear characteristic of elements, like alley cropping or Dehesa types, were neglected.

2.2. Classification of ES

The Common International Classification of ES-scheme (CICES) by the European Environment Agency (Haines-Young and Potschin 2018) provides a sophisticated and detailed reference classification instrument that is supposed to include a complete collection of ES. The classification is structured in five hierarchic levels with increasingly detailed descriptions of the ES being considered (figure 1). A coding system is used from section to class level consisting of a sequence of numbers (table 1). A detailed tabulation including all levels according to the current version CICES v5.1 is available at https://cices.eu (last access 30 January 2021). For this work, we performed a group-level classification, including all relevant ES of windbreaks. This resulted in 28 individual items which were bundled into eight functional ES units (table 1) following Raudsepp-Haerne *et al* (2010).

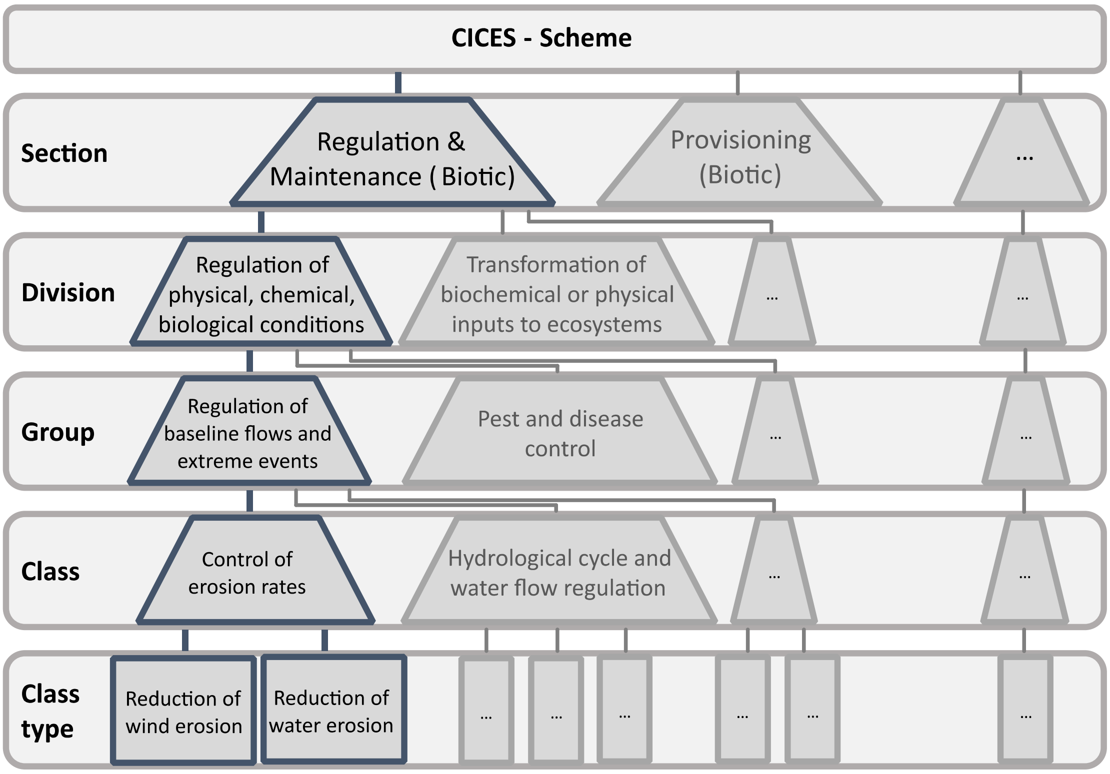

Figure 1. Hierarchy of the CICES-scheme with exemplary delineation of the class types wind and water erosion. Adapted with permission from Haines-Young and Potschin (2018).

Table 1. Classification system and bundling as used in this study. The character x in the CICES codes serves as wildcard for multiple optional numbers according to the CICES-scheme.

Ecosystem Service Bundle	Description	Codes of CICES groups and classes included in the bundle[a]
Biomass production	Wild or cultivated edible plants and animals, fibers, biomass for material or energy use; medicinal plants; effects on yield on adjacent fields	1.1.1.x, 1.1.5.x, 1.1.6.1
Biodiversity and genetic resources	Biodiversity; reservoir of seeds, spores, gametes; individual genes for bioeconomic or conservation use	1.2.1.1, 1.2.1.2., 1.2.1.3, 1.2.2.3, 2.2.2.2, 2.2.2.3,
Pollination, pest and disease control	Enhanced pollination, pest and disease control in adjacent fields and landscapes	2.2.2.1, 2.2.3.1, 2.2.3.2
Balance of nutrients and harmful substances	Regulating effects on nutrients, pesticides, contaminants, mainly in soil	2.1.1.1, 2.1.1.2, 5.1.1.3
Atmospheric conditions	Sink or source of air contaminants; greenhouse gas balance; regulation of noise, smell, visual screening	2.1.2.x, 2.2.6.1, 5.1.1.2, 5.1.2.1
Soil protection	Erosion control; physical soil degradation aspects	2.2.1.1, 2.2.1.2, 2.2.1.4, 2.2.4.x
Water balance	Regulation of water balance in amount and quality	2.2.1.3, 2.2.5.1, 2.2.6.2, 4.2.x.x.
Cultural ecosystem services	Effects for human wellbeing and culture; recreation, aesthetic aspect, space for research and teaching, cultural heritage, spiritual places, …	3.x.x.x.

[a] According to the official scheme of CICES V5.1 (Haines-Young and Potschin 2018).

2.3. Systematic review according to the PRISMA-protocol

To ensure high reproducibility in the reviewing process, the methodology for this work was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses-protocol (PRISMA), which suggests the sequential workflow for conducting and documenting systematic literature reviews (Page *et al* 2021). The literature database Scopus (www.scopus.com) was used; the queries were conducted from Austria, Germany, and Slovak Republic; and the reference date was 1 March 2021. Individual search runs were performed for each ES bundle with different search terms, as listed in supplementary S1, and the publication type was restricted to original research articles.

As a first step, titles and abstracts of detected publications were screened for relevance, in a second step the full texts of the chosen records were included. The criteria for choosing articles as relevant were: (a) treating vegetative windbreaks as an explicit research subject, (b) comparative studies with control treatments, i.e. sampling took also place at locations without windbreaks or considerably lower windbreak density, (c) quantitative outcomes available according to minimum scientific standards (replication, descriptive statistics given). These sources are denoted as strong evidence (Mupepele *et al* 2016). All publications that met the criteria were included in the analyses, and references are given in supplementary S2.

The results are presented and discussed in two ways. Systematic quantitative analyses of search outcomes build the first part. They inform about the extent of available knowledge, specific characteristics of the research fields and the relations between the different ES bundles. In the second part, selected studies for each ES bundle are presented and discussed to give a qualitative impression of the most relevant topics and the dimension of scientific con- or dissensus. Even though systematic reviews provide the strongest level of evidence (Mupepele *et al* 2016), they were only included in the discussion but not in the quantitative analyses to avoid redundancy and misinterpretations due to different selection criteria.

3. Global results of the systematic review

An introductive literature analysis showed that the research field dealing with windbreaks and its synonyms grew more than twice as fast as the number of overall scientific publications listed in the database Scopus since the 1990s (figure 2). The oldest publication using the term 'ecosystem services' was from 1984 (Pearsall 1984) and initiated an exponential growth at a speed more than six times as fast as for global publications. The most abundant synonym in the entity of publications was 'hedgerow' with 8922 hits (revealed by a query of the respective term together with the restrictive term [arable OR agricult*]) followed by 'windbreak' with 4033, 'shelterbelt' with 3640, and 'tree row' with 1236 hits. Other synonyms yielded numbers below 300. This variability approved the necessity to formulate a combination of appropriate search terms to cover the whole desired research field (cf 2.1).

All finally relevant abstracts from the systematic review as described in section 2 were compiled to a word cloud which repeatedly illustrates the dominance of the terms hedgerow and windbreak (figure 3). Soil was a central element as it links four of the eight ES bundles. The word cloud gives an impression of the diversity of approaches in the covered fields of research as ecological, landscape-related, economical, and agricultural items are comparably present. Widely lacking are nevertheless terms which would have indicated links to society or culture.

All search campaigns in Scopus detected a total of 6193 publications and 224 (3.6%) were considered as relevant after the screening and content analyses (figure 4). The percentage of finally selected relevant papers from all search hits varied between 12.3% (biodiversity) and 1.4% (water balance; figure 4). Nine publications yielded information about more than one ES bundle and were included as duplicates as the queries were performed separately for each ES bundle. These nine publications represent only four percent of all finally relevant articles ($n = 224$) what emphasizes the need for more interdisciplinary research.

