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Review

Windbreaks in the United States: A systematic review of producer-reported benefits, challenges, management activities and drivers of adoption

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ABSTRACT

Windbreaks are an agroforestry practice used to provide simultaneous economic, environmental and social benefits that occur when trees are deliberately integrated into an agroecosystem. To date, no systematic review has been conducted on windbreak adoption in the U.S., which is needed to assess whether broader trends exist that may affect future research, extension delivery and policy development. This synthesis covers windbreak adoption studies in the U.S. from the earliest identified study in 1949 through 2020. A key finding from this synthesis is that producers use windbreaks on agricultural lands mostly for indirect economic benefits (soil erosion control, livestock protection, wind protection and snow control). This is followed by direct agricultural benefits (increased crop and livestock production) and intrinsic values (aesthetics and wildlife habitat). Direct economic benefits from forestry (timber and non-timber forest products) were often ranked last, despite most producers utilizing their windbreak trees for some economic gain. Windbreak satisfaction was also found to be high among U.S. producers (72–99%), with the beneficial functions varying by windbreak type (field, livestock, and farmstead). The main drivers causing producers to remove windbreaks were poor condition, age, and conflict with farming practices, while the primary reasons for non-adoption of windbreaks were lack of land and windbreak upkeep. Key information gaps needing further investigation include a greater understanding of producer-reported challenges and management activities associated with windbreak planting and maintenance, identifying and monetizing windbreak systems capable of producing marketable products, and valuation of ecosystem services provided by windbreaks over space and time and the potential for developing those markets.

1. Introduction

Windbreaks are an agroforestry practice involving linear plantings of trees and shrubs that are strategically integrated into an agricultural landscape to simultaneously provide economic, environmental and social benefits that can occur when trees are deliberately managed in an agroecosystem. Depending on their location and functional purpose, windbreaks in agroecosystems are classified as field, livestock or farmstead, and specific design arrangements may also be called hedgerows, shelterbelts, living snow fences or vegetated environmental buffers. Windbreaks are also utilized for many non-agronomic purposes, but those are not considered in this synthesis.

The benefits of windbreaks are numerous and dependent on the windbreak's intended function. When designed for wind reduction purposes, these systems can create more favorable conditions that enhance field and orchard crop production (Osorio et al., 2018; Kort, 1988) (Table 1), improve crop quality and marketability by reducing damage caused from wind-blown particle abrasion (Norton, 1988) or fruit rubbing against other parts of the plant during high wind (Peri and Bloomberg, 2002; Norton, 1988), decrease premature fruit drop (Hodges and Brandle, 2006; Norton, 1988), reduce the spread of crop diseases like citrus canker (Tamang et al., 2010), reduce honey bee mortality during the winter (Hendrickson, 2015; Conrad, 2013), increase foraging of honey bees during times of high wind (Hennessy et al., 2020), increase livestock production during inclement weather (Anderson and Bird, 1993), reduce risk of livestock mortality during

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Table 1
Relative responsiveness of various crops to shelter provided by windbreaks.

Crop	No. of field-years	Mean yield increase (%)
Oats	48	6
Spring wheat	190	8
Maize	209	12
Soybeans	42	16
Rye	39	19
Grass hay	14	20
Winter wheat	146	22
Barley	30	25
Raspberry	2	27
Tomatoes	3	29
Plum	2	34
Snap beans	2	40
Millet	18	44
Strawberry	3	56

Source: Data from Bagley (1964), Baldwin (1988), Brandle et al. (2009), Norton (1988), Kort (1988), and Osorio et al. (2018).

winter storm events (Brandle et al., 2004; Gregory, 1995), reduce soil erosion, increase water-use efficiency, reduce energy and heating costs (Dewalle and Heisler, 1988), and offer control of blowing snow, dust, odor, and chemical sprays (pesticides, herbicides, etc.) (Hand et al., 2019; Brandle et al., 2004; Laughlin, 1989).

When used for non-wind purposes, windbreaks can provide shade for livestock, visual screening, aesthetics, recreational opportunities and wood and nontimber forest products (NTFPs) (Hand et al., 2019; Tyndall, 2009; Grala et al., 2008; Brandle et al., 2004). Windbreaks have also been recognized for their value in providing ecosystem services, which often extend beyond the farm. Benefits include enhancement of biodiversity, wildlife habitat (Workman et al., 2003), carbon storage (Schoeneberger et al., 2017; Sauer et al., 2007), pollinator habitat (Bentrup et al., 2019), and soil and water quality protection (Brandle et al., 2004).

The ability to simultaneously provide economic, ecological and public benefits is one of the reasons why windbreaks are increasingly viewed as a strategy for sustainable intensification and diversification of agroecosystems. Furthermore, as conversations increase about how to more effectively sequester carbon, reduce greenhouse gas emissions (i.e. Project Drawdown and Trillion Trees Initiative) and adapt to changes already occurring, agroforestry systems, including windbreaks, are being recognized as an effective and strategic approach. This is due to agroforestry's co-benefits; while it enhances climate change resiliency and mitigation, it also increases agricultural production and diversification (Frischmann et al., 2020; Schoeneberger et al., 2017). This multifunctionality is critical for producers looking for more resilient and productive agricultural systems now and into the future, especially in regions where wind erosion and wind-related crop losses are already a problem and are expected to become more severe. For example, projected trends in plant community shifts due to warming and drying have the potential to significantly increase the susceptibility of soils to wind and water erosion across the western U.S. (Edwards et al., 2019). This has important financial implications that will likely increase wind-related crop damage indemnity payments in the U.S, which amounted to $2.3 billion from 1989 to 2018 (AgRisk Viewer, 2020) (Fig. 1).

Though the benefits of windbreaks are numerous, few studies have explored the degree to which producers value these benefits. Furthermore, even fewer studies have focused on those producers who actually have windbreaks on their land, including investigations of the challenges and costs of establishing or managing existing windbreaks and whether producers are satisfied with their systems. For producers to more effectively assess the utility of windbreaks, a more complete picture of the benefits, costs, and management requirements, as perceived by those with windbreak experience, needs to be provided. This is especially true given that producers are more likely to adopt a new farming practice if their peers have done so successfully (Fregene, 2007; Rogers, 1995) or the information about the practice originated from producers themselves (i.e. farmer-to-farmer knowledge transfer) (Garbach and Long, 2017; Prokopy et al., 2008). Obtaining information from producers using windbreaks is of critical importance to understand the drivers that lead to windbreak establishment and retention, as well as windbreak removal.

While individual studies of windbreak adoption are of great value, they are usually limited by geographic region and sample size, making it

