Putting Down Roots

Analyzing the economic and environmental benefits of continuous living cover for Minnesota's farmers, water and climate

Friends of the Mississippi River

Forever Green Partnership

Clean Water Land & Legacy Amendment

ecotone

October 2023

Photo Credit: Dodd Demas for FMR

Prepared by Ecotone Analytics GBC

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Ecotone Analytics Impact Analysis
Final Report and Technical Appendix
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Acknowledgments

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Executive Summary

Project introduction: Exploring the future of continuous living cover (CLC) crops in Minnesota

It is well-established that year-round living roots on agricultural land - also known as "continuous living cover" or "CLC" agriculture – are critical for reducing runoff pollution and enhancing soil health and farm resilience.

Just as importantly, CLC cropping systems produce marketable agricultural products that can diversify farm revenues and enhance farm prosperity. However, until now, the potential environmental and economic impacts of specific CLC cropping systems have not been assessed at a landscape scale.

Just how many acres of CLC crops could we expect in Minnesota in the future? What could the environmental impacts of those systems be? As markets for CLC crops mature, how might on-farm revenues and profits be impacted?

This report provides a detailed analysis of the potential long-term environmental impacts of a mature portfolio of CLC cropping systems in Minnesota and the economic opportunities these systems can provide to farmers, businesses and communities.

Key Findings

The adoption of CLC cropping systems at scale in Minnesota has the potential to provide important statewide benefits by 2050.

Reduced nitrogen loss	23%
Reduced soil erosion	35%
Reduced on-farm GhG emissions	3%
Increased on-farm gross revenues	3%
Increased on-farm net returns	20%

Project Goal

The goal of this project was to examine the potential environmental and economic effects of increased adoption of CLC cropping systems on Minnesota farmland between 2023 and 2050, relative to the status quo or "business as usual" scenario.

This analysis is modeled on the example of well-known GhG reduction 'wedge models' that marry the expected market growth of renewable technologies with associated GhG reductions. Such models help us understand the percentages (or 'wedges') of change provided by a future portfolio of activities.

Project Methods

This report utilized a detailed literature review and interviews with subject matter experts to develop (1) a range of adoption scenarios for select CLC cropping systems in Minnesota based on future crop prospects (see Table 7 in the appendix) and (2) the expected environmental and economic impact of those systems relative to the status quo ("business as usual") scenario.

This report focuses on the "medium" adoption and "medium" impact scenarios to describe the environmental and economic outcomes we could reasonably envision from a future portfolio of CLC cropping systems. We include the upper and lower boundary scenarios in Technical Appendices 10-14.

Six CLC crop categories were defined for this analysis:

- 1) Perennial grains (Kernza, perennial wheat, etc.)
- 2) Winter annual oilseeds (winter camelina, pennycress)
- 3) Winter annual cereals and legumes (hybrid winter rye, winter pea, etc.)
- 4) Woody perennials (hazelnut, poplar, elderberry, etc.)
- 5) Perennial oilseeds (perennial sunflower, perennial flax)
- 6) Perennial forage and pasture (alfalfa, cool and warm season grasses, etc.)

Note: Perennial horticultural crops such as apples and grapes are not included in this analysis in order to focus on those crops within the Forever Green Initiative's research portfolio. Horticultural crops may still contribute beneficial economic and environmental impacts.