Patterns in the global distribution of finally relevant studies vary widely (figure 5). Generally, Europe, the USA, China, and Canada produce by far the most publications, and Africa is highly underrepresented. Whereas in Asia soil protection studies dominate, in Europe and North America biodiversity has highest relevance, in Australia and New Zealand biomass production. In the southern hemisphere, the role of water resources is dominant which is rarely investigated in Europe. Cultural ES are topics of one-third of the studies in Japan and also remarkably relevant in Central and Northern Europe and in the USA.

The capacity of windbreaks for providing ES is based on specific effects, which were repeatedly described in the analyzed studies (table 2), for example, effects on pollination, nutrient losses or greenhouse gases (GHG). These effects were mainly linked to the respective research hypotheses and subsequently the base for the quantitative study design. This allows a systematic analysis of the ES or disservices of windbreaks as a result of positive or negative effects. An overall view shows a strong dominance of positive effects, especially for the ES bundles biodiversity and genetic resources; pollination, pest and disease control; atmospheric conditions; soil protection; and cultural ES (table 2). No apparent

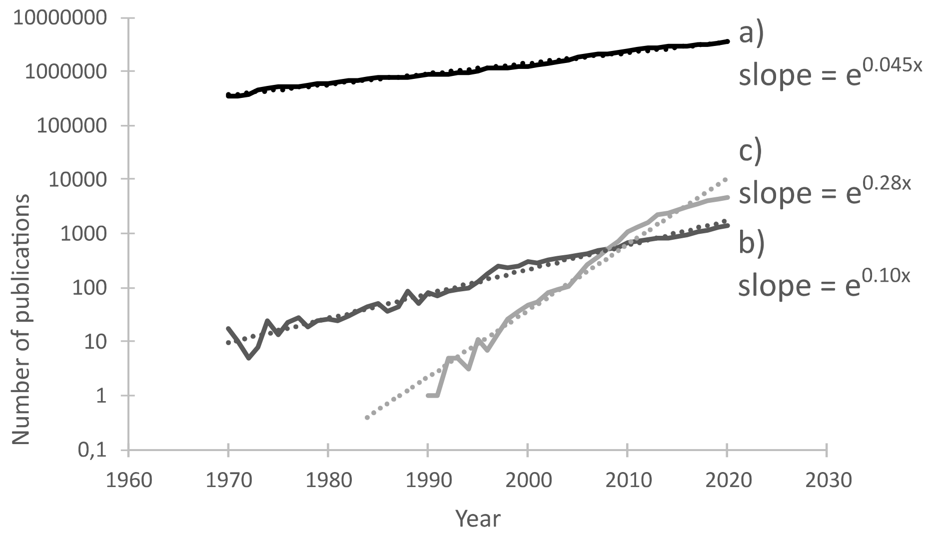

Figure 2. Temporal evolution of (a) the number of all publications in the database www.scopus.com (black; detected by search terms which were selected to be as inclusive as: [for OR 'and' OR in OR a]), (b) related to windbreaks and its synonyms in agricultural context (dark grey; search terms: [hedgerow OR 'hedge row' OR windbreak OR 'wind shelter' OR 'wood* strip' OR shelterbelt OR 'wood* margin' OR 'wood* field margin' OR 'wood* border' OR 'tree belt' OR 'wood* field edge' OR 'wood* edge' OR 'tree row'] AND [arable OR agricult* OR pasture]), and (c) dealing with ecosystem services (light grey; search term: ['ecosystem service']).

Figure 3. Most common phrases within the abstracts of all research papers meeting the inclusion criteria. Font size relates to relevance. Common words and numbers are removed. Reproduced with permission from wordart.com.

effects were found for biomass production, balance of nutrients and harmful substances, and water balance. Even though this might be biased by the formulation of the research hypotheses, which are usually formulated positively, the outbalance is clear. Characteristic outcomes for the single ES bundles are presented in detail in section 4 and discussed in section 5.

4. Effects of windbreaks on the individual ES bundles

4.1. Biomass production

4.1.1. Windbreak effects on adjacent crop yield and livestock

Research on the effects of wind speed reduction on crop growth is highly concentrated on grass, oilseed,

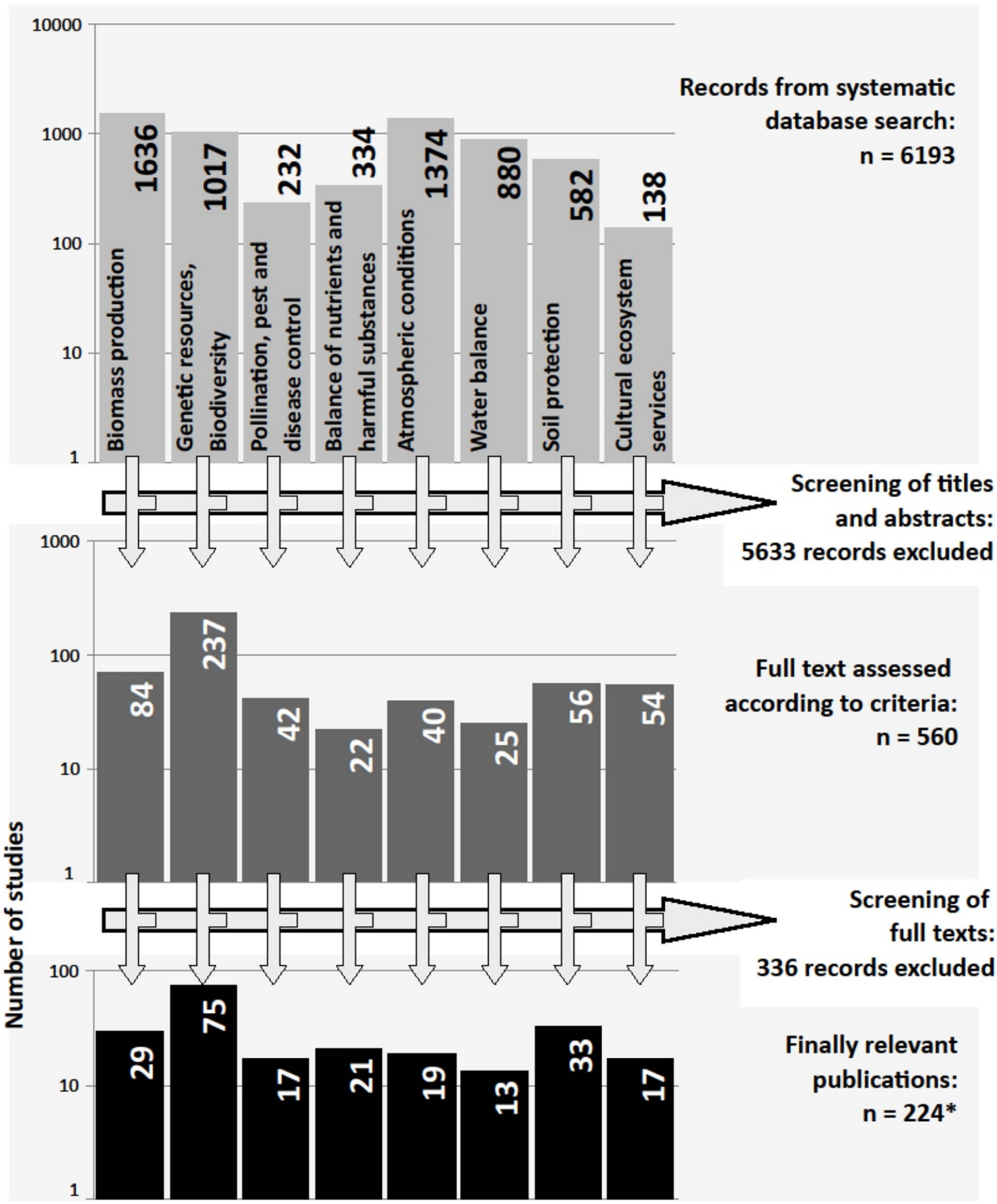

Figure 4. Flow chart of the literature review process according to PRISMA (Page *et al* 2021), including overall numbers on the right side and numbers for all ES bundles in the barplots. *: the search was conducted for each ES bundle separately, in the number of finally relevant publications, nine records are included which deal with multiple ES bundles. Adapted from Page *et al* (2021). CC BY 4.0.

pulse, and nightshade family crops even though wind shelters are an obligate prerequisite for many types of high-value vegetables which are more vulnerable to damages from wind and abrasion (Hodges and Brandle 1996). The results of most reviewed studies indicated that a yield reduction up to a distance of one to two windbreak heights occurred, which was followed by a yield increase up to a distance of around 8–12 heights and subsequent free field conditions. Faster development of muskmelons (Zhang *et al* 1999, Hodges *et al* 2006) and snap beans (Hodges *et al* 2004) was found in the sheltered areas, which implied economic benefits, especially on high-value marketable crops earning higher prices due to earlier selling possibilities. Fruit crops as kiwi fruits lose quality to damages by wind up to 44% (McAneney *et al* 1984). For potatoes in an Andean region, Visscher *et al* (2020) found a decline of yield in the near surroundings of windbreaks. Sutter *et al* (2018) hypothesized that the increased abundance of pollinators in windbreaks influence adjacent oilseed rape but did not find a significant influence of pollination on yield. In contrast, allelopathic effects of eucalyptus hedgerows were found to delay plant development of