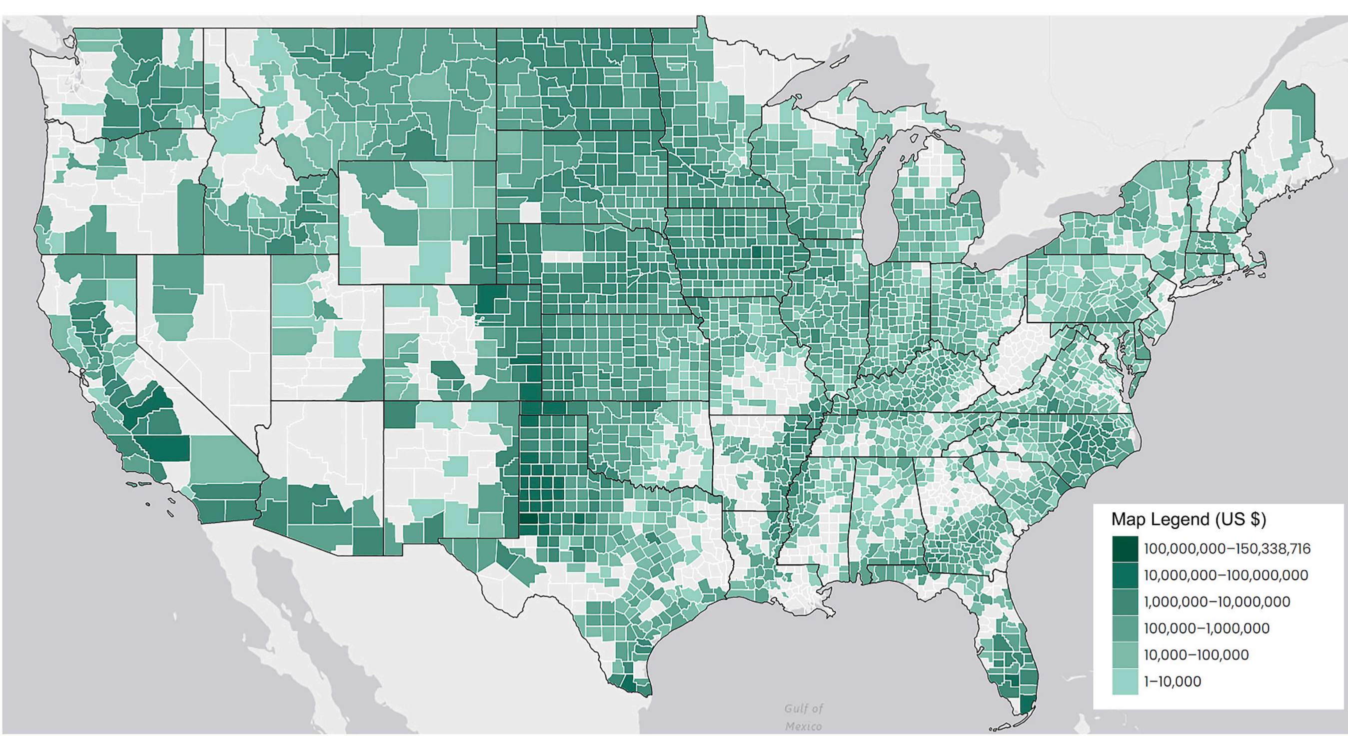

Fig. 1. USDA Risk Management Agency payment indemnities for crop damage from wind by U.S. counties (1989 to 2018).

difficult to assess whether broader trends exist that may affect future adoption, research, extension delivery and policy development. Instead, a systematic review is warranted. To date, there has been no systematic review of windbreak adoption in the U.S. that would allow for an analysis of these broader trends. As such, this study will synthesize the U.S. windbreak adoption literature with the goal of aggregating the benefits and challenges being reported by agricultural stakeholders and to identify whether predictive drivers of adoption exist. To achieve this, we raise the following research questions:

1. What are the primary benefits and challenges being reported by U.S. agricultural producers using windbreaks?
2. Are these producers satisfied with their windbreak plantings and are they retaining them?
3. What windbreak maintenance and management activities are producers reporting?
4. What are the primary drivers affecting willingness or intent to adopt windbreaks in the U.S and how do these drivers vary by windbreak type?

Through this synthesis, our goal is to provide general guidance on how to more effectively communicate with producers and guide future research, policy and program development related to windbreak use. Ultimately, we hope this leads to an increase in windbreak utilization on farms where it makes the most economic, environmental and socio-cultural sense.

2. Methods

2.1. Eligibility criteria and study selection

The PRISMA methodology for systematic reviews was followed for this study (Moher et al., 2015). The review included all U.S-based studies providing quantitative and qualitative information obtained from producers, natural resource professionals and other stakeholders on windbreak use, perceptions and drivers of adoption. A comprehensive search for relevant studies was conducted using Web of Science, Scopus, AGRIS, ProQuest, and CAB Direct. We also examined the first 100 results from Google Scholar per search term. The literature search was completed in October 2019, and repeated May 2020 for recently published articles. For each database, studies were filtered to include only those conducted in the U.S. and published in English. No time range, or other exclusionary terms were selected. The search terms included various ways windbreaks are described (i.e. windbreak, shelterbelt, hedgerow, vegetative environmental buffer, timberbelt, and living snow fence) and the more general term, agroforestry. These keywords were also paired with survey research terms (questionnaire, focus group, interview, adoption, and survey). Studies, which included both peer reviewed and grey literature, were then selected for inclusion through a three-step process: 1) screen each title, abstract and set of keywords ($N = 1878$), 2) full text read of potentially relevant articles ($N = 96$), and 3) analysis of references from included studies.

Most of the studies that were excluded during Step 2 involved U.S. agroforestry survey studies that included windbreaks but combined data from other agroforestry practices and/or reported only whether producers were aware or interested in the practice in general. A handful of conservation-related studies were also removed because they pooled opinions of producers with treeless conservation practices into their data analysis.

2.2. Data analysis

Quantitative data from each study were collected and initially summarized in Microsoft Excel. An effort was made to assess whether a meta-analysis was feasible. However, due to the variability in the studies, a meta-analysis was not possible without violating the fundamental rules guiding that type of analysis (Borenstein et al., 2009). Instead, the less quantitative method of vote-counting was used for the analysis of windbreak benefits and concerns as drivers of adoption. The methodology involved coding three possible outcomes of the effect of an independent variable (perceived windbreak benefit and concern) on a dependent variable (adoption). The three outcomes were: positive significant, negative significant or no statistical relationship in either direction. For all other analyses, a comprehensive synthesis approach was deemed most appropriate.

Following initial data analysis, authors from several studies were contacted regarding data clarification or to request supplemental data. Through these data requests, new information was obtained for the following studies: Hand et al. (2019), Garbach and Long (2017), Simroth et al. (2017), Du et al. (2017), Tomczak (2009) and Workman et al. (2003).

2.3. Statistical analysis

Statistical analyses were conducted on three of the datasets described above (Hand et al., 2019; Tomczak, 2009; Workman et al., 2003). Statistics were also calculated from several studies that only presented descriptive results but provided enough data for expanded analyses (Ferrill, 1988; Dearmont et al., 1983). All statistical analyses were performed in IBM SPSS Statistics for Windows, Version 26 (IBM Corp., Armonk, N.Y., USA). More specifically, Pearson's chi-square with post-hoc Cramer's V was used to compare whether age was associated with past or future windbreak planting using data from Ferrill (1988) and whether time period was associated with windbreak presence or removal in Tomczak (2009) and Dearmont et al. (1983). Mann-Whitney *U* Tests were also used to compare windbreak adopters to non-adopters in Hand et al. (2019) for farming status, hectares farmed, age, years farming, level of education, percent of household gross income from off-farm sources, and in Tomczak (2009) for value of windbreaks, and in Workman et al. (2003) for windbreak retention, age, farm size, years farming, and hours farmed per week. All statistical tests used a level of significance of $p < 0.05$.

3. Results and discussion

3.1. Summary of windbreak studies

The earliest study in this synthesis is from 1949, with the most current being 2019. In total, 32 windbreak studies were included in this synthesis, with 25 providing practice-specific information from producers with windbreaks, 11 covering drivers of adoption, and 7 studies focusing on pre-adoption willingness to participate, pay or accept (Table 2).

The location of the producer respondents for this review was concentrated in the Midwest, Rocky Mountain, and Southeast regions of the U.S. (Fig. 2). The higher density of producer responses from the Midwest region is not surprising, given that the region has higher annual average wind speeds when compared to the rest of the U.S. (National Renewable Energy Laboratory (NREL), 2020). An attempt was also made to correspond survey responses with producer windbreak inventory data. However, no national inventory of windbreaks exists in the U.S. The closest data source would be state-level windbreak establishment and/or renovation through cost-share programs like USDA's Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP). However, these datasets provide an incomplete windbreak inventory, as they only represent producers establishing windbreaks through these programs. The lack of producer inventory data on windbreaks represents a tremendous gap in our understanding of how prevalent windbreaks are across the landscape.

Table 2
Summary of U.S. studies addressing behaviors, attitudes, perceptions, and intentions regarding windbreaks ($N = 32$).