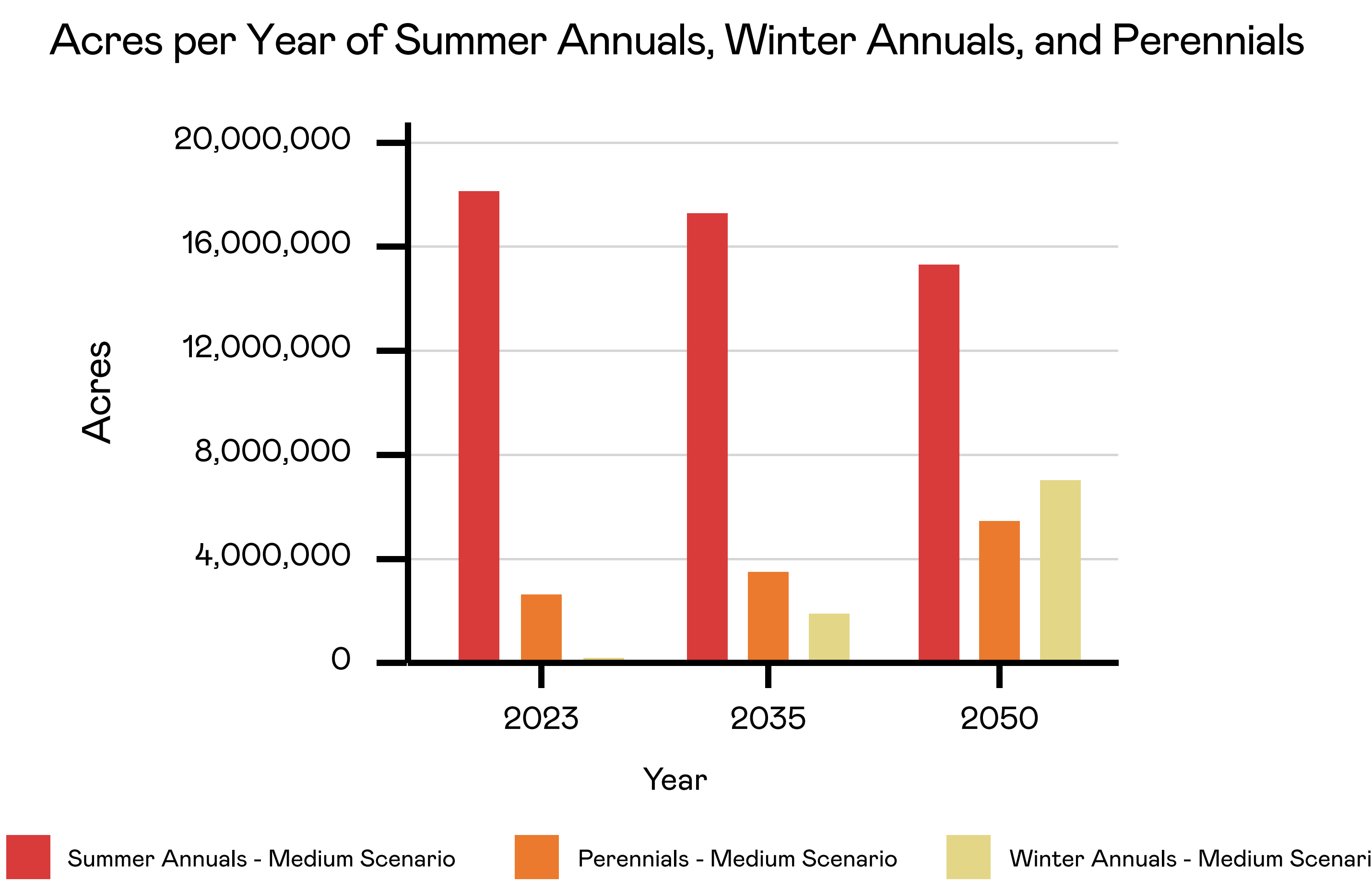
Project Findings

1. Understanding crop acreage and land use

Of the six CLC crop categories analyzed, winter annuals – crops planted in fall and harvested in the late spring or early summer – are expected to realize the largest total acreage, due largely to (1) their ability to integrate with existing summer annual crops and (2) the projected market value of winter annual oilseeds. Perennials also show a steady increase in the likelihood of adoption (Figure 1), building on existing perennial legumes and grasses included in forage and hay production.

Figure 1 shows approximately 21.8 million cropland acres, including summer annuals and perennials. These two crop categories do not share acreage in a given production year. However, since winter annuals are grown on the same acres as summer annuals, just at different times of the year, the increase in winter annuals does not add to the total number of acres of cropland in production in Minnesota.

Figure 1: Change in acreage over time



2. Quantifying land use: Establishing a Minnesota "CLC score"

Even if we ignore the period of the calendar with frozen soils, when agricultural ground cover has less impact on the movement of water and nutrients across the landscape, most farms are only covered with living vegetation and roots less than half of the year.

For this report, we developed a "continuous living cover (CLC) score" that measures the percentage of the year that cropland soils are protected by living roots and vegetation. The CLC score excludes the period of frozen ground because soils are less vulnerable to erosion and leaching when they are frozen.