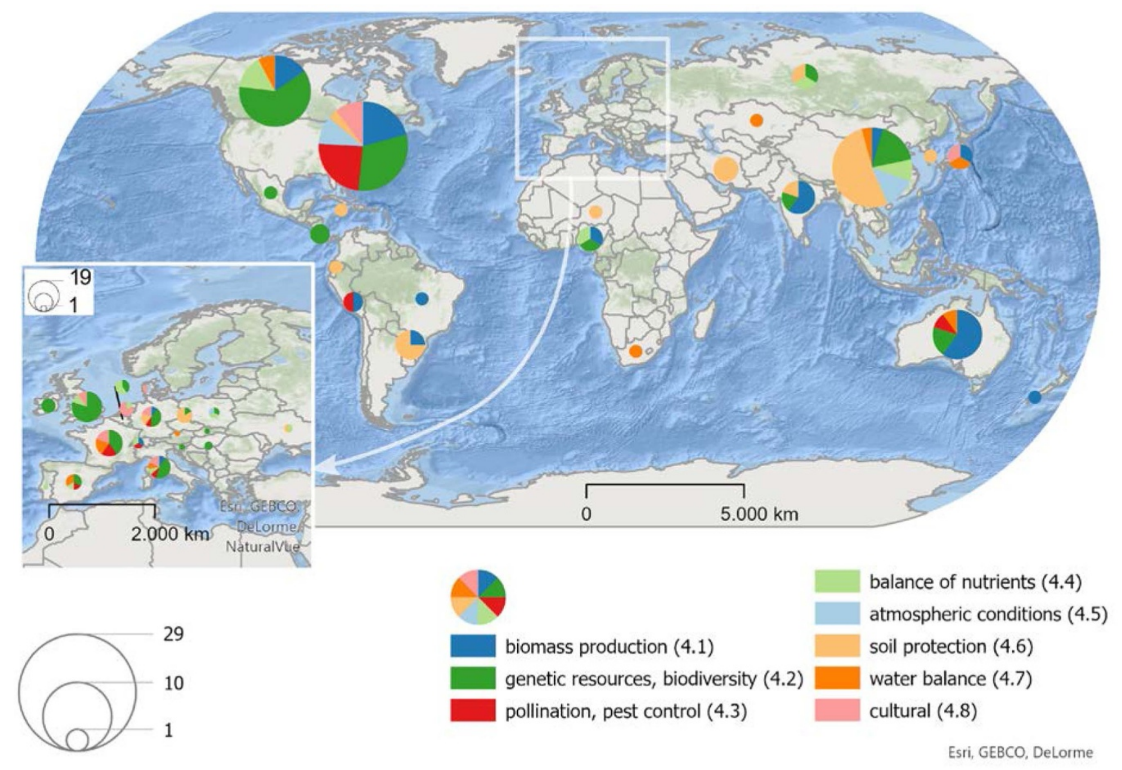

Figure 5. Geographical distribution of relevant publications with fractions of ecosystem service bundles. Legend labels simplify the names for the investigated ecosystem bundles; numbers in brackets refer to the corresponding sub-sections. Studies which included data from multiple countries were counted in each country treated. Basemap reproduced from Esri (2014). Sources: Esri, GEBCO, NOAA, Garmin, HERE, and other contributors. Country borders reproduced from Esri (2019).

winter wheat in India up to a distance of 9 m (Patil *et al* 2002).

Quantitative effects of livestock protection are rarely investigated in comparative studies. The living conditions for livestock in the area protected by windbreaks were modeled by He *et al* (2017). The authors found a maximum productivity gain of 27% at an optimal porosity of 0.5, mainly due to effects of temperature regulation.

4.1.2. Areal and regional analyses

On a regional scale, yield responses to windbreak abundance are analyzed less frequently. Li *et al* (2020) linked growth-related satellite sensing data with landscape indices to determine an optimal windbreak area ratio. For a region in Northwest-China, they reported that a fraction of 3.5% of the area covered by windbreaks would optimize cotton yield. A similar approach even though at field scale was done by Iwasaki *et al* (2019) in Japan who monitored the normalized difference vegetation index using an unmanned aerial vehicle and found the highest growth rates of maize at a distance of three to five windbreak heights.

Only a few studies included the loss of productive area by windbreaks, as was done by Osorio *et al* (2019). They analyzed yield data of no-till farms with different windbreak abundance in the US Great Plains and stated that 71% of windbreaks compensated yield losses due to their areal demand positively if located perpendicular to the prevailing wind direction.

4.2. Biodiversity and genetic resources

4.2.1. Diversity of species and abundance

In comparison of habitat types, double numbers of mean flower-visiting insects within field margins and hedgerows compared to pastures (Balfour *et al* 2015) and of avian species in woody margins compared to fields with weedy margins (Kross *et al* 2020) were observed. Also, Gardiner and Dover (2008) recorded a doubling (within the period 2012–2013) and even a tripling (2013–2014) of rarefied species in hedgerows compared to bare fallow. However, Brambilla *et al* (2020) found a negative relation between species richness and windbreaks and a slightly higher number of earthworm species was observed in adjacent fields than in hedgerows (Holden *et al* 2019).

Faunal species richness and abundance are not clearly related to the distance from windbreaks. There were positive relations (Pfister *et al* 2015, Pardon *et al* 2019, Lajos *et al* 2020) as well as negative relations by distance (Moisan-DeSerres *et al* 2015, Pfister *et al* 2015) recorded. Even more unclear patterns were reported as Rivest *et al* (2019) observed a decrease of earthworm species richness until a distance of 8 m

Table 2. Main effects of windbreaks grouped by ecosystem service bundle. Numbers correspond to all relevant references; as not all of these publications were explicitly discussed in section 4, the numbers in brackets correspond to publications which were discussed there. Some references included multiple parameters, hence were counted multiple times (i.e. sums are not necessarily corresponding to lengths of reference lists). If not indicated otherwise, positive effect means higher degree and negative effect lower degree of ecosystem service fulfilling in comparison to control (columns 4–6).

			Number of references		
Ecosystem service bundle	Sub-category	Main indicator for windbreak effect	Positive effect	No effect/ relation	Negative effect
Biomass production	Crop yield and livestock production adjacent to windbreaks	Plant growth and yield, livestock productivity	17 (7)	5 (1)	4 (1)
	Areal and regional analyses	Biomass production or yield of (parts of) landscapes	1 (1)	2 (2)	0 (0)
Biodiversity and genetic resources	Biodiversity[a]	Biodiversity compared to other habitats	20 (5)	4 (0)	3 (2)
		Species richness related to distance to hedgerows	5 (4)	1 (1)	4 (3)
		Species richness related to increasing length, width and/or density of hedgerows	14 (7)	4 (0)	0 (0)
		Species richness/abundance related to the age of the hedgerows	3 (3)	2 (1)	1 (1)
Pollination, pest and disease control	Pollination	Effect on cash crops	4 (4)	2 (2)	0 (0)
	Disease and pest control	Effect on cash crops	11 (6)	3 (1)	0 (0)
Balance of nutrients and harmful substances	Nutrient build-up	Concentration of nitrate in soil	1 (1)	1 (1)	1 (1)
		Concentration of ammonium in soil	1 (1)	1 (1)	0 (0)
		Concentrations of total N compared to control	6 (6)	2 (2)	0 (0)
		Concentrations of P, available N, Mg, or K compared to control	4 (4)	0 (0)	0 (0)
	Nutrient losses	Losses of N to groundwater or run-off[b]	3 (3)	1 (1)	1 (1)
		Losses of Ammonium to groundwater or run-off[b]	1 (1)	0 (0)	2 (2)
		Losses of P to groundwater and run-off[b]	2 (2)	0 (0)	1 (1)
	Pesticides	Off-site spray drift[b]	3 (3)	0 (0)	0 (0)
Atmospheric conditions	Regulation of greenhouse gases	Carbon dioxide emissions or global warming potential[b]	4 (4)	2 (1)	0 (0)
	Particulates	Aeolian transport[b]	4 (4)	1 (1)	0 (0)
	Odors	Aeolian transport[b]	9 (6)	0 (0)	0 (0)
Soil protection	Water erosion	Run-off and soil loss[b]	10 (8)	0 (0)	0 (0)
	Wind erosion	Wind speed, sediment flux and soil loss[b]	19 (14)	0	0
	Soil stability	Accelerating aggregate formation	2 (2)	2 (2)	0
Water balance	Regulation of water availability	Continuous water availability in and surrounding windbreaks	6 (6)	6 (6)	1 (1)
Cultural ecosystem services	Societal perception	Well-being, health, existence value or similar	10 (6)	2 (1)	0 (0)
	Landscape analyses and research subjects	Landscape quality indicators and subject for education and research	5 (5)	0 (0)	0 (0)

[a] Other individual effects, not categorized 17 (9).