Authors	State	Sample size	Respondents	Study description
Burlison et al., 1975	ID	203	Farmers	A vegetation and ethnographic survey to assess performance of windbreak tree plantings.
Cable and Cook, 1997	KS	1738	Farmers	Interviews of farmers to assess the extent of windbreak planting, removal and maintenance activities. Also assessed farmers' beliefs about windbreaks.
Cook and Cable, 1990	KS	957	Hunters	A willingness to pay study on the opportunity to hunt in windbreaks.
Cook and Cable, 1995	KS	180	Academics	A visual perception study of windbreaks' effect on scenic beauty.
Dearmont et al., 1983	NE	613	Farmers (550) NRPs (63)[a]	A survey to assess perceptions regarding windbreaks, inventory existing windbreaks, and to understand reasons for removal and establishment.
Demchik, 2001	MN	107	Farmers (86) Extension (9) Academics (12)	A survey of farmers to assess their interest and programming needs in agroforestry and a survey to extension educators and professors to ask their impression of farmer interest and barriers to product production.
Dorr, 2006	MO	603	Farmers (364) NOLs[b] (239)	Survey of farmers and non-operator landowners to assess their attitudes and structural characteristics that affect their interest in different agroforestry practices.
Du et al., 2017	23 Northern States	39	State DOT[c]	Survey of northern state DOT staff to assess whether they use living snow fences for drifting snow. States included: AK, CT, IA, IL, IN, KS, KY, MD, MI, MN, MT, ND, NH, NJ, NY, OH, PA, UT, VT, WA, WI, WV, WY.
Erickson and Young, 1992	MI	41	Farmers	Survey of centennial farmers (operated by same family for 100+ years) to assess attitudes about woodlots and windbreaks.
Erickson et al., 2002	MI	112	Farmers (65) Landowners (47)	Survey of non-industrial private forest landowners to assess their motivations for retaining and protecting woodlots, including windbreaks.
Ferber et al., 1955	SD	331	Farmers	Interviews of farmers to assess crop yield response of field windbreaks and overall satisfaction of plantings.
Ferrill, 1988	NE	163	Landowners	A survey of landowners to assess their reasons for and against planting trees, which included windbreaks.
Garbach and Long, 2017	CA	109	Farmers	A survey of farmers to determine the drivers of adoption of field edge plantings, which included windbreaks.
Grala et al., 2008	IA	45	Farmers	Focus group of farmers to assess interest and opportunities for fee hunting in/adjacent to windbreaks.
Grala et al., 2010	IA	1374	Farmers (576) Landowners (798)	A survey to examine the impact of field windbreaks on visual appearance of agricultural land and assess respondents' perceptions of windbreak benefits.
Grala et al., 2012	IA	1374	Farmers (576) Landowners (798)	A survey to assess the monetary value of aesthetics associated with windbreaks.
Hand and Tyndall, 2018	ND, SD, NE, KS	35	Farmers	A survey of operators managing agriculturally marginal farmland to assess the potential for biomass-based bioenergy.
Hand et al., 2019	ND, SD, NE, KS	454	Farmers	Focus group of operators managing agriculturally marginal farmland to assess the potential for biomass-based bioenergy.
Isaacson, 1999	NE	179	NRPs[a]	A survey of natural resource professionals (NRCS and U.S. Forest Service) regarding how communication strategies affect landowner adoption of windbreaks.
Laughlin, 1989	MT, ND	896	Farmers (815) Landowners (91)	Survey of farmers/landowners to create a database on the relationship between windbreak species performance and management practices and/or environmental condition.
Lorimor and Kliebenstein, 2004	IA	562	Farmers	Survey of pork producers to establish baseline information about odor control technologies, which included windbreaks.
Peterson and Vaske, 2017	CO	416	Landowners	Survey of landowners' approval for various forest management practices, including windbreaks.
Reynolds, 1983	MN, ND	200	Farmers	Survey of farmers to assess their perceptions of shelterbelts.
Simroth et al., 2017	TX, OK, NM, CO, KS, NE	43	Farmers	Survey to obtain general feedlot information, including use of windbreaks for livestock protection.
Stoeckeler and Williams, 1949	SD, NE	508	Farmers	Survey of farmers with windbreaks to estimate how much value they place on them as a management practice.
Sullivan et al., 2004	IL	470	Farmers (94) Academics (194) Landowners (182)	Photo questionnaire of farmers, residents and academics to assess approval of different types of buffer conditions for six buffers types.
Teel and Lassoie, 1991	NY	334	Farmers	Survey of dairy farmers to assess the type of woodland management and agroforestry practices used on site.
Tomczak, 2009	NE	420	Farmers	A follow-up survey to Dearmont et al. (1983) to see if perceptions of field windbreaks and use has changed over time.
Tuskan and Laughlin, 1991	MT, ND	896	Farmers (815) Landowners (91)	Survey of farmers/landowners to create a database on the relationship between windbreak species performance and management practices and/or environmental condition.
Tyndall, 2009	IA	410	Farmers	A willingness to pay study of pork producers on using shelterbelts.
Workman et al., 2003	AL, GA, FL	1039	Landowners (742) Extension (297)	Survey of agricultural and natural resource extension agents and foresters in AL, GA, and FL to gain insights into the perceived benefits and concerns of agroforestry.
Wyatt et al., 2012	MN	205	Farmers (45) NRPs[a] (160)	Focus groups of farmers and an online survey of natural resource professionals to assess the barriers of improving adoption of living snow fences.

[a] NRP = Natural Resource Professionals.
[b] NOL = Non-operator landowners.
[c] DOT = Department of Transportation.

3.2. Windbreak benefits, challenges and management considerations

3.2.1. Producer-reported windbreak benefits

The benefits of windbreaks as reported by producers are numerous. Windbreaks can be organized into broad functional categories that include field, livestock and farmstead. While some beneficial attributes are shared between these three broad windbreak types, such as wildlife habitat and soil and water conservation, their design and primary function vary. For field windbreaks, producers have reported the following benefits: wind protection, crop protection, yield improvement, wildlife habitat, aesthetics, privacy, recreation, soil and water conservation, income generation from wood products and non-timber forest products (NTFPs), increased property value, carbon storage, and snow control (Hand et al., 2019; Hand and Tyndall, 2018; Wyatt et al., 2012; Tomczak, 2009; Laughlin, 1989; Dearmont et al., 1983; Burlison et al., 1975) (Fig. 3). Regarding the benefit of enhancing crop production, Tomczak (2009)(b) found that 62% of surveyed farmers in Nebraska reported increased yields due to their field windbreaks, while 9% indicated no effect and 28% reported some yield decrease. An earlier study in the same region by Dearmont et al. (1983) reported a similar finding with 63% believing there to be a yield increase, 21% no yield effect and 15% reporting a yield decrease. In contrast to farmers in Nebraska, a survey of farmers in South Dakota found that 88% reported crop yield gains associated with their field windbreak plantings, with 12% reporting no gain and < 1% reporting a yield decrease (Ferber et al., 1955).

Of the producer-reported benefits, crop yield improvement from field windbreaks is one of the more extensively reported functions in the biophysical research literature (Osorio et al., 2018; Baldwin, 1988; Kort, 1988; Norton, 1988). For example, Osorio et al. (2018), used combine harvester data from producers to assess yield response of winter wheat (*Triticum aestivum* L.) and soybean (*Glycine* max L.) adjacent to windbreaks. Both winter wheat and soybean production increased significantly when protected by windbreaks, with average yield gains of 10% and 16%, respectively (Osorio et al., 2018).

Similar to field windbreaks, producers with livestock windbreaks utilize the altered microclimate for a suite of beneficial functions that include: livestock protection, yield improvement, extended forage opportunities, odor management, livestock fencing, visual screening, public relations and aesthetics (Hand and Tyndall, 2018; Simroth et al., 2017; Tyndall, 2009; Lorimor and Kliebenstein, 2004; Cable and Cook, 1997; Teel and Lassoie, 1991; Burlison et al., 1975; Stoeckeler and Williams, 1949) (Fig. 4). Producers have also reported benefits associated with snow management, where livestock windbreaks are used to reduce snow drifts in the feed yard, saving both time and fuel associated with snow removal (United States Department of Agriculture (USDA), 1997).

Regarding livestock protection, Simroth et al. (2017) found that 43% of feedlot managers in the High Plains region of the U.S. (TX, OK, NM, CO, KS, NE) were using some form of protection around finishing pens to mitigate the harmful effects of cold winds on cattle performance. Of those using wind protection, 50% were using windbreaks (D. Thompson, Personal Communication, February 29, 2020). Cable and Cook (1997) reported similar findings for producers in Kansas, with 59% of respondents citing livestock protection as one of the primary functions of their windbreaks. The ability of livestock windbreaks to increase animal welfare and yield improvement have also been verified in several research studies. More specifically, Anderson and Bird (1993) reported that cattle fed in pens adjacent to windbreaks gained 0.11 kg more per day during the winter months when compared to a control group. Brandle et al. (2004) also reported increased survival and milk production of livestock that were protected by windbreaks during winter storms.

In addition to improving livestock performance, producers have also reported using a hybrid type of windbreak that some call a vegetative environmental buffer (VEB) for use in odor and dust mitigation. A study of Iowa pork producers by Tyndall (2009) found that 21% of the respondents were using windbreaks specifically for odor management, with a majority of the operations being in the largest size class (> 5000 head). Furthermore, 66% of respondents without windbreaks indicated interest in planting trees for use in odor mitigation. The odor removal capacity of windbreaks has also been documented in the biophysical literature. For instance, Parker et al. (2012) reported that strategically placed trees and shrubs outside of swine barns in Missouri could reduce odor concentrations by 49% directly adjacent to the VEB and 66% at a distance 15 m downwind. Hernandez et al. (2012) reported similar findings, with odorous gas emissions being reduced by 40–60% immediately following a shelterbelt for a swine facility in Iowa.