In the "medium adoption" scenario, this report finds that Minnesota's "CLC score" improves from 48% in 2023 to 77% in 2050. This increase is projected to have substantial environmental and economic benefits.

3. Environmental impacts

To determine the environmental benefits associated with each adoption scenario, we analyzed three key metrics: (1) nitrogen loss, (2) soil erosion, and (3) greenhouse gas emissions.

We found that incorporating winter annuals and perennials alongside conventional summer annuals would have a significant positive impact in reducing soil erosion, nitrate runoff, and greenhouse gas emissions.

Under a "medium adoption" and "medium environmental performance" scenario, this report finds that the addition of CLC crops can support a significant reduction in nitrogen loss (-23%) and soil erosion (-35%) by 2050.[1]

Not surprisingly, the greenhouse gas emissions outcomes are more complex. Because winter annuals add a second crop to an acre in a year (double cropping), there is the potential for increased on-farm greenhouse gas (GhG) emissions, depending on the farming practices utilized.

While on-farm GhG performance is highly variable and subject to uncertainty, the medium scenario for on-farm GhG emissions shows a modest increase in GhG emissions for winter annual oilseeds (14%), while all other CLC crops, excluding winter annual oilseeds, reduce emissions by 17%[1]. When combined, the "medium" scenario produces a net reduction in on-farm GhG emissions of 3%.

Box 1: On-farm vs. Full Lifecycle Greenhouse Gas Emissions

It is important to distinguish between on-farm GhG emissions and "full lifecycle" GhG emissions, especially in the case of winter annual oilseeds, which can have off-farm GhG benefits due to the use of the crop. When included in transportation fuels, winter annual oilseeds like camelina and pennycress result in significant lifecycle greenhouse gas reductions compared to conventional fossil fuels and biofuels (including summer annual oilseeds like soybeans) (Zanetti et al., 2021). These "downstream" GhG reductions are not included in the on-farm GhG performance wedges of this analysis but should be taken into account when evaluating the overall climate impacts of CLC systems. Preliminary analysis shows that winter oilseeds' positive impacts on GhG emissions applied to transportation fuels outweigh the potential increase in on-farm emissions on average (Ecotone estimate - see Technical Appendix 15).

4. Economic impacts

All crops included in this analysis are intended to provide direct economic value – either being harvested and sold for commercial use, used as forage for livestock, or both. While the environmental impact assessments used a "wedge model" approach to depict ecosystem benefits over time, our economic analysis used a different approach.

There are various uncertainties inherent in long-term economic forecasting. In order to understand the economic value proposition of CLC crops, this analysis applied the acreage scenarios from the environmental wedges to 2023 market conditions to see how a shift in CLC crop acreage would change the on-farm economics of Minnesota farms today.

We found that CLC crops could support an increase in both total on-farm gross revenues (+3%) and net returns (+20%), primarily due to a combination of (A) double cropping systems that support additional revenue streams and (B) the high potential value of winter annual oilseeds and perennial forage.

[1] Relative to the 2023 business-as-usual baseline of conventional summer annual crops

Summary & Takeaways

Our findings suggest that CLC cropping systems can play a significant role in achieving the state of Minnesota's environmental goals while enhancing agricultural prosperity. The adoption of CLC cropping systems has the potential to support the reduction of nitrogen loss (23%), soil erosion (35%) and on-farm GhG emissions (3%) while increasing on-farm gross revenues and net returns by 3% and 20%, respectively, relative to business-as-usual cropping systems.

The adoption of a portfolio of CLC crops over the coming decades can increase the productivity of Minnesota's agricultural lands, generate new economic opportunities and access new markets, all while protecting our water and furthering climate mitigation. In addition, research shows that expanding CLC crops will improve climate resilience, air quality and boost the biodiversity of pollinators and other wildlife.