[b] Positive effect means reduction.

from the windbreak and a subsequent increase of species richness until a distance of 50 m. Contrary, Földesi *et al* (2019) measured an increase in hoverflies until a distance of 10 m with a subsequent decline of total species richness. The abundance of different spider species showed different, sometimes contrary relations to the distance from windbreaks (Pfister *et al* 2015).

Table 3. Correlation coefficients for species richness and hedgerow variables from literature.

Characteristic	Correlation coefficient	Source
Length	0.00034	Assandri *et al* (2016)
	0.65	Sanderson *et al* (2009)
	0.0007	Silva *et al* (2008)
	$\exp^{0.319}$	Sybertz *et al* (2020)
	$\exp^{3.3896}$	Sybertz *et al* (2020)
Width	0.4	Conover *et al* (2009)
	0.66	Litza *et al* (2020)
Age	0.076	Kremen *et al* (2008)
	−0.329	Lenoir *et al* (2019)

Bates and Harris (2009) demonstrated that the total number of mammal individuals varied only slightly (from $n = 174$ to $n = 185$) if the cross-sectional area of the hedge was more than doubled and the mean hedge height increased by a factor of 1.5. Dense hedgerows (gaps <50%) showed a doubling of the mean abundance of Hymenoptera compared to open ones (gaps >50%; Volpato *et al* 2020).

4.2.2. Variable biodiversity as a response to windbreak dimensions and management

The presence of windbreaks not only influences ES but also varies in effectiveness by a broad range of characteristics of the windbreaks itself. The biodiversity indicators within the screened studies were captured based on species richness commonly expressed as bird abundance, forest species, mammals and plant species. Nearly all studies report positive correlation coefficients for hedgerow structure and species richness (table 3).

Different compositions of hedgerow plants caused a variation in species richness. Exotic plants, for example, harbored fewer bees than native ones (Morandin *et al* 2013). A study of caterpillars showed a similar pattern with higher species richness, abundance and interaction diversity for native hedgerows that consisted of indigenous biomass than in novel hedgerows with mainly non-native plant biomass (Richard *et al* 2019). However, not only the type of plants but also the plant diversity led to an increasing abundance as it was the case for arthropods (Gámez-Virués *et al* 2010). A comparison of abundance and species richness in old field, orchard and pine hedgerows did not show significant differences (Sullivan *et al* 2012).

Different trends are reported concerning the age of hedgerows. Kremen *et al* (2008) and Piper (2006) found a positive relationship between the number of species and the hedgerow age. Kremen *et al* (2008) modeled an effect size for species richness by a coefficient of 0.076 ± 0.023 per year after the restoration of the hedges. In contrast, in young exotic plant hedgerows planted between 2007 and 2008, a mean number of nine bee species within all four study sites was recorded compared to mature exotic plant hedgerows (planted in 1996) with three bee species (Morandin *et al* 2013). Other studies (e.g. Litza *et al* 2019) either saw no differences in species richness or species abundance by different age stages of hedges or even recorded adverse effects for young (ca. 8 years old) hedgerows by a coefficient of -0.329 ± 0.060 (Lenoir *et al* 2019).

Management effects of hedgerows were investigated by the management practices and the cutting frequency of hedgerows. Organic farming had positive effects on species richness (micromoths, spiders, and beetles) compared to conventional treatment (Fuentes-Montemayor *et al* 2011, Fukuda *et al* 2011). Another positive management effect on species richness was the fencing of shelterbelts from neighboring grass paddocks (Fukuda *et al* 2011). The effects of tillage and herbicide use was controversy reported positive and negative (Jobin *et al* 1997, Miñarro *et al* 2009).

The duration of the period after the last hedgerow cutting was positively related to species richness of bats and insects (Froidevaux *et al* 2019). However, a saturation effect of bat species richness was visible after no cutting for at least 6 years. Studies of moths larvae abundance revealed higher positive effects of cutting in autumn than in winter (Facey *et al* 2014). For the species richness of Lepidoptera, the cutting period showed a more positive effect for trimming in winter as the cut is done incrementally (raising the cutter bar by approximately 10 cm each time the hedge is cut) vs the cut is done at the same height (Staley *et al* 2016). A study in the southern UK showed only minimal effects of cutting on species richness (Stanbury *et al* 2020).

4.3. Pollination, pest and disease control

4.3.1. Pollination

To isolate the pollination effect, phytometer experiments were conducted where pollination-dependent plants are placed in the observed field spots during florescence. In a field trial in Germany, potted strawberry plants were placed on different landscape elements during the flowering time to compare the pollination capacities. Near windbreaks connected to forest areas, the commercial value of strawberries per plant was 149% higher than in grass margins (Castle *et al* 2019). Unconnected windbreaks, in contrast, did not significantly increase the value. Similarly, Morandin *et al* (2016) placed canola plants in fields bordered with and without hedgerows and extrapolated the yield benefits of hedgerow presence being 21% or \$571 per hectare. In oilseed rape fields, being mainly dependent on wind pollination, an average increase of 4% (up to a maximum of 18%) in insect pollination potential was found due to the presence of hedgerows (Sutter *et al* 2018). A positive but not quantified effect of hedgerows was observed by Dainese *et al* (2017) and Kay *et al* (2018). Sardiñas and Kremen (2015) found no effect of hedgerow presence on seed set in adjacent sunflower fields and postulated that the benefits of hedgerows need to be evaluated considering variability in crop management and landscape characteristics.

4.3.2. Pest and disease control

Sutter *et al* (2018) observed an apparent effect of the proportion of hedgerows in the landscape with maximum predation of 23% of pollen beetle in oilseed rape when hedgerows covered 26% of the landscape. Fewer individuals from five out of seven pest groups at the edges and 67% higher parasitism of stinkbug eggs were found in Californian tomato fields bordered by hedgerows (Morandin *et al* 2014). Thomson and Hoffmann (2010) found higher predator abundance (on average 246% of control) and parasitism of moth eggs (approx. by a factor of 16, even though on very low level for both treatments, which undermines informative value) in vineyards surrounded by windbreaks. Fields that had non-woody field margins showed on average, four times higher damage of sunflower seed crops by moths than in fields with woody borders, while damage rates by birds were not affected by the type of margins. The orientation of hedgerows bordering apple orchards in France was correlated ($r = -0.3$ for perpendicular hedgerows having highest values and parallel hedgerows lowest) to codling moth abundance, while the effect of hedgerow density was not significant (Ricci *et al* 2009).

Several studies used more complex models to evaluate their results, hence the outcomes are not as easily comparable as in the above presented based on relational analysis. The study of Maalouly *et al* (2013) revealed a significant effect of hedgerow orientation on codling moth density but no effect of hedgerow length and quantities on moth egg parasitism. Contrarily, the length of hedgerows in landscapes was found to decrease undesired occurrences like aphid abundance and weed seeds (Badenhausser *et al* 2020) or pooled pest insects (Penn 2018) in adjacent fields.

4.4. Balance of nutrients and harmful substances

4.4.1. Nutrient build-up

Windbreaks often have a positive effect on nutrient build-up of soils. Compared to arable fields or unsheltered controls, average increases in concentrations under windbreaks ranging from 7% (available magnesium, Mg) to 64% (available potassium, K) were found in the reviewed studies. The only exceptions were the extractable mineral nitrogen (N) species nitrate (NO_3^-) and ammonium (NH_4^+), where no trend was visible.

Mean NO_3–N concentrations in the soil of an agricultural ecosystem in China were not affected by the distance from a shelterbelt down to a depth of 200 cm (Qiao *et al* 2016). Zhong *et al* (2020) reported up to 37% higher mean NO_3–N concentrations in fields sheltered by mulberry windbreaks compared to an unsheltered control. Lang *et al* (2019) differentiated between hedgerows which mainly consisted of 40–100 year old deciduous broadleaved trees and shelterbelts with 20–50 year old coniferous trees. Mean NO_3–N concentrations were generally higher in the arable soil than under the trees at both sites (Lang *et al* 2019).

Concentrations of NH_4^+ were less often investigated than NO_3 concentrations. Windbreaks had no uniform effect on soil NH_4–N concentrations. Mean NH_4–N concentrations were on average 50% higher under the trees compared to the arable fields in the study of Lang *et al* (2019), but mulberry hedgerows did not affect soil NH_4–N concentrations (Zhong *et al* 2020).