As with field and livestock windbreaks, the microclimate modifications from farmstead windbreaks have their own suite of beneficial functions (Fig. 5). However, while farmstead windbreaks are the most common type of windbreak, they are also the least studied from both a social science and biophysical perspective. Among the studies in this review, only Laughlin (1989) had a separate analysis describing producer-reported benefits of farmstead windbreaks, which included: wind protection/enhanced working environment, shade, aesthetics, energy savings, snow control, increased property value, noise control, and wildlife habitat. Regarding increased property values, Laughlin (1989) found that 94% of farmer respondents believed that farmstead windbreaks increased farmland value. An analysis by Dewalle and Heisler (1988) investigated home energy conservation and found that farmstead windbreaks reduce energy costs by 10–25% for farm or ranch homes in the northern portions of the U.S. and Canada. These findings were similar to a report by National Association of RC&D Councils (NARC and DC) Report: RC&D Survey of Agroforestry Practices (2000) with energy savings of 15–25%.

While numerous studies have investigated producer-reported benefits of windbreaks, few have addressed how those benefits rank in comparison to one another. The difference between benefits in general and a ranking of benefits is an important distinction to make, especially when presenting information to natural resource professionals and producers. A prime example of this difference was described in Cable and Cook (1997), who reported that wildlife habitat improvement was the most commonly selected response from a list of reasons for why producers have windbreaks, with 65% of producers selecting that option. However, when asked to rank their top reasons for having windbreaks, the protection of livestock and reducing wind damage to crops were the highest ranked options, with wildlife habitat improvement falling to the lowest ranked option (Table 3). This information has important implications for windbreak outreach, implementation, and design. For instance, if outreach is focused on wildlife habitat improvement, which may be an incidental benefit to many producers, it may not be effective in encouraging future windbreak plantings if producers are more interested in other windbreak functions.

While ranking various windbreak functions may provide more insight, the way these ranked questions are often structured in surveys makes it difficult to synthesize the information. Of the studies ranking windbreak functions, only Tyndall (2009) asked open-ended questions regarding windbreak benefits, with the remaining studies providing the respondents with a list of functions to be ranked (Table 3). This characteristic of most surveys is not a critique of their methodology, but it makes it challenging to assess broad trends, given that the set of functions to be ranked are predetermined by the researcher and varies between studies. Further complicating data synthesis is the fact that windbreaks can be organized into three primary groupings (field, livestock and farmstead), with each having a different set of functions. However, given this variability, some trends do become apparent when synthesizing the data.

1. Indirect economic benefits from agriculture, such as soil erosion control, livestock protection, wind protection and snow control tend to be the most highly ranked benefits across all windbreak types.

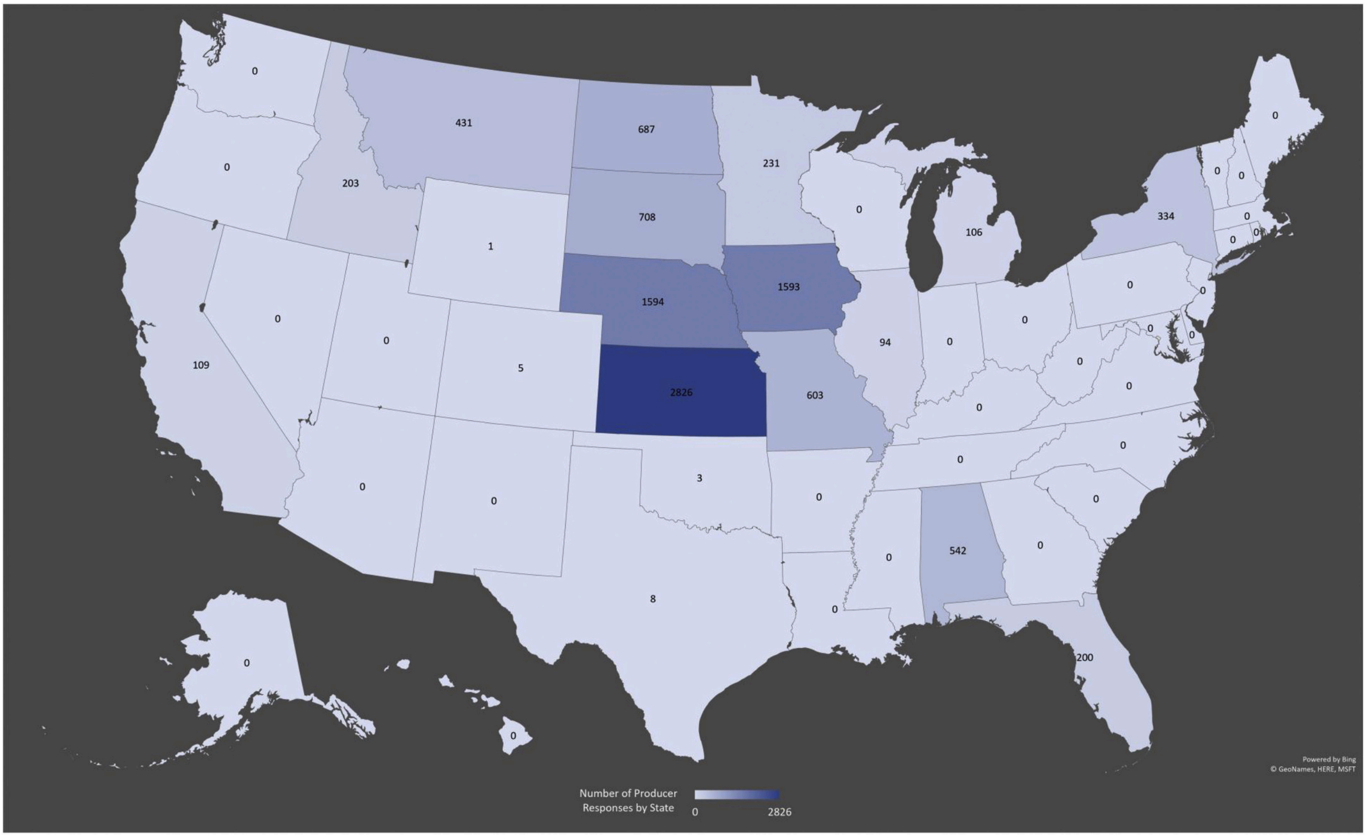

Fig. 2. Producer responses by state for all studies included in review. States with darker shading indicate a greater concentration of surveyed respondents.

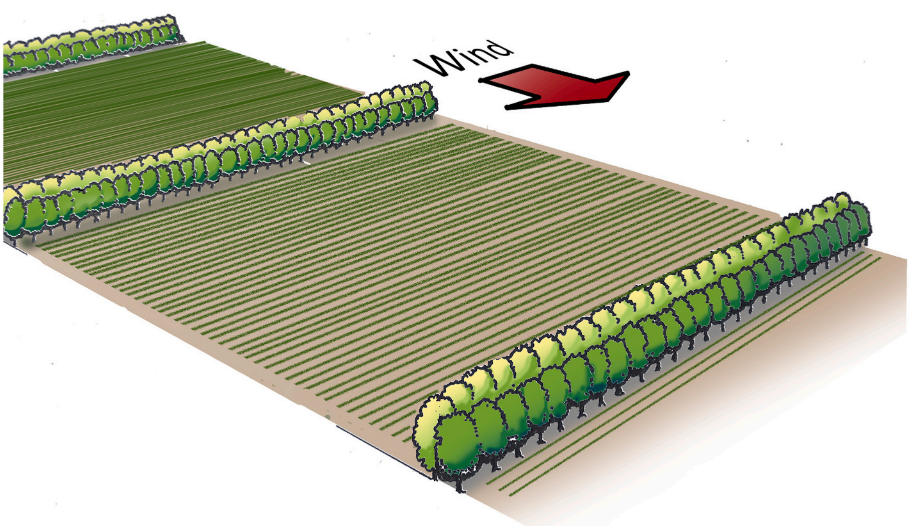

Fig. 3. Conceptual diagram of a field windbreak. Field windbreaks commonly have one to three rows of trees and/or shrubs, due to balancing yield benefits and land out of crop production. On the leeward side, the protected zone generally extends eight to ten times the height of the windbreak. By modifying the microclimate, windbreaks can increase crop yields from 6 to 56% depending on crop type (Baldwin, 1988; Kort, 1988; Norton, 1988).