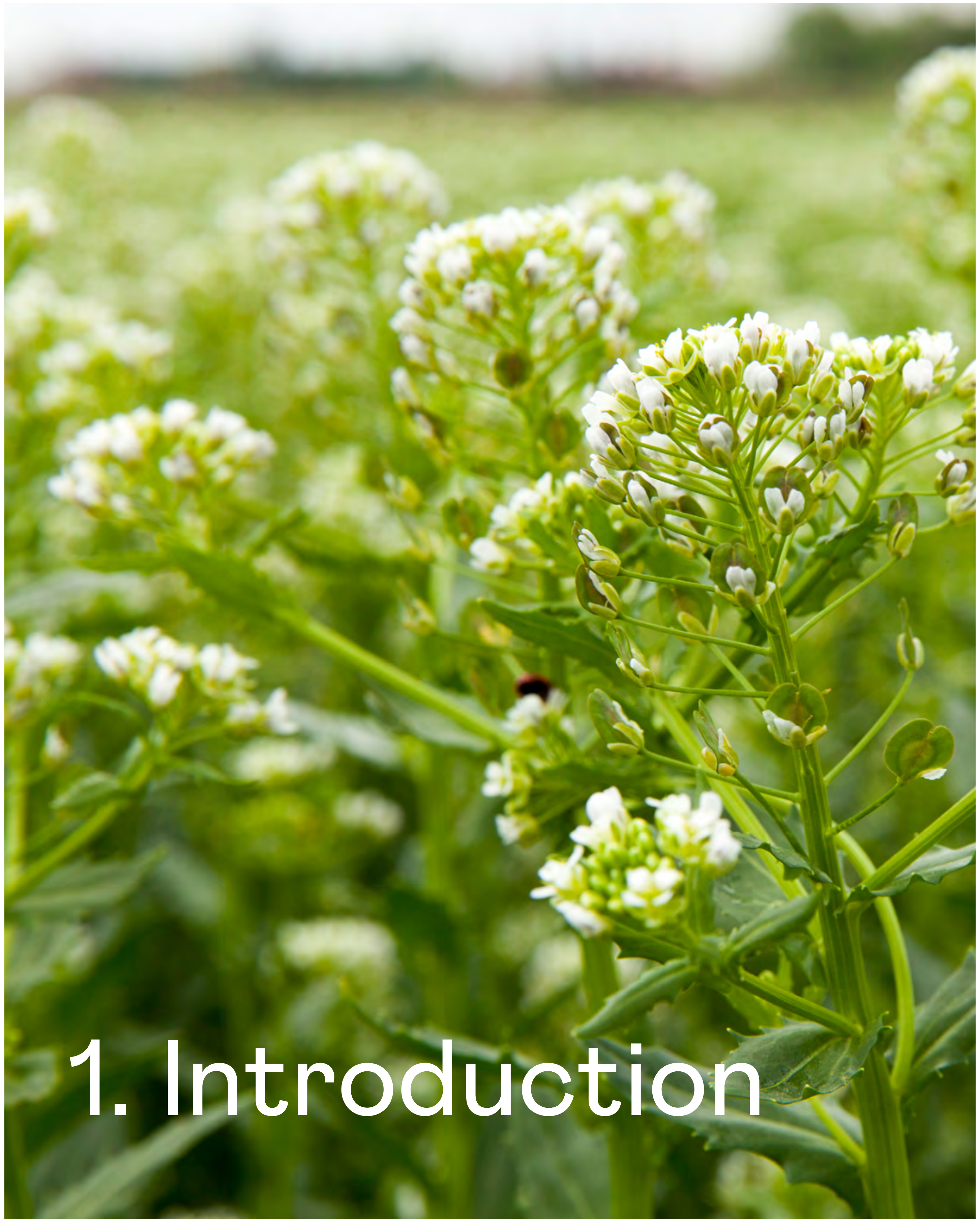
Implications for Policy and Investment

This report shows how investing in "continuous living cover" agriculture can provide a significant benefit to our environment, public health, and rural economies.

All Minnesotans stand to benefit from such investments, as CLC systems can enhance rural development (farm diversification, supply chains, and business development), public health (water quality and nutrition), climate resilience and resource conservation (low-carbon fuel feedstocks, water management and landscape adaptation), and more.

Although long-term growth will be driven and sustained by consumer demand, the public sector has an indispensable role to play in cultivating this still-nascent industry: supporting scientific research into novel winter-hardy crops, building out supply chains and commercial enterprises, and allowing farmers to field-test these new crops and systems without risking their livelihoods.