Windbreaks positively affected the available N estimated by alkali-hydrolysable N, which increased on average by 24%. Available N concentrations tended to increase if mulberry windbreaks were present—on average by 20% (Zhong *et al* 2020). Chendev *et al* (2020) recorded the maximum concentration of available N in the soil under a 50 year old oak tree shelterbelt in Russia. Compared to the adjacent field, the mean concentration was 28% higher under the trees. Total N (N_t) concentrations were often higher under the perennial vegetation. The highest increase (by factor 4) was observed by Jaskulska and Jaskulska (2017) under an old (200 year old) shelterbelt, followed by Holden *et al* (2019), who reported 58% higher mean N_t concentrations in the soils under windbreaks compared to arable fields. In other studies, mean N_t concentration was not affected by the distance from a tree row (Oelbermann and Voroney 2007, Pardon *et al* 2019).

Soil phosphorus (P) concentrations were generally positively affected by windbreaks. For instance, on average 32% higher concentrations of available P were measured in the soil below a windbreak (Chendev *et al* 2020) and a tree row compared to adjacent fields (Pardon *et al* 2019). In addition to 13% higher concentrations of available P, Zhong *et al* (2020) also reported an increase in total P concentrations up to 37% if mulberry windbreaks were present. Available Mg and K were scarcely considered in the reviewed publications. In two studies conducted in Belgium, available Mg concentrations were positively but only weakly affected by tree rows (increase by 9% and 4%), but available K concentrations were increased by 18% and 24% (Pardon *et al* 2017, 2019). According to Chendev *et al* (2020), available K concentrations were higher by a factor of 2.5 in the soil below a sheltered belt compared to adjacent fields.

4.4.2. Nutrient losses

Nutrient losses from soil generally tended to decrease if windbreaks were present; only NH_4 losses showed an opposite trend (table 3). Nitrate leaching and NO_3–N concentrations in the groundwater were higher in adjacent arable soil than below the trees (Jaskulska and Jaskulska 2017, Kay *et al* 2018). Mulberry windbreaks reduced NO_3–N runoff losses on average by 63% (Zhong *et al* 2020). However, NO_3 concentrations in the soil solution under windbreaks were up to five times higher than in adjacent arable fields in Northern England (Holden *et al* 2019). In another study, NO_3–N concentrations in groundwater were not affected by the distance from a windbreak (Qiao *et al* 2016).

Ammonium and P in solution were determined in very few studies. Mean NH_4–N concentrations were reduced in the runoff from mulberry-sheltered fields (Zhong *et al* 2020) but were 25% higher in the groundwater under hedgerows and shelterbelts than under cultivated fields (Jaskulska and Jaskulska 2017). Higher mean PO_4–P concentrations in the groundwater were observed under cultivated fields than under adjacent windbreaks (Jaskulska and Jaskulska 2017), and mulberry windbreaks reduced total P and total dissolved P in the runoff by up to 78% (Zhong *et al* 2020). However, mean PO_4^{3-} concentrations in soil solution were significantly higher and up to ten times greater under windbreaks compared to arable fields in Northern England (Holden *et al* 2019).

4.4.3. Pesticides

The only pollutants which were investigated in connection with windbreaks are pesticides. Windbreaks always had a positive effect, i.e. they reduced off-site spray drift up to 97.9% (Lazzaro *et al* 2008, Wenneker and van de Zande 2008) or spray deposits downwind of spray release (De Schampheleire *et al* 2009). The degree of off-site spray or deposition reduction was dependent on the optical porosity of the Windbreaks. However, a clear effect of the distance in the lee of the windbreak was not found in any study.

4.5. Atmospheric conditions

4.5.1. GHG

Agriculture is a main contributor of GHG such as N_2O, CO_2 and CH_4 to the atmosphere, that are formed in the soil through various processes. The establishment of windbreaks in the agricultural landscape can be a measure to reduce the emission of GHG from the soil into the atmosphere. Amadi *et al* (2017) studied GHG exchange dynamics along a gradient from within a windbreak to the center of the adjacent field. They found that the establishment of windbreak altered the properties of surrounding soils, enhanced C storage, and reduced N_2O emissions while maintaining a strong CH_4 sink. The influences of shelterbelts on soil GHG emissions appeared to range up to 1.5 tree heights from the windbreak. Tree root distribution may be a key factor in determining the spatial range of windbreak effect on GHG emissions in adjacent fields (Amadi *et al* 2018), but also organic carbon distribution, soil temperature and soil moisture were determining the GHG fluxes. Furthermore, changes in precipitation patterns and soil moisture regimes due to climate change were concluded to affect soil–atmosphere exchange of GHGs in windbreaks, hence no clear statement was possible about their effect.

In a comparative study in Canada, the production of the potent greenhouse gas N_2O was found lower in areas with shelterbelts and hedgerows than in adjacent herblands, and the uptake of CH_4 from the atmosphere was lower in these systems while CO_2 emissions were higher (Kwak *et al* 2019). Considering the global warming potential, seasonal variability impeded clear advantages of a specific land use system. Baah-Acheamfour *et al* (2016) found a lower global warming potential under agricultural systems including trees, mainly by increased uptake of CH_4 and reduced N_2O emission. Szajdak *et al* (2018) studied different ages of windbreaksf in terms of their GHG production potential and related it to enzyme activities in the soil. Emissions of N_2O were higher in the adjoining cultivated fields than under windbreaks, whereas no differences were found for CO_2.

4.5.2. Particulate matter (PM)

PM is a severe source of air pollution, where it exerts adverse effects on human health and the tree canopy can serve as a sink for particles (Chen *et al* 2015). Due to the large canopy area and the turbulent air movement created by their structure, trees effectively trap more particles than shorter vegetation. Chang *et al* (2019) observed a filtering effect on the leeward side of poplar windbreaks in Northern China only for larger particles (PM10, reduction of 27%), while smaller particles (PM1 and PM2.5) were not filtered sufficiently. The reduction of mainly PM10 particles, rather than smaller ones was also found by Chen *et al* (2015) and Hua *et al* (2016). In a wind tunnel experiment using four rows of cornstalks and glass beads (diameters ranging from 10 to 50 μm), filtering efficiency positively correlated with particle size (Bouvet *et al* 2007). PM is closely linked to dust particles carrying pesticides as insecticides, fungicides and herbicides. In a study in Israel, a significant reduction of pesticides and PM was found for all planted trees (pine, eucalyptus and carob trees; Zaady *et al* 2018).

4.5.3. Odors and noise

Several studies from Canada and the U.S. have investigated whether windbreaks help reduce odors from livestock facilities which can emit large amounts of pollutants. Barrington *et al* (2006) found that a windbreak with only a single row of deciduous trees with an optical porosity of 35% could already reduce the odor dispersion distance by 20%, on average.

Hernandez *et al* (2012) and Lin *et al* (2007) confirmed these results. Lin *et al* (2007) also summed up that conifers offer more wind resistance than deciduous trees, likely because of their more robust and less flexible branches.

The effect of windbreaks on the attenuation of noise was mainly investigated in urban areas. The studies investigated various depths, tree species, height, visibility of vegetation barriers. Karbalaei *et al* (2015) found that the maximum reduction in noise value was achieved by shrubs and trees of 100 m in width and the mixture of conifers and broad leaves of 100 m and 50 m in width. However, also a less deep tree belt along a road may reduce traffic noise (Van Renterghem 2014). Ow and Ghosh (2017) found that a depth of vegetation barrier of 5 m was the ideal depth for traffic noise reduction.

4.6. Soil protection

4.6.1. Water erosion

Windbreaks were found to delay runoff and reduce the accumulated sediment yields by 10%–45% compared to control plots (Yang *et al* 2019). Accordingly, McDonald *et al* (2002) showed that contour windbreaks reduced runoff by 45% and soil erosion by 35% compared with annual crop monoculture. The introduction of windbreaks which are oriented across the slope and therefore reduce the slope length, led to a considerable reduction in potential soil loss by 33.3% (Frank *et al* 2014). Belyaev *et al* (2009) showed that slopes with slope-crossing windbreaks are characterized by a substantial reduction of average soil redistribution rates by more than 80% using radiocaesium as a sediment tracer. In the surroundings of windbreaks, soil deposition rates of 8–16 t ha^{-1} yr^{-1} were recorded in the black soil region in Northern China (Fang *et al* 2012). Deng *et al* (2015) also proved that the effect of farmland shelterbelts on gully erosion varied with distance and recommended as an optimal planting density of 1100–1300 m km^{-2} of farmland shelterbelts for the prevention of gully erosion.

The soil protective effect of windbreaks is often presented in combination with other conservation measures. The introduction of windbreaks in a modeling study on regional scale revealed a reduction in total soil loss by 33% while the combination with greening of discharge paths and a change from conventional to no-till management resulted in a reduction by 92% (Frank *et al* 2014). The field study by Dai *et al* (2018) under natural rainfall showed that windbreaks and downslope tillage reduced the runoff depths comparing to bare land by 37% and sediment loss by 86%.