2. Direct economic benefits from agriculture (increased crop yield, increased livestock production, and increased property value) and intrinsic benefits (aesthetics and wildlife habitat) are the next tier of highest ranked functions across windbreak types.
3. Direct economic benefits from forestry (wood products and non-timber forest products) are often the lowest ranked tier of benefits reported by windbreak adopters.

Of the various functions provided by windbreaks, wood products and NTFPs were ranked low when compared to other windbreak functions. A likely explanation for the low ranking of wood products is that the land area in trees is small compared to the area they influence, and the prospect of large volume removal is unlikely unless entire windbreaks are being removed. Single tree removal may also reduce the functionality of the windbreak, unless the windbreak was multiple rows of trees and harvest was conducted strategically to prevent gaps or damage to

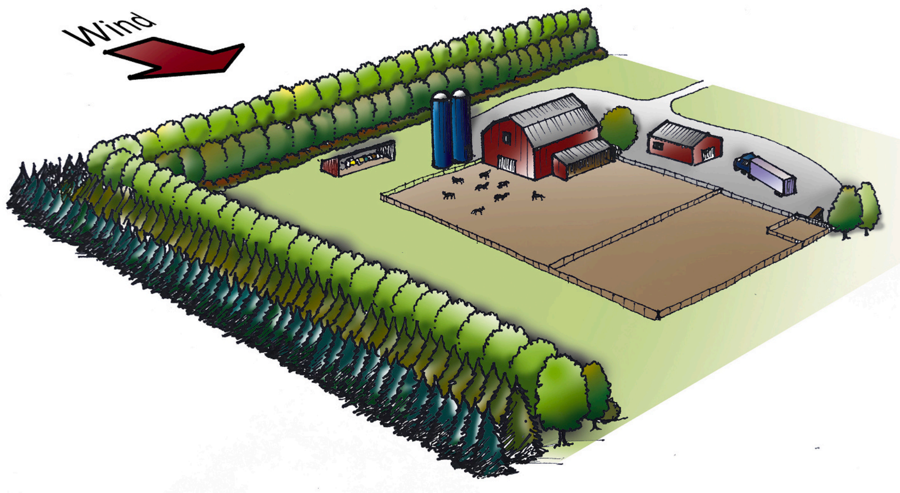

Fig. 4. Conceptual diagram of a livestock windbreak. Livestock windbreaks generally include five or more rows of trees and shrubs with several rows consisting of evergreen species. Livestock windbreaks can be planted in many configurations from L-shape to U-shape to semi-circular.

adjacent trees. The cost of single tree removal may also be cost-prohibitive if the producer is not logging themselves and machinery needs to be brought onsite. Hence, direct economic benefits from harvesting trees for timber, firewood, pulpwood, etc. are not as great as the other functions the trees serve as part of a larger agroecosystem.

In the context of harvesting NTFPs, two of the more common financial incentive programs in the U.S. used by producers for windbreak establishment, the Conservation Reserve Program (CRP) and the Conservation Reserve Enhancement Program (CREP), have restrictions on harvesting products during the contract period. In addition to limiting the ability to harvest during the contract period, these restrictions may also affect the type of tree and shrub species planted initially by discouraging species suited for harvesting fruit, nuts, or other NTFPs.

While direct economic benefits from forestry are not a highly ranked benefit of windbreak use, several studies have shown that most producers do harvest and utilize the trees in their windbreaks for some income generation. For instance, Demchik (2001) reported that 68% of windbreak adopters in Minnesota generated products from the trees in their windbreaks. The most popular forest-related product streams were firewood (90%), timber (70%), pulpwood (46%), fruits (19%), nuts (6%), medicinal herbs (3%), and maple syrup (3%). Laughlin (1989) reported similar findings for producers with windbreaks in Montana and North Dakota, with 60% of respondents using their windbreaks for direct revenue generation, which included habitat for game production, timber, firewood, fruit and nut production, and Christmas trees. However, the low ranking by producers for direct economic benefits from forest products across studies in this review suggests that this form of income generation is likely a small part of their overall business. Unfortunately, none of the studies in this review discussed how much revenue came from windbreak tree-related products, representing an area of great research need.

3.2.2. *Producer-reported windbreak challenges and reasons for windbreak removal*

The body of literature describing producer-reported challenges of managing windbreaks is small, with few survey studies addressing the fundamental questions relating to windbreak establishment and/or maintenance. To date, Burlison et al. (1975) and Laughlin (1989) are the most comprehensive studies addressing this topic for U.S. producers. In

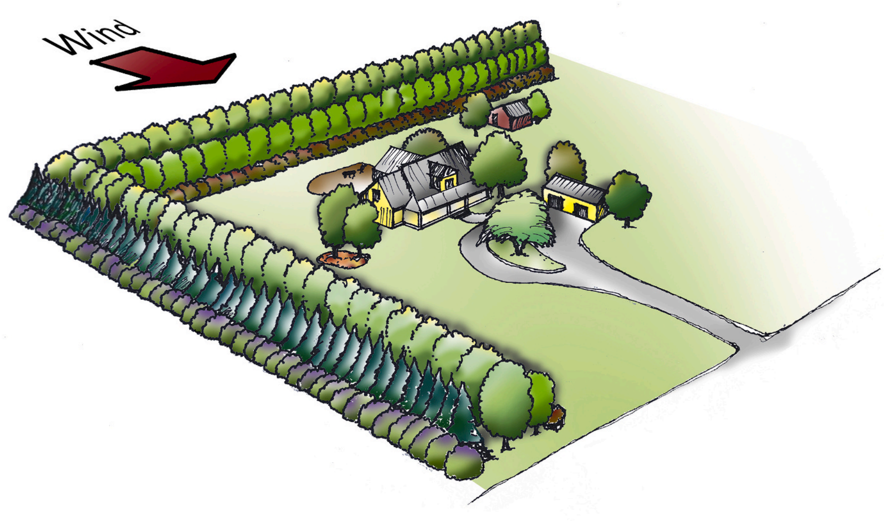

Fig. 5. Conceptual diagram of a farmstead windbreak. Farmstead windbreaks usually consist of four or more rows of trees and shrubs, often planted in a L-shape or arc. Annual energy savings for home heating using windbreaks can be up to 10–25% in the northern portions of the U.S. (Dewalle and Heisler, 1988).

Burlison et al. (1975), an ethnographic survey of Idaho producers was paired with a vegetative survey, allowing for comparison between producer-reported windbreak challenges to the actual health and vigor of the trees growing on their sites. The greatest challenges reported by producers were related to how to care for their plantings (weed control, irrigation, and protection), how to properly plant the trees and identifying which tree species were most suitable for their site. The authors reported that these challenges were apparent when examining producers' windbreaks, with 25% being in poor condition. Furthermore, they found that producers were reporting issues with herbicides originating from weed control around the trees in the windbreaks and from herbicide drift from adjacent crop fields. Together, both herbicide sources were responsible for 11% of the planting failures or poor performance. These findings were similar to those described in Laughlin (1989), in which producers reported challenges related to how to best care for trees following planting, how to minimize herbicide and weather damage, and how to best control for weeds.

For some producers, the benefits of windbreaks may not outweigh the costs, resulting in windbreak removal. Table 4 synthesizes some of the primary reasons for windbreak removal, with the most common reasons being: 1) poor condition, 2) age, 3) conflict with irrigation, farm machinery or farming practices, and 4) crop competition.

While poor condition and age are related because tree mortality causes gaps in the windbreak, Schaefer et al. (1987) found that poor condition was most related to weed control during the early years of windbreak establishment. Without such maintenance, trees struggled in a continual state of poor condition. The issue of windbreak removal due to poor condition and age has also been reported in vegetative survey studies (Burlison et al., 1975) and geospatial analyses looking at windbreaks across the landscape (Karle and Carman, 2020; Burke et al., 2019; David and Rhyner, 1999).

In addition to condition and age, producers reported windbreak removal due to conflicts from the adoption of new farming practices, with center pivot irrigation being one of the primary drivers (Table 4). Geospatial studies have also confirmed this removal pathway (Kellerman et al., 2017; Baltensperger, 1987), with both edge-of-field and within-field windbreaks being affected (Fig. 6).

In some cases, producers also reported windbreak removal due to the implementation of other conservation methods. Hand and Tyndall (2018) reported that some farmers in their survey did not feel that windbreaks were necessary anymore because they were using reduced tillage or no-till practices. An earlier study by Reynolds (1983) reported similar results, with younger farmers relying more heavily on annual conservation measures like cover crops. Interestingly, the older farmers in this study who lived through the Dust Bowl believed that windbreaks should be a permanent conservation feature, illustrating how a devastating agricultural event can shape one's opinion about windbreaks.