A strategic combination of public and private investment can drive Minnesota agriculture toward this envisioned future—and beyond—making our state stronger, healthier, and more prosperous.



Putting Down Roots

Analyzing the economic and environmental benefits of continuous living cover for Minnesota's farmers, water and climate.

1.A Project Goal: Providing an Evidence-based Vision of a CLC Future for MN

Friends of the Mississippi River, in partnership with the University of Minnesota's Forever Green Initiative, engaged Ecotone Analytics to conduct an analysis modeled on the example of well-known GhG reduction 'wedge models' that marry the expected market growth of renewable technologies with associated GhG reductions. Such models help us understand the percentages (or wedges) of change provided by a future portfolio of activities.

In this project, we developed scenarios of the expected acreage devoted to select continuous living cover (CLC) systems (perennials and winter/summer annual rotations) in Minnesota through 2050, under low, medium and high adoption scenarios.

From there, this analysis calculated the coefficient-derived expected ecological services (i.e. benefit per acre) from that scale of activity as well as the potential economic effects of that activity. The ecological services were modeled in the wedge analysis format, showing the relative contribution of each crop over time towards an environmental benefit, while economic effects were showcased in various, point-in-time scenarios due to the more limited data and uncertainties around future market conditions.

Photo Credit: Forever Green Initiative

1.B Introduction to CLC Crops and Cropping Systems

The vast majority of Minnesota's cropland is used to grow conventional summer crops like corn, soybeans, and spring wheat, which are planted in the spring and harvested in the fall. Because of their short growing season, the predominance of such "summer annual" crops means that fields often lie bare and brown for the rest of the year, leading to erosion and runoff of fertilizers. These farm runoff pollutants such as nitrogen and phosphorus are the leading sources of pollution to Minnesota's groundwater and surface water.

To restore water quality and aquatic life, we need more green, living cover and living roots in the soil on our agricultural landscape year-round. There are two main options for achieving this goal of "continuous living cover" or "CLC," an acronym we will use often in this report.

1. Perennial crops: Perennial crops live and produce a harvest for multiple years and don't need to be replanted after each harvest. Perennial crops included in this analysis consist of perennial grains, oilseeds, woody perennials, grasses and forage crops. These are the perennials that are under the purview of the Forever Green Initiative's (FGI) research. Additional perennials outside of FGI's purview and as a result not included in this analysis consist of fruit and nut trees, turf, ornamental grasses, and herbaceous perennials. These crops may be incorporated into future analyses.

2. Winter annual crops: Winter annual crops are planted late in the growing season - either between rows of mature summer annual crops (ex: corn) or after the summer crop is harvested. Winter annuals grow for a period in the fall and lie dormant over winter. They emerge early in springtime and quickly mature to be harvested or grazed (depending on the crop). Importantly, summer annuals (ex: soybeans) can be planted in the spring between rows of winter annuals or after winter annuals are harvested - enhancing continuous vegetative cover without displacing the conventional summer annual crop.

   Similar to winter annual crops, conventional cover crops are planted following similar timelines and thus provide cover in the fall, winter and spring, but unlike winter annuals, they are typically not harvested for an economic benefit. Instead, they are planted solely to benefit soil, water and wildlife conservation and are terminated prior to (or just after) the following cash crop is planted. Marketable winter annuals (e.g. oilseeds like camelina) are sometimes referred to as "cash cover crops" because of the function they perform in covering the land when it would otherwise be bare - but can be harvested and sold for profit, unlike more traditional cover crops like winter rye. Cover crops are included in this analysis as a conservation practice that is distinct from winter annual crops.

Farmers who are comfortable growing summer annuals like corn, but who want to achieve continuous living cover, could add certain winter annuals into their rotation, essentially giving them three harvests over two years. Farmers could also rotate a portion of their acreage to high-value perennial crops such as Kernza® perennial grain, providing a resilient crop that will produce yields over multiple growing seasons and which is well suited to areas that are not ideal for growing summer annual crops, such as sloped areas of fields.

In both cases, perennial and winter annual crops can be used in sequence with summer annuals over time in a way that occupies more of the calendar with plant life while diversifying farm income and enhancing farm prosperity.

Why CLC - and what is our vision?