4.6.2. Wind erosion

Wind speed on the leeward side of a windbreak significantly increases with increasing relative distance (multiples of the height H of the windbreak) from the windbreak (Vacek *et al* 2018). In respective studies, the protective leeward distances varied between 5H (Michels *et al* 1998) and 50H (Torshizi *et al* 2020a, 2020b) with a mean of 15H depending on windbreak geometry and wind speeds. The differences in windbreak efficiency in terms of the wind-speed reduction reached between 9.7% and 15% (Vacek *et al* 2018, Miri *et al* 2021), 50% (Böhm *et al* 2014), 78% (Dufková 2007), and a maximum of 85% at 1H (Peri *et al* 2002).

The effects of several characteristics like the optical porosity, the windbreak height, distance between hedgerows and their orientation were investigated in relation to wind erosion. Hedges of 2 m in height reduced soil flux by 47%–77% compared with unsheltered control plots (Michels *et al* 1998). The stated values of optimal optical porosity in terms of wind velocity reduction vary from lower than 20% (Řeháček *et al* 2017) to 50% and 80% (Zhang *et al* 2007) with the mean around 40%–50%. Investigating seasonal changes, an optical porosity of 20% reduced wind speed by 37% in October and 64% in May (Středa *et al* 2008). Based on computational fluid dynamics investigations, it was found that the percentage reduction in wind velocity measured at a distance of 15H, for one-row, two-rows of trees and two-rows arranged alternately was approximately 20%, 30% and 50%, respectively (Bitog *et al* 2012).

The highest soil loss reduction due to windbreak effect after nine wind erosion events (average wind speeds >7.9 m s^{-1}, peaks of 20 m s^{-1}, duration of one storm 4–20 h) in Central Patagonia was observed by 81% and the lowest by 42% (Sterk *et al* 2012). Dufková (2007) showed that the content of non-erodible soil particles is higher on the leeward sides. Effective protection against wind erosion can be provided by windbreaks, especially when the soil is not protected by the vegetation cover of crops (Kučera *et al* 2020).

4.6.3. Soil stability properties

At eight sites in the northern Great Plains (USA), the fraction of water stable aggregates was compared below tree windbreaks, annual crops and perennial grassland. Soil under the trees was more stable than under annual crops, whereas grassland showed higher stability (Khaleel *et al* 2020). Wang *et al* (2018) examined the formation of characteristics for soil stability below shelterbelts of different age and composition. The fractions of clay and silt increased, whereas the fraction of sand decreased with shelterbelt age in the 0–5 cm soil layer. Geometric mean diameter of soil aggregates and the fraction of water stable aggregates increased with increasing planting time, indicating that plant growth accelerated soil formation. Windbreaks affected soil particle distribution by effectively intercepting clay particles from surface runoff of water and soil (Li *et al* 2015). Comparably, a cascade of windbreaks perpendicular to slope direction led to a higher fraction of clay compared to slopes without windbreaks where fine soil particles were eroded (Xie *et al* 2015).

4.7. Water balance

4.7.1. Regulation of water availability in and surrounding windbreaks

Windbreaks change the water regime by transpiration, interception and rooting. Thomas *et al* (2012) explained the increased capillary rise and decreased drainage near windbreaks by the higher transpiration of the permanent vegetation of the windbreak. They found that the hedgerow effect on soil moisture was more visible during a dry year than during a wet year. Ghazavi *et al* (2008) reported that soil water potential, spatial rainfall distribution, soil rewetting and the groundwater level were influenced in distances of up to 9 m to windbreaks. The water consumption of the windbreaks led to drier soils and a delayed rewetting near to windbreaks. On the other hand, in climates with snow, land with windbreaks had 29% more snow water equivalent than the unstructured landscape (Kort *et al* 2012).

Fu *et al* (2019) found increased transpiration from poplar windbreaks due to rising temperatures under arid conditions, as higher air temperatures led to a greater atmospheric demand for water. On the other hand, a windbreak reduced the evapotranspiration leeward of the windbreak (Gerersdorfer *et al* 2009). For this reason, the question arises whether areas with or without windbreaks have higher water demands. This question was investigated by Thevs *et al* (2017). When windbreaks were added to areal evapotranspiration models, a slight reduction of water consumption of the whole crop-windbreak system was found for corn, potato, and pear under the assumption of 500×500 m^2 field sizes, whereas for a 200×200 m^2 field size, water consumption was higher for all crops investigated except for pear (Thevs *et al* 2017).

Windbreaks influence the microclimate of their surroundings. Air temperatures beneath the windbreaks were lower and steadier than surrounding areas in a Mediterranean climate (Sánchez *et al* 2010). Additionally, when temperatures of the fields were compared to sites where windbreaks had been removed, significant differences in temperatures were detectable belowground and at the soil surface. Iwasaki *et al* (2020) developed a model for estimating windbreak effects on soil temperature. Their model could reproduce the increase of 0.4 °C–0.8 °C in soil temperature in distances of three to four heights due to wind reduction and the decrease of 0.9 °C–1.0 °C in soil temperature in a distance of 0.5 heights of the hedge due to shading effects. Reduced windspeeds of 50% and 75% leeward of windbreaks, as modeled by Gerersdorfer *et al* (2009), reduced evapotranspiration for field conditions in Austria. Consequently, their model resulted in a minor and later water stress compared to open field conditions. Campi *et al* (2009) found that temperature and wind speed were influenced by windbreak presence, leading to a decrease of evapotranspiration and increased water use efficiency by 64% compared to open field conditions in a Mediterranean climate. In South African vineyards, wind speed reductions caused a reduction of reference evapotranspiration of 15.5% during the whole year and 18.4% over the growing season (Veste *et al* 2020). Baker *et al* (2021) assessed the climate conditions where windbreaks effectively regulate the microclimate in paddocks. The most prominent effects were observed in summer and during the afternoon. Windbreaks were most effective at reducing wind when speeds were high.

In a Mediterranean region, windbreaks caused higher average soil water contents than the singular tree system Dehesa (Sánchez and McCollin 2015). Windbreaks impact surface water, depending on their rooting depth and density, which shows noticeable differences between crop lands, bare soil, and perennial windbreaks (Ghazavi *et al* 2008). At the watershed scale, windbreaks decreased predicted water flow at the outlet by 4.5% compared to flows of watersheds without windbreaks over a simulation period of 17 years (Benhamou *et al* 2013).

4.8. Cultural ESs

4.8.1. Societal perception

Surveys are the most commonly applied method to collect data about the value of cultural ES. Hence, the quantitative outcomes of such studies are of a different character to the technical studies presented above. The subjects are mostly asked about their perception of windbreaks and their value. As target groups, the surveyed persons are often divided into non-farmers and farmers who are responsible for the installation and maintenance of hedgerows. For both groups, the increased aesthetic or scenic value was the most frequently indicated ES in the collection of studies from several different countries. Often, the socio-cultural background of the respondents, mainly affinity with agriculture and environment as well as educational level, had a significant influence on the preferences (Oreszczyn and Lane 2000, van Zanten *et al* 2016). A monetary evaluation via the willingness to pay for the establishment of windbreaks for aesthetical purposes in Iowa, USA, was surveyed by Grala *et al* (2012). Nearly half of the respondents (46%) were willing to pay USD 1 and 22% assured payment of USD 50.

In several regions, the existence of windbreaks and specific traditional methods for the maintenance is seen as cultural heritage; for example in England (Oreszczyn and Lane 2000), France (e.g. Burel and Baudry 1995), and Japan (Fukamachi *et al* 2011).

Especially amongst non-farmers, a wide range of possibilities for recreational activities was stated as reasons for the subjective preference of landscapes with a high density of hedgerows. It was found that aesthetic and recreational value are the most relevant reasons for landscape preference, whereas knowledge about other ES delivered by landscape elements was weak (Plieninger *et al* 2013). Most of the mentions for existence value came from farmers and were linked to the protection of property borders, which is not the most obvious characteristics of a cultural ES.

Some disservices of landscapes and landscape elements that are not considered in CICES were found to affect regional inhabitants' well-being. For example, the visual screening is seen positively by tourists or recreation seekers but causes the feeling of being imprisoned and lacking view for permanent inhabitants (e.g. Burel and Baudry 1995).

4.8.2. Landscape analyses and research objects

Besides surveys, few studies analyzed geodata to create knowledge about the ES of hedgerows. Groot *et al* (2010) calculated a cultural heritage value dependent on the extent and orientation of hedgerow networks and tried to optimize landscape design by balancing the linked landscape character with ecological quality and implementation costs. Following an even broader approach, Parra-López *et al* (2008) determined the welfare of society provided by agricultural landscapes and used hedgerow presence as a prominent variable parameter being highly relevant for landscape value.

Hedgerows are a subject of scientific importance, which is intrinsically demonstrated by the content of this manuscript. Moreover, Gosling *et al* (2016) showed the suitability of hedgerow research for citizen science projects which increase the awareness for their ES deliverance and even the social and political background of hedgerow planting and maintenance systems were subjected already (Busck 2003). Additional special services of hedgerows that can be classified to cultural ES include increasing traffic safety by landscape elements near roads (Jaarsma *et al* 2013).