Another primary reason producers reported removing their windbreaks was due to crop competition. Trees and shrubs grown in windbreaks will compete for resources and inhibit the growth of crops if grown too close together. However, if using appropriate spacing, studies have found that there is a net benefit in yield for many crops, even when considering the loss of arable land in the windbreak and the reduced yield directly adjacent to the trees (Osorio et al., 2018; Kort, 1988). Despite these findings, field windbreaks often suffer from observability. If producers cannot see increases in yield directly, they may not believe there to be a benefit. This is especially true for producers who have always had windbreaks and may not have a baseline in which to make yield comparisons. Furthermore, the loss in yield directly adjacent to the windbreak is much more visually apparent than the boost in crop yield across the rest of the field that is protected.

3.2.3. *Producer satisfaction and windbreak retention*

Though windbreak removal occurs, the overall satisfaction reported by producers is highly positive, especially for studies focusing specifically on field windbreaks (Table 5).

Table 3
Top ranked producer-reported benefits of having field, farmstead and livestock windbreaks.

		Importance Ranking										
Authors	Type of Windbreak	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Laughlin, 1989	Field	Soil Erosion Control	Wind Protection	Snow Control	Crop Protection	Wildlife Habitat	Aesthetics	Increase Crop Yield	Livestock Protection	Increase Property Value	Improve Water-Use Efficiency	Wood Products
Dearmont et al., 1983	Field	Soil Erosion Control	Livestock Protection	Snow Control	Increase Crop Yield	Aesthetics	Wildlife Habitat	Wood Products				
Tomczak, 2009(b)	Field	Soil Erosion Control	Livestock Protection	Snow Control	Other	Wildlife Habitat	Increase Property Value	Wood Products	Increase Crop Yield	Aesthetics		
Laughlin, 1989	Farmstead	Aesthetics	Wind Protection	Snow Control	Energy Savings	Increases property Value	Livestock Protection	Wildlife Habitat	Soil Erosion Control	Noise Control	Improves Water-Use Efficiency	Wood Products
Tyndall, 2009	Livestock	Odor Reduction	Visual Screening	Aesthetics	Energy Savings							
Hand et al. (2019)(b)	Farmstead Field Livestock	Wind Protection	Livestock & Crop Protection	Aesthetics	Privacy	Hunting, Fishing, Recreation	Enhance Water Quality	Enhance Soil Quality	Carbon Storage	Wood Products	Non-Timber Forest Products	
Workman et al., 2003 (b)	Farmstead Field Livestock	Soil Erosion Control	Aesthetics	Long-Term Return	Wildlife Habitat	Shade	Enhance Water Quality	Increase Biodiversity	Increase Property Value	Improves Farm Interest	Increase Financial Security	Enhance Water Quantity
Cable and Cook, 1997	Farmstead Field Livestock	Livestock Protection	Crop Protection	Soil Erosion Control	Wildlife Habitat							

While the studies in Table 5 point to a high level of satisfaction and retention of windbreaks by producers, they also represent snapshots in time when the studies were conducted. Of the windbreak studies in this synthesis, only Tomczak (2009) studied windbreak use over time, using the same sample population. In this study, a questionnaire was sent to the same sample population of farmers in eastern Nebraska as reported in Dearmont et al. (1983). One of the major findings reported in this study, which our team verified with post-hoc statistics, was that use of all types of windbreaks increased significantly between 1983 and 2009, with use of field windbreaks increasing from 27% to 40% ($p = 0.000$), livestock windbreaks increasing from 57% to 68% ($p = 0.001$), and farmstead windbreaks increasing from 86% to 95% ($p = 0.000$) (Tomczak, 2009(b)). The increase in use among this sample population of farmers suggests that, as a group, they were satisfied with their windbreaks and planted more of them.

3.2.4. Windbreak management and maintenance activities

Though guidance exists on management practices recommended for windbreak establishment and maintenance (Strine, 2005; Wilson and Josiah, 2004; Finch, 1988; Dronen, 1988), few studies have investigated what activities producers actually carry out, how successful they are, or the time requirements associated with those activities. Of the 32 U.S. windbreak survey studies we synthesized, only four addressed these topics in depth. In Tomczak (2009)(b), only 22% of the surveyed farmers with windbreaks had conducted windbreak maintenance in the past 10 years. Of those conducting maintenance, the primary activities being reported were removing dead and diseased trees (68%), tree trimming and thinning (61%), replanting trees (39%), fencing (18%), and spraying for tree pests (14%). In contrast to the low rate of windbreak maintenance in Tomczak (2009), Cable and Cook (1997) reported that 80% of farmers in Kansas were conducting some form of management and maintenance. The primary activities were fencing out livestock (44%), weed control (29%), pruning of branches (28%) and replanting to fill gaps (27%). Farmers also cited that limited time was the greatest constraint preventing further windbreak maintenance. A study of Montana and North Dakota farmers by Tuskan and Laughlin (1991) reported that 51% of producers used weed control, 16% used insect control, 10% used fertilizers, less than 1% irrigated during windbreak establishment, and less than 5% used root dip during windbreak establishment. The average time commitment for these management activities was 31.5 h/year (Laughlin, 1989).

The most comprehensive study of producer-reported windbreak maintenance and management activities was detailed in Burlison et al. (1975). What makes this study unique is that it compared producer-reported management activities with the actual performance of the windbreaks on site. The authors reported that recommended management and maintenance activities for tree care in windbreaks were not being followed by producers. More specifically, they found that 90% of respondents did not follow recommended windbreak tree spacing requirements, while 94% did not follow site preparation guidelines involving cultivation, irrigation, and weed control. Consequently, 25% of the surveyed windbreaks were in poor vigor and 50% were too close to the crops they were supposed to protect. The authors also reported that 75% of the planting failures they encountered could have been prevented and were controllable by the landowner (Burlison et al., 1975). Interestingly, 75% of the farmers surveyed said they wished that they had used more assistance from extension agents. These findings are similar to Laughlin (1989), who reported that only 6% of respondents reported attending a windbreak education program, yet 98% of respondents desired more windbreak education. These studies suggest that producers are interested in windbreak assistance and information, but possibly do not have the time and flexibility to coordinate assistance and/or attend training events. Furthermore, there may also be a disconnect between recommended management and maintenance practices to what is occurring on the ground. The lack of information on this topic is an area of both research and extension need if windbreak adoption is to increase and tree plantings are to be successful into the future.

3.3. Drivers effecting windbreak adoption

While many of the windbreak studies investigated beliefs, attitudes, and management actions by producers and landowners, few studies were structured to assess the effect of these variables on actual adoption of windbreaks, and fewer yet had consistent variables to allow for comparisons. We provide a summary of key results from these studies, which may offer direction for tailoring windbreak assistance and outreach efforts.

3.3.1. Capacity

In some cases, age has been shown to be negatively associated with adoption of agricultural conservation practices (Prokopy et al., 2008; Prokopy et al., 2019) and the windbreak studies generally supported this observation. Adopters in Alabama, Florida, and Georgia were significantly younger (average age of 58) than non-adopters (average age of 66 years) ($p = 0.000$) Workman et al., (2003)(b). Ferrill (1988)(b) found similar results, with the youngest age group (20–44 years) planting a larger percentage of windbreaks in York County, Nebraska. Dorr (2006) also found age to be negatively associated with windbreak adoption for producers in Missouri ($p = 0.024$). In contrast, age was not significant between windbreak adopters (58 years) and non-adopters (58 years) in the Northern Great Plains region ($p = 0.707$) (Hand et al., 2019).

While availability of information on windbreaks, including producer access, use, and information type, is hypothesized to enhance adoption, few studies have investigated the actual impact. Laughlin (1989) found that Montana and North Dakota landowners with prior windbreak education placed greater value on windbreaks and had higher adoption. Garbach and Long (2017) evaluated the role of information sources on the adoption of windbreaks and hedgerows by producers in California. Adopters accessed information from more sources (7.08 ± 0.21) compared with non-adopters (4.49 ± 0.37) out of a list of nine possible choices ($p < 0.01$). Adopters rated personal observation and

Table 4
Reasons for Windbreak Removal in the United States.