The sight of a bare and exposed field in autumn, while now commonplace in the Midwest, is a somewhat recent historical development. Until the middle of the 20th century, it was typical for an American farmer to raise a diverse mix of small grains, forage or pasture for livestock, vegetables and even tree crops.

With the introduction of modern farm machinery, advances in crop breeding, and industrial supply chains, it became both possible and profitable to focus on the highest-yielding crops – often summer annuals like corn and soybean. Meanwhile, domestic farm policymakers embraced the mantra of "fencerow to fencerow," rewarding the intensification of summer annual production systems at scale at the expense of perennial vegetation.

While conventional summer annual cropping systems are typically highly productive and potentially profitable for producers, integrating CLCs into such systems has the transformational potential to protect soil, water and wildlife while driving new economic opportunities for growers, industry and communities across Minnesota and the upper Midwest.

Making CLCs work

Our vision for the successful adoption of CLC cropping systems is an environment where three interconnected pillars of innovation work in tandem to bring these cropping systems forward in a sustainable manner.

1. Technology push: Cropping system research and development. Plant breeders are identifying and developing winter-hardy annuals with high market value for their oil content and protein; perennial grains that have multiple uses as food, forage, and biofuel; and perennial tree/shrub crops like hybrid hazelnuts and elderberries with excellent nutritional profiles. Investment in crop research and development, supported by multidisciplinary teams of geneticists, breeders, agronomists, food scientists, environmental scientists, and farmers, is the foundation of developing new CLC cropping systems.
2. Market pull: Commercialization, adoption and scaling. CLC systems have an advantage over conventional agricultural conservation strategies in that they are poised to provide significant new income streams for producers. However, many emerging CLC crops are novel and do not yet benefit from robust networks of value chain enterprises, entrepreneurs, and industries built around scaling them up. Support for commercialization initiatives can open the doorway to new, lucrative market opportunities and provide the market pull necessary for CLC systems to operate on a landscape scale.
3. Societal lift: Fostering a favorable social and agronomic environment. CLC systems don't yet benefit from the full suite of policy support, technical assistance, and funding support available to conventional summer annual crops. New policies, educational programming, funding, incentives and other support for CLC systems is warranted as these systems scale up. In addition, equity-focused strategies and practices can provide enhanced access to emerging CLC systems for marginalized stakeholders.

A "silver buckshot" approach

It is tempting to seek a single "silver bullet" solution to a problem as big and seemingly intractable as agricultural sustainability. However, each farm operation, agribusiness and community has different aims, abilities, and opportunities, and there is no single solution to the challenges we face.

In this report, we describe a "silver buckshot" approach that deploys numerous different cropping systems across the landscape in a manner that serves to enhance cropland sustainability, farm prosperity and natural resource health throughout Minnesota's agricultural landscape.