5. Discussion

5.1. Discussion of the literature review process

The used definition of the ES bundles was chosen to assure a possibly enclosed treatment of the topics. Nevertheless, overlaps or synergies between the sections appeared frequently, for instance, between biodiversity and pollination and pest control and between soil protection, nutrient cycling and water balance. This was reported in comparable studies (Cord *et al* 2017, Winkler *et al* 2017) and poses further interdisciplinary research challenges. The great diversity of possibilities and strategies in landscape management additionally hampers the comparison of results over wide parts of the globe. For instance, in numerous studies from South-East Asia, the term windbreak was used for herbaceous or shrub stripes arranged at small distances to each other what causes low comparability of results with European or American tree-based windbreak types.

Another challenge was modifying the relatively new ES terminology to publications from times before introducing this framework. Furthermore, we only considered publications that distinctly determined the effect of the presence of windbreaks. Most of the identified studies from literature search needed to be rejected due to their design, which did not include a control treatment without windbreaks or less windbreak density. As a result, the numbers of publications included in the systematic review for the single ES bundles are certainly not exhaustive. Still, by the study design and the broad formulation of search terms, we assured to elaborate a highly representative overview of the available scientific knowledge.

A large number of publications related to the topic, as found in the primary searches, showed high interest across different environmental disciplines and pointed out the relevance of windbreaks for ES. There are few examples for mid- or long-term monetary valuation of hedgerow presence based on a possibly holistic inclusion of multiple ES or functionalities. Such studies would yield the most robust arguments to be perceived in landscape management decisions; hence, more research is needed in this direction (Smith *et al* 2021).

5.2. Discussion of results for ES bundles

5.2.1. Biomass production

A quantitative function relating yield ratio to the distance from a windbreak would be desired. Differences in the investigated distances and reference values (e.g. maximum yield or average given, averaging distance, reference distance, detection limits) as well as orientation and crop hinder the revelation of such an outcome. In other reviews or synthesis reports, the effect of windbreaks on surrounding crop yield varied between a yield gain of up to 120% (Kort 1988) and a reduction of 16% (van Vooren *et al* 2017). Hence, the formulation of a general effect is undue (figure 6). Attempts to predict yield depending on distance from a windbreak were made sporadically (Sun and Dickinson 1997) but did not find a considerable response in later research.

The actual biomass production of windbreaks and the quantitative benefits of livestock protection are hardly investigated and published according to the quality criteria in this review. Nevertheless, these are essential components in a holistic view of the ES of windbreaks and offers farm and landscape scale opportunities. The biomass products that are produced within windbreaks include amongst others fruits, medicine plants, fuel biomass, mulching material and soil amendments. Protective effects for

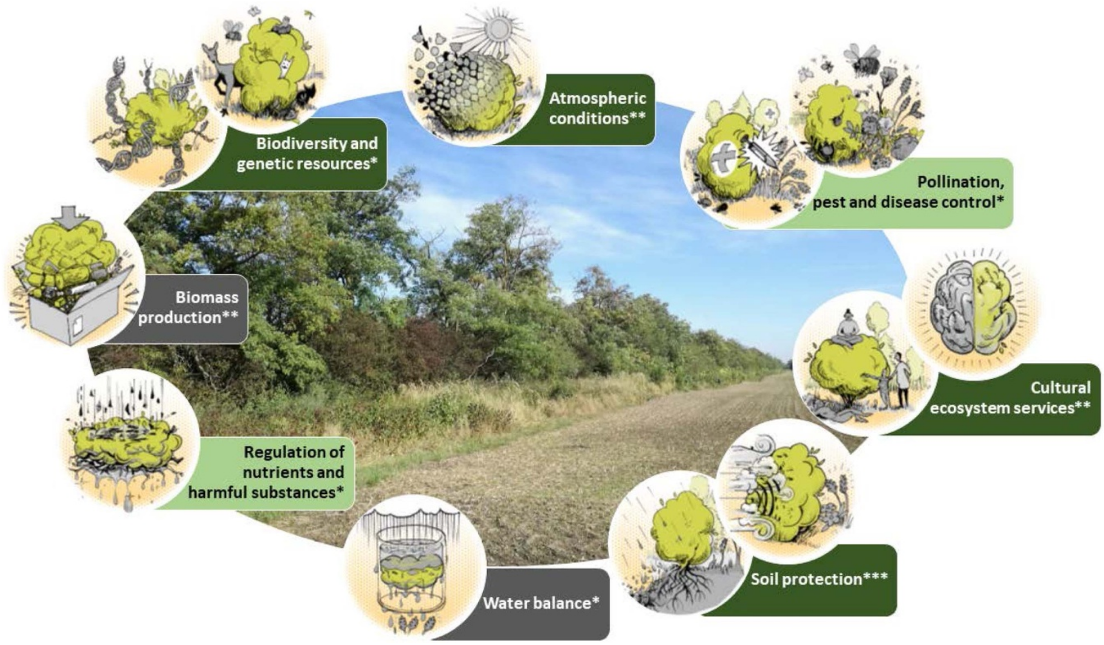

Figure 6. Illustration of the different ES bundles of windbreaks together with an estimated summary of the literature outcomes. The color of text fields shows the subjective positivity of the effect of windbreaks (green: strongly positive, light green: positive, grey: no clear effect, no negative effects which would be red). The asterisks give an impression about the extent of the quantitative data base (***: strong data base; *: weak data base). Reproduced with permission from Weninger *et al* (2020).

livestock could include higher health and productivity due to temperature control and wind protection as well as a more diverse diet (Gregory 1995).

There have certainly been numerous studies that presented their yield monitoring results mainly in grey literature which is hardly available and was hence not detected in our search. For illustration, see the references in Kort (1988) and Bird *et al* (1992), where numerous and diverse sources were collected from the beginning of the 20th century on. As yield is still the most relevant argument for farming and landscape planning decisions, research needs to continuously sustain and extend its engagement in the monitoring and interpretation as presented in this section. The highest need for future research was detected in the revelation of yield or income relations at a farm or landscape scale, including possibilities for incomes from windbreak products.

5.2.2. Biodiversity and genetic resources

Biodiversity is the broadest and least clearly defined topic amongst the investigated ES bundles and comprehended the highest number of relevant publications. Several studies outlined neither positive nor negative effects of windbreaks on biodiversity as they compared hedgerow systems themselves in an absolute manner. The general trend of all reviewed studies tended to point out a positive effect of windbreaks on biodiversity (figure 6). Most of the windbreak characteristics as length and width were clearly positively related to species richness, and therefore windbreaks were providing ES within the framework of biodiversity. In principle, the length, the width and the porosity of hedgerows were decisive for a higher number of species richness.

Biodiversity of plants and genetic resources were rarely touched in studies. Furthermore, neither measurements of biodiversity nor indexes of species richness were explicitly defined in any study. This showed the need for future study approaches including comparable measures for biodiversity in dependence of landscape structural indicators.

5.2.3. Pollination, pest and disease control

For both pollination and pest control, the number of studies revealing a positive effect was higher even though the negative results, especially pest danger, must not be neglected. A large number of discarded studies dealt with the sheer abundance of pollinators, pests or predators, often restricted to single species or families, which is somewhat misleading in the context of our research aim. Reviews or meta-studies with comparable focus pointed out a similar scarcity of research on the actual effect of landscape characteristics on pollination or pest control outcomes (Holland *et al* 2017, Mkenda *et al* 2019, Staton *et al* 2019) or revealed insignificant and variable effects due to lack of knowledge about key factors affecting the effectivity of windbreak design (Albrecht *et al* 2020). Generally, an extensive range of overlap exists between these special topics and the broad field of research about habitat preferences or quality and biodiversity. Pollination and pest control are also relevant for the yield in adjacent fields; hence another intersection exists with the ES bundle biomass production (e.g. Holzschuh *et al* 2012).

5.2.4. Balance of nutrients and harmful substances

The major part of the literature addressing the dynamics of nutrients and pollutants focus on riparian buffer strips, hence only 14 studies were found relevant for our review. Hence, the data basis for interpretation is weak (figure 6). Riparian buffer strips were not considered in this study since they are specifically planted to protect water bodies.

Hedgerows often positively affect nutrient build-up, which is usually explained by higher above-ground and below-ground litter input compared to arable crops and also the input via throughfall water (Pardon *et al* 2019). Hedgerows and shelterbelts also appear to act as biochemical barriers that take up nutrients from adjacent arable fields and thereby reduce nutrient losses in runoff or remove nutrients from groundwater. Nevertheless, higher nutrient concentrations in the soil solution or groundwater below hedgerows and shelterbelts may also occur as a consequence of increased mineralization of accumulated soil organic matter leading to an increased release of nutrients or due to lower nutrient uptake of the perennial vegetation compared to arable crops (Holden *et al* 2019).