	Rank							
Authors	1st	2nd	3rd	4th	5th	6th	7th	8th
Dearmont et al., 1983	Conflict with Irrigation	Age and Poor Condition	Conflict with Farming Practices	Crop Competition	Field Consolidation	Snow Drift Issues	Preparing Site for New Windbreaks	No Value in Windbreaks
Laughlin, 1989	Poor Condition	Age	Conflict with Equipment	Gain Acreage	Crop Competition	Snow Drift Issues	Field Consolidation	Conflict with Irrigation
Cable and Cook, 1997	Gain Acreage	Crop Competition	Conflict with Irrigation	Conflict with Equipment				
Tomczak, 2009(b)	Conflict with Farming Practices	Age and Condition	Conflict with Irrigation	Crop Competition	No Value in Windbreaks	Field Consolidation	Preparing Site for New Windbreaks	Other

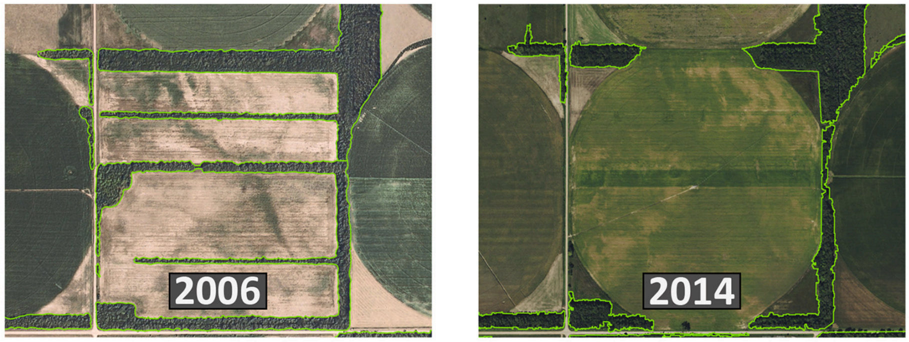

Fig. 6. Windbreak removal associated with the installation of center pivot irrigation. Highlighted green indicates tree cover from the High-Resolution Land Cover of Nebraska (2014) dataset (Kellerman et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Producer satisfaction and retention of windbreaks in the U.S.

Authors	Type of Windbreak	Study Description
Hand et al. (2019)(b)	Farmstead Field Livestock	79% reported windbreaks to be useful or very useful
Tomczak, 2009(b)	Field	97% reported that their windbreaks have value as a soil conservation practice
Grala et al., 2008	Field	90% reported that windbreak benefits outweigh costs
Lorimor and Kliebenstein, 2004	Livestock	99% reported being satisfied or indifferent (< 1% unsatisfied)
Cable and Cook, 1997	Farmstead Field Livestock	90% reported being satisfied with windbreak performance
Tuskan and Laughlin, 1991	Field	88% reported that field windbreaks were meeting objectives
Tuskan and Laughlin, 1991	Farmstead	94% reported that their farmstead windbreaks were meeting objectives
Dearmont et al., 1983	Field	93% reported that their field windbreaks have value as a soil conservation practice
Burlison et al., 1975	Farmstead Field Livestock	72% reported being moderately to highly satisfied with their windbreaks
Ferber et al., 1955	Field	88% reported that their field windbreak increased crop yields

communication with other producers as the most useful source of information, suggesting the importance of peer-to-peer interactions.

Another type of capacity is support provided by natural resource professionals to landowners (Prokopy et al., 2019; Prokopy et al., 2008). Isaacson (1999) conducted a survey of technical service providers to see how their attitudes and communication strategies affected landowner adoption of windbreaks in Nebraska. Technical service providers who used more methods to obtain information about windbreaks helped establish significantly more windbreaks than those using fewer modes of communication. This contributed to strength of attitude toward windbreaks by technical service providers, which also had a significant impact on the number of windbreaks they helped implement. As attitude became more favorable, the number of windbreaks they helped established increased, indicating the importance of communication efforts to natural resource professionals.

3.3.2. *Farm characteristics*

Prior research indicates that larger farm size can be associated with increased adoption of conservation practices Prokopy et al., 2008; Prokopy et al., 2019). This was the case for windbreaks in two studies investigating this variable. In the southeast U.S., Workman et al. (2003)(b) found that farmers with windbreaks were more likely to farm larger acreages (226 ha) than farmers without windbreaks (182 ha) ($p = 0.041$) and in the Northern Great Plains, Hand et al. (2019)(b) found windbreak adopters farmed significantly more land (923 ha) when compared to non-adopters (675 ha) (p = 0.024).

Land tenure is hypothesized to influence adoption of conservation practices and can be an important factor for many practices that require a longer establishment period before returning benefits like windbreaks (Raedeke et al., 2003; Soule et al., 2000). Reynolds (1983) found that adoption of windbreaks in the Red River Valley in the North Central U.S. was significantly reduced if the lands were rented, since both landlord and tenant did not want to plant windbreaks because they believed the money, time, and effort invested would benefit the other party. In contrast, a more recent study in the Northern Great Plains found that the number of hectares rented was not significantly different between windbreak adopters (465 ha) and non-adopters (417 ha) (p = 0.707) Hand et al., (2019)(b). This finding was also reported in a recent comprehensive review of conservation practices, where no consistent pattern of adoption was identified in relation to land tenure (Prokopy et al., 2019).

3.3.3. *Windbreak benefits and concerns*

Across studies, the most consistent area of investigation on drivers of adoption was centered on perceptions about windbreak benefits and concerns. Table 6 provides a vote-counting analysis, where the dependent variable was adoption of windbreaks by producers and the independent variables were perceived windbreak benefits and concerns. Based on these studies, increased windbreak usage was generally associated with farmers who valued soil conversation, aesthetics, and crop and livestock protection (Table 6). Some benefits associated with increased adoption were likely due to the regional context of the specific survey, which may also relate to wind risk and crop types. Garbach and Long (2017) found that adopters valued beneficial insects in the Sacramento Valley where vegetable crop production is high, while snow management was valued by adopters in Montana, North Dakota, and Minnesota (Wyatt et al., 2012; Laughlin, 1989) and fencing in pastures and marking boundaries between farms was most valued by producers in New York (Teel and Lassoie, 1991). Regional variation is important to note as it may be adapted for a local context.

While perceived benefits have been shown to increase windbreak use, perceived concerns are conversely associated with reduced adoption (Table 6). Fewer studies investigated concerns, but the common issues included interference with farming operations, maintenance, and lack of land. Other concerns focused on start-up costs and sources of weeds, pests/diseases, and nuisance wildlife. There was considerable variability in these results, suggesting the need for more research to better understand the impacts of concerns on windbreak adoption.

Table 6
Results of vote-counting meta-analysis where the dependent variable was windbreak adoption by producers and independent variables were perceived windbreak benefits and concerns.

Independent variable	Sig+	Insig	Sig−	Total
Perceived benefits				
Soil conservation	4	2	0	6
Aesthetics	4	1	0	5
Crop production	3	1	0	4
Livestock protection	3	0	1	4
Wildlife habitat	2	2	1	5
Snow management	2	0	0	2
Beneficial insects	1	0	0	1
Increase property value	1	0	0	1
Perceived concerns				
Interference with farming	2	0	1	3
Maintenance	2	1	1	4
Lack of land	2	1	1	4
Start-up costs	1	2	1	4
Nuisance wildlife	1	1	1	3
Source of weeds	1	0	0	1
Source of pests/diseases	1	0	0	1

3.4. Pre-adoption studies of willingness to participate, pay and accept

Pre-adoption studies can provide insight into the potential drivers and motivations behind decision making. When examined in conjunction with surveys of adopters, these studies also shed light on whether perceived benefits and challenges are being weighted fairly. This is important information for how natural resource professionals design and deliver programming. For instance, Garbach and Long (2017) reported that non-adopters were significantly more concerned about rodents and insects in their field edge plantings, which included hedgerows and windbreaks, than producers already using those systems. Tyndall (2009) reported a similar concern of windbreaks among non-adopters. However, multiple studies of producers with windbreaks have shown this perceived challenge to be of little concern (Table 4), illustrating how a potential barrier may be weighted too heavily and inhibit adoption.

In a willingness to participate study by Wyatt et al. (2012), farmers in Minnesota were asked about their interest in implementing living snow fences (LSF) on their property to control blowing snow across highways in the state. LSF are rows of trees or shrubs, often planted in cropland at some distance from the road, with the intended benefit of controlling snow and reducing road hazards. Farmers indicated that they would be more willing to participate in the program if there were more flexible contracts, adjustable payments, increased incentives and insurance against risk and liability, should an accident occur adjacent to their property. The study also reported that natural resource professionals felt the biggest factors that may enhance adoption are more time and funds to assist landowners and the need for department of transportation staff to work with landowners and conservation agency officials in each district (Wyatt et al., 2012).