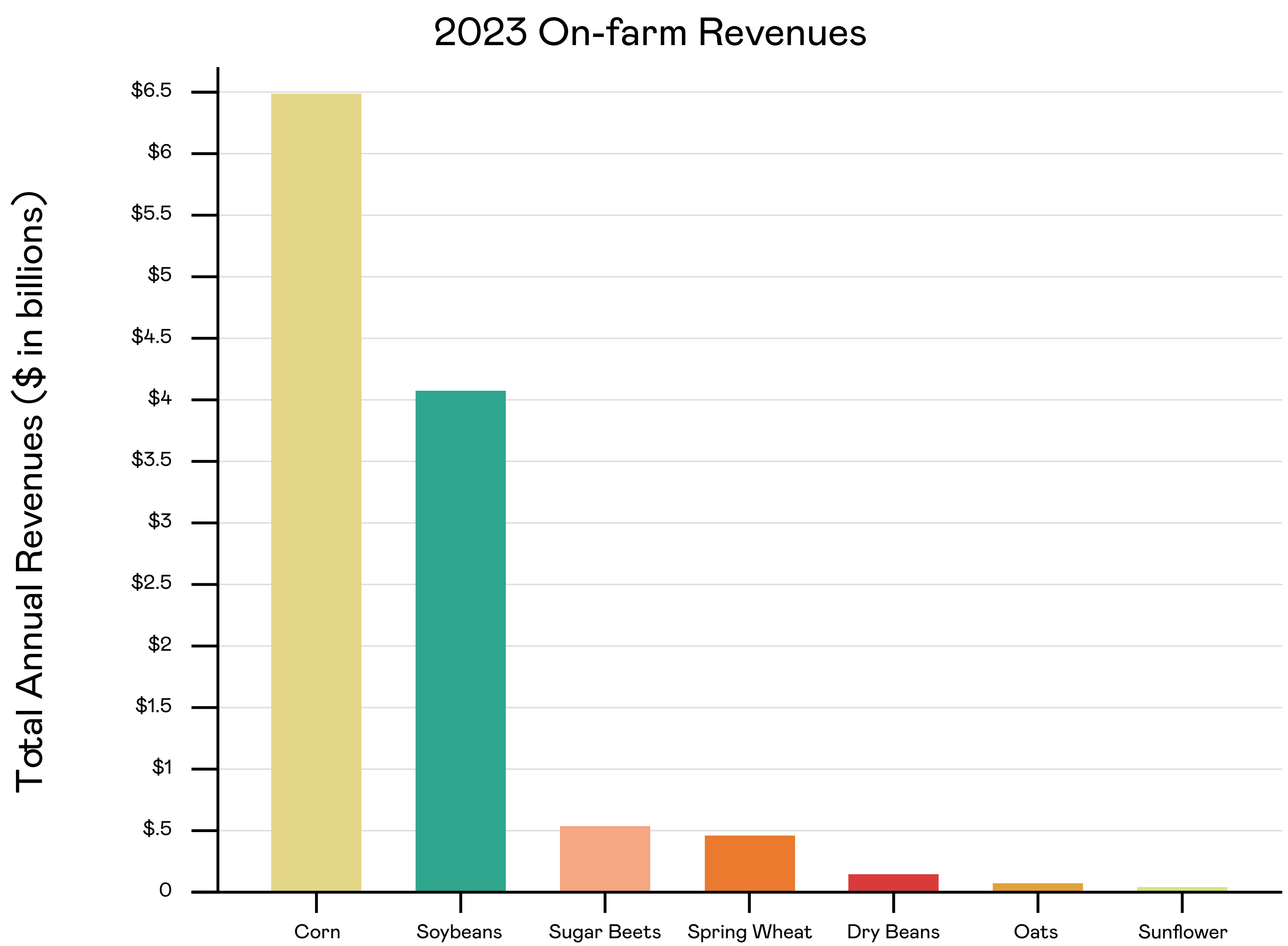
1.C Introduction to Current Crop Production in MN

There are approximately 21 million acres of cropland in Minnesota with over 25 million acres in farmland when including row crops, non-row crops, and livestock operations (USDA - NASS, 2022). Cropland in Minnesota is predominantly used for summer annuals, those crops that need to be replanted every year, with most being planted in the late spring and harvested early fall. Corn and soybeans are the dominant annuals and crops in general in the state, being grown on over 70% of cropland in the state, approximately 15.5 million acres. Due to the amount of land they are grown on, it is not surprising they are also the leading sources of crop revenue in the state by a large margin. Together, corn and soybeans provide over an estimated $10 billion in annual revenue to Minnesota farmers.

However, an estimated 20% of these acres are unlikely to be profitable any given year due to marginal growing conditions and contribute disproportionately to soil erosion and water quality (Basso et al., 2019).

Figure 2 provides a sense of both the scale of revenues from conventional summer annuals in Minnesota and how that scale compares across the major individual crops. Corn and soybeans are the largest sources of summer annual crop revenue in Minnesota and, as a result, are important to the on-farm economics of many growers in the state.

Figure 2.
On-farm Revenues of Conventional Summer Annuals in Minnesota



Additional annual crops grown in MN and included in our analysis include spring wheat (which often covers over 1 million acres per year) along with oats, sugar beets, dry beans, and others (which collectively occupy hundreds of thousands of acres each year). Many of these annual crops, excluding corn and soybeans, are considered short-season crops, given they require a smaller portion of the growing season to reach maturity and be harvested. This allows for easier integration with winter annuals that might otherwise compete with corn and soybeans due to overlap in planting and harvest dates of winter annuals and corn or soybeans. See Section 2.d for details on the economics of CLC crops.