The very few studies found dealing with the effects of windbreaks on harmful substances clearly showed that hedgerows usually act as a barrier to pesticide spray drift. The effectiveness in reducing spray drift mainly depends on the canopy development and thus on the growth stage but also the tree species present. Hedgerows usually achieve maximum drift reducing capacity in full leaf, therefore, differences in the leaf development of tree species should be considered for the planting of hedgerows (Wenneker and van de Zande 2008).

The causes and mechanisms underlying the observed effects of hedgerows on nutrient build-up and losses were often not specifically investigated. Additionally, the selection of investigated harmful substances was found surprisingly narrow. Hence, a vast gap of knowledge was detected and future research needs to aim on the understanding of processes involved in the cycles of nutrients and substances as affected by landscape elements. As environmental chemicals are increasingly recognized in public discussion and regulations, knowledge about the effectivity of windbreaks and landscape elements in risk reduction is strongly needed.

5.2.5. Atmospheric conditions

Very few studies directly examined the effects of windbreaks on soil GHG fluxes, and no clear conclusion about a net effect on global warming potential may be drawn. To better understand the processes and influencing parameters behind the production of GHG, transect measurements in the adjacent cropped fields, long-term studies, studies with shelterbelt systems of different tree species (e.g. N_2 fixing plants), ages, and designs are needed to improve the effectiveness of windbreaks as a strategy to mitigate agricultural GHG emissions. The multiple microclimatic factors influenced by windbreaks are particularly important for building GHG budgets.

In comparison to GHG, the effects of windbreaks on the transport of PM, pesticides, and odors are well investigated. Windbreaks are most efficient in removing larger particles within the fine dust spectrum (PM10). Within an optimal range of densities, windbreaks are dense enough to trap particles of various size and porous enough for letting polluted air pass through the filtering windbreak instead of over it. For smaller particles, the management recommendation would be thick and tall windbreaks. Nevertheless, the removal of PM1, PM2.5 and also pesticides is essential for health effects. Annual air quality services of tree-based agricultural systems were calculated as high as 462 USD ha^{-1} (Alam *et al* 2004).

Volatile organic compounds are under-represented in literature on atmosphere and windbreaks but have an indirect global warming potential by interacting with NO_x to form ozone and by competing with CH_4 for atmospheric oxidants which keep CH_4 from being destroyed before reaching the stratosphere. Furthermore, long-term research is needed to reliably assess the effect of windbreaks on GHG cycles.

5.2.6. Soil protection

The soil protective effect of windbreaks is often considered the most relevant effect (e.g. Van Vooren *et al* 2017). The analyzed studies clearly revealed positive effects, and the enhanced soil protection by windbreaks was often linked to direct ecological and economic benefits for agricultural sites. The positive effects added up from reducing the eroding force (wind speed, water runoff) and increased soil resistance at the leeward side of the shelterbelts. The extent of these effects was highly dependent on the factors that determine the efficiency of windbreaks: height, distance, porosity, orientation, length, and location in the landscape. Additionally, the combination of protection measures (e.g. no-tillage, contour ridge practices) may raise efficiency in countering both wind and water degradation processes (Frank *et al* 2014, Chen *et al* 2020). More information is needed about strategies for appropriate management of windbreaks and the differences in the magnitude of the effects determined by management measures. Additionally, reliable guidelines are lacking for the spatial arrangement of elements like windbreaks to optimize the protective effect in dependence of different regional characteristics.

5.2.7. Water balance

Windbreaks in cropping systems affect the water balance in a field beyond their growing space and rooting zones. Their effects on soil moisture, water balance, and field productivity at a local scale cause direct responses on field-scale. Managing soil moisture and water flux near windbreaks may contrast with the primary purpose of windspeed reduction and optimal sunlight exploitation. Large overlaps exist with other ES bundles like biomass production, balance of nutrient cycles, soil protection, and atmospheric conditions.

For protecting crop fields, the north to south orientation recommended for optimizing radiation input may be altered for water logging, frost and erosion risks (Trentacoste *et al* 2015). Species considerations should account for water consumption, rooting depth and soil type, because these factors predetermine the vitality and resilience of the windbreak. With higher evapotranspiration rates than seasonal crops, windbreak vegetation may impact water balance and soil moisture in counterproductive ways to crop yields, especially in dense windbreak networks and for crops within close distance.

To estimate the effect of windbreaks on water balance, the water requirements of different species are mostly known and can serve as basis. Nevertheless, quantitative information is rare and field research is needed to verify the estimations. Well-equipped study sites like the growing network of Critical Zone Observatories enable such insights and should include landscape structures (Luo *et al* 2019).

5.2.8. Cultural ESs

Compared to the technically dominated sections before, a wider range of different approaches and research disciplines was found in the search results for cultural ES. Generally, windbreaks are seen predominantly positive and were frequently stated to add cultural or aesthetical value to landscapes. The requirement for quantitative outcomes in our review process omitted an even broader view. Numerous excluded publications discussed the role of windbreaks in a regional and ethnographic context and often in essayistic form (e.g. Gardner 2009, Sheridan 2016). Hence, further review studies allowing for a broader implementation of such sources will reveal a broader impression of the socio-cultural context of windbreaks which may subsequently serve as a design basis for and improve the relevance of scientific or interdisciplinary studies.

Remarkably, a high fraction of studies regarding cultural ES included outcomes in monetary form. Such surveys often included a willingness-to-pay or a similar approach but mainly treated whole landscapes as subjects without distinct link to hedgerows (e.g. van Berkel and Verburg 2014).

5.3. Geographical context of results

As this review includes studies from all over the world, the large differences in climatic, geographic and socio-economic characteristics need to be considered when interpreting synthesized results. In particular, the growth conditions may well determine the potential of windbreaks to fulfill their functions or to even exist, as exemplified in Karst regions with degraded soils, water-limited Steppe areas, and storm-affected islands or coasts (Allen *et al* 2010, Stanturf *et al* 2014). Once trees are lacking on such extreme sites, the establishment of new woody vegetation is additionally hampered. Similarly, the growth conditions determine the effectivity of windbreaks at smaller scales as well, for instance different slope positions or small-scale differences in soil water balance. Water is a determinant for many other ES like biodiversity, nutrient balances, and greenhouse gas emissions. Hence, to consider the climatic water balance in the interpretation of regional studies potentially increases the value of the evaluations (IPCC 2014). In our review, we included at least rough information about the water regime whenever possible.

Besides such geobotanical considerations, the geographical situation determines the most relevant research questions aiming on the effects of windbreaks (figure 4). For instance, soil protection is well investigated at the Loess Plateau in China with its highly erodible soils and a high demand for agricultural productivity (Shi and Shao 2000). When field sizes are large and the diversity of arable crops is low, the enhancement biodiversity is demanded and windbreaks are investigated as viable tools. This is especially the case under the settings of an industrialized agriculture as prevalent in some parts of European countries or the USA. Cultural ES and odor, dust, and noise attenuation are similarly important in areas with high abundance of industrial livestock production or urban spreading, respectively. In summary, geographic differences in studies about the ES of windbreaks are likely to be influenced by the formulation of a particular research question which is a result of regional societal needs and problems. The data basis for an objective quantitative analysis of the potential of windbreaks to fulfill different ES in dependence to the geographic conditions is hence still lacking.

6. Conclusions and outlook

Peer-reviewed information about the effectiveness of windbreaks was found for all eight considered bundles of ES. While our review was designed for covering an as broad as possible range of research disciplines, a surprisingly low degree of interdisciplinarity was found in the screened sources. Different ways of summarizing analyses of relevant literature were applied and revealed the diversity of ES fulfilling. The outcomes of these quantitative analyses provide a good impression about the degree of clarity in the different research branches and allow the detection of fields with the highest demand for further research. Namely, especially the effects of windbreaks on the cycles of water and nutrients at plot and landscape scale still lack understanding while soil protection is the most clearly investigated ES.

The assessments of windbreak ES showed a clear dominance of effects that are considered positive by a major part of society. Nevertheless, the validity of summarizing quantitative statements about the degree of positivity or negativity is often hampered by the large heterogeneity of study designs and study objects. The large majority of research was not designed to deliver arguments for or against the installation or maintenance of vegetated windbreaks in agricultural landscapes. Scientific data acquisition is mainly done on plot or regional scale, while parts of landscapes or landscape elements are hardly investigated. That enlightens the need for further developments aiming at well-equipped experimental field sites and furthermore a measurement-based evaluation system that yields comparable indicators for ES services. As a basis for holistic estimations of the multiple functions and services of vegetated windbreaks in rural landscapes, the presented overview with its broad scope may serve as inspiration.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Listed here are the references cited in the manuscript except for section 4 which includes the actual results of the systematic review. The complete list of references and screening results for section 4 is grouped by ES bundles and attached in supplementary S2

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