Another important type of pre-adoption study relates to willingness to pay (WTP) or willingness to accept (WTA). Because some of the benefits of windbreaks are non-market, these studies can be used to provide a more complete picture of benefits and costs of windbreak establishment and maintenance. Furthermore, many of the benefits of windbreaks are also public goods, which extend beyond the farm. As such, there may be situations where the government or even the public may be willing to pay for these goods and services, with snow control, recreation, aesthetics, soil conservation and carbon storage being examples for windbreaks. For example, many of the windbreaks in the U.S. are established using USDA conservation programs, such as CRP or EQIP because of the public conservation benefits they create.

In a WTP study by Cook and Cable (1990) the economic benefits of recreational hunting in windbreaks was studied. Most hunters in Kansas (81.2%) hunted in or adjacent to windbreaks and were willing to pay $18 for a daytrip and $57 for an overnight trip to hunt at their favorite windbreak site. In total, this represents a net economic value of $21.5 million per year for hunting in windbreaks in Kansas (Cook and Cable, 1990). However, a WTA study by Grala et al. (2008) found that farmers may feel uncomfortable charging a fee to hunters to use their windbreaks. In this study of Iowa farmers, 95% allowed/practiced hunting in or around their windbreaks, yet none of the 45 farmers surveyed were currently charging a fee to do so. Furthermore, while 55% of respondents indicated that there was a market for fee hunting, 55% felt that it was a weak market, 45% a moderate market and 0% a strong market. The primary reasons why farmers said they wouldn't charge a fee was due to a feeling that it was against local tradition and was unfair to hunters who may not be able to afford the fee (Grala et al., 2008).

In addition to recreation, windbreak WTP for aesthetics has been investigated. Grala et al. (2012) surveyed farmers and non-farmers to assess WTP for a one-time payment to fund the planting of field windbreaks for aesthetic purposes in Iowa. Results showed that respondents were willing to pay a one-time payment of $4.77 to $8.50, with non-farmers willing to pay more. These findings were similar to Sullivan et al. (2004), who reported that non-farmers had higher aesthetic approval ratings for more extensive windbreak and odor buffer designs when compared to farmers, who had significantly higher approval ratings for the no windbreak or odor buffer options. Grala et al. (2010) also reported significantly higher visual appearance scores for windbreaks from non-farmers when compared to farmers in Iowa.

These willingness to participate, pay and accept studies are unique in that they show how public benefits, such as snow control, recreation, and aesthetics may factor in the decision making for a landowner to adopt windbreaks. These studies suggest that non-farmers value non-market public benefits higher than farmers, who are more focused on personal/on-farm benefits because they are paying the direct cost of establishing and maintaining the windbreaks. Willingness studies can also inform economic policy and programming needs to overcome financial barriers and to incentivize adoption of a practice like windbreaks. By placing value on these non-market benefits, it may help justify future cost-share and financial incentive programs or increase current incentives for windbreak establishment and maintenance. Valuation of non-market benefits will also be crucial as ecosystem service markets develop for carbon storage, soil erosion control, wildlife habitat, etc., with windbreaks being a potential option for producers to increase the environmental integrity of their agroecosystem, while simultaneously generating revenue.

4. Conclusions and recommendations

This review provides the most comprehensive synthesis of empirical studies conducted in the U.S. on factors that motivate and hinder the adoption of windbreaks by producers. Based on this synthesis, several conclusions can be made:

- Producers most value windbreaks for indirect economic benefits from agriculture (soil erosion control, livestock protection, wind protection and snow control), followed by direct agricultural benefits (increased crop and livestock production) and intrinsic values (aesthetics and wildlife habitat).
- Direct benefits from forestry were often ranked last, despite most producers utilizing their windbreak trees for some economic gain.
- The benefits of windbreaks are variable and dependent on whether the system is a field, farmstead or livestock planting.
- Windbreak removal is primarily driven by 1) poor condition of the trees, 2) age of vegetation, 3) conflict with irrigation and farm machinery, and 4) competition with crops.
- Overall satisfaction of windbreaks is high among producers, ranging from 72 to 99%.

- Lack of land and concerns over maintenance are the greatest drivers inhibiting adoption of windbreaks.
- Several perceived windbreak challenges were major concerns by non-adopters, but not by adopters. For example, non-adopters feared windbreaks would harbor pests and insects, but this concern was not evidenced by producers using windbreaks.

Through this synthesis, we have also identified several focus areas for future survey and case study research that could help support windbreak decision making and adoption. This list is not meant to be all-inclusive but rather a starting point to guide future discussions and next steps.

Recommendations on windbreak management & inventory

- Determine types and characteristics of producers who have adopted windbreaks.
- Evaluate the effects of agricultural and conservation policies and programs on windbreak adoption, management and retention.
- Investigate the impact of leased land on windbreak adoption.
- Investigate the influence of climate variability on decision making regarding windbreak establishment and management.
- Increase windbreak research in regions with limited information reported from producers (Fig. 2).
- Develop case studies on how producers have successfully incorporated windbreaks into their current farming systems, including operations with center pivot irrigation.
- Assess which windbreak establishment and maintenance activities producers are using, associated time requirements of those activities and their effectiveness. Also investigate whether these activities are in line with recommended procedures.
- Assess which trees and shrubs producers have found to be most effective in providing specific functions for each windbreak type. Correspondingly, assess producer access to these and other windbreak plants.
- Investigate the concerns and challenges reported by windbreak adopters.
- Conduct a national inventory of U.S. producers regarding windbreak management and drivers of adoption.

Recommendations on windbreak benefits and costs

- Update yield response to windbreak presence for different crops. While there is abundant research on this topic from the 1970s – 1990s for row crops, more research needs to be conducted involving current farming practices, newer crop cultivars, and non-row crops.
- Develop additional case study research on productivity response of livestock to windbreak presence, using data from established commercial systems.
- Assess the products and resources farmers are extracting from their windbreaks, and their economic value. Also evaluate landowner interest in producing marketable products from their windbreaks and their interest in leasing their windbreaks to others to manage and harvest.
- Investigate the value of ecosystem services provided by windbreaks over space and time and the potential of developing markets for these services.
- Assess whether producers value windbreak functions like soil erosion control, livestock protection, wind protection, snow management, etc. from an intrinsic and/or extrinsic viewpoint.
- Better quantify the overall economic costs and time requirements of establishing and maintaining windbreaks.
- Investigate producer interest in potential emerging functions for windbreaks (e.g., mitigate pollen dispersal and gene flow (Meyer et al., 2017), decrease wildfire exposure, increase carbon sequestration, reduce climate risks, reduce spread of pathogens such as avian flu (Wells et al., 2017)).
- More research on farmstead windbreaks and how producers use them for beneficial purposes, especially for energy savings and increased home value.

While the review covers 32 studies spanning 70 years, several shortcomings in the literature base were observed. One of the primary challenges facing this synthesis was the large variation in research frameworks and statistical models used in the quantitative studies. Studies should be tailored for the research questions at hand; however, a lack of consistency in methodologies hindered comparisons and prevented use of a full meta-analysis. Studies rarely acknowledged previous windbreak adoption research. In some cases, respondents who had implemented windbreaks were not separated from respondents that did not have windbreaks, which made drawing inferences between adopters and non-adopters impossible. Furthermore, many of the studies combined field, livestock and farmstead windbreaks together in the data analysis, which complicated interpretation of the results. Windbreaks are also a long-term practice that can span multiple generations of producers and yet there was limited information on adoption and retention over time. There was also limited use of qualitative methods which can help explain nuanced contextual factors related to decision making and adoption. To enhance the utility and rigor of future adoption research on windbreaks and perhaps studies of agricultural adoption in general, we offer the following suggestions:

- Use previous windbreak adoption research to help formulate new studies.
- Conduct longitudinal studies to better assess retention, trends, and producer satisfaction over time or replicate past studies.
- Expand the use of mixed methods to provide a more complete assessment.
- Use consistent terminology to refer to producer demographic questions such as land tenure, farm household income, and on- and off-farm employment.
- Differentiate direct and indirect benefits of crop and livestock protection and production through consistent definitions in windbreak survey questions.
- Separate windbreak adopters from non-adopters in questions and analysis.
- Differentiate windbreaks based on their primary function (field, livestock and farmstead).

Finally, our goal for this study was to provide better guidance on how to more effectively communicate with producers and guide future research and program development. Ultimately, we hope the information from this synthesis empowers producers and those that advise them to more effectively establish and manage windbreaks where it makes the most economic, environmental and socio-cultural sense.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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