1.D Environmental Externalities and the “Big Brown Spot”

This ‘status quo’ of crop production in Minnesota, while generating large revenues, does also create one of the most significant hurdles to achieving Minnesota’s environmental goals: the “Big Brown Spot.”

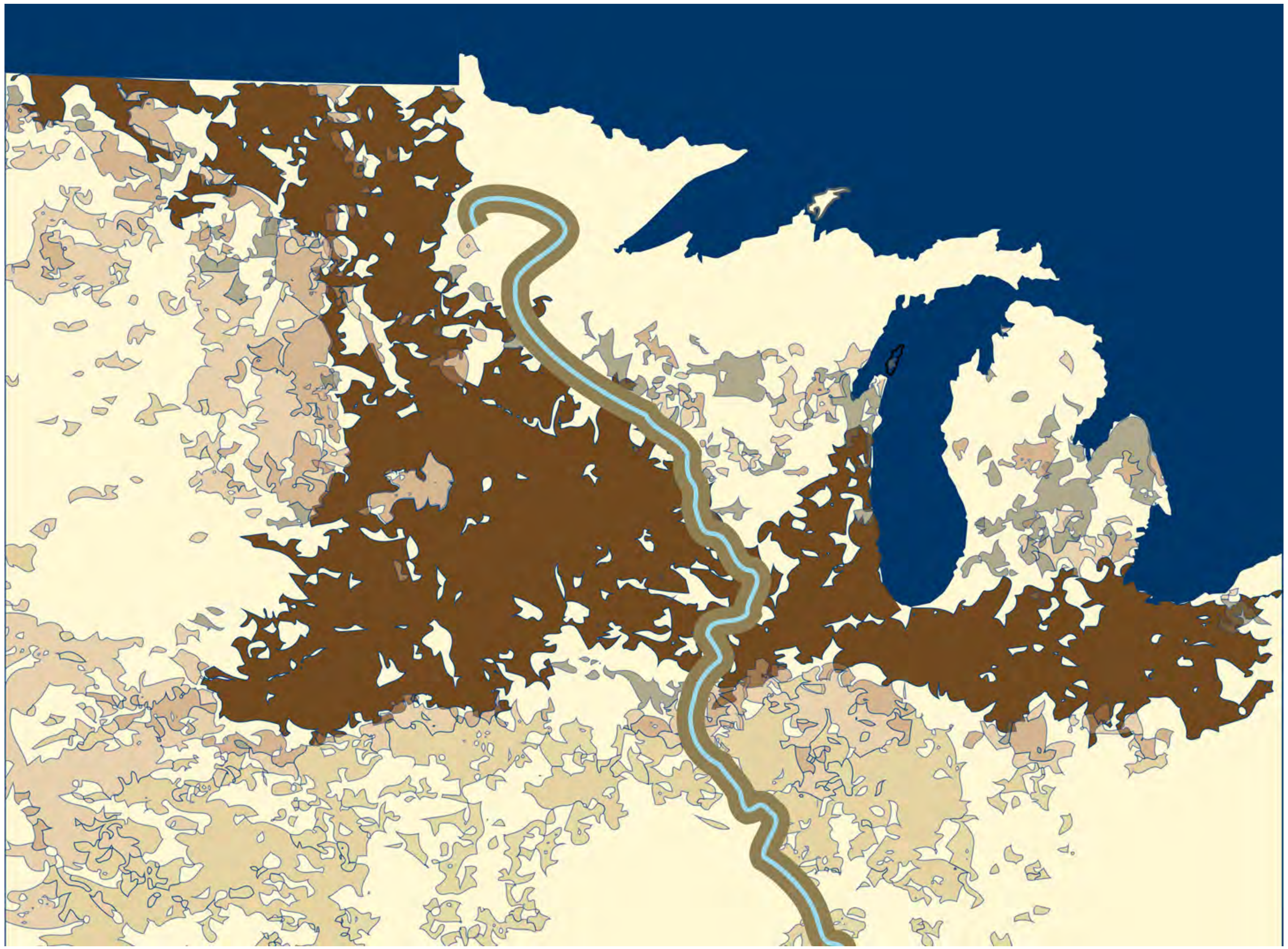
In Upper Midwestern areas dominated by annual row crops like soybeans and corn, crop harvest typically begins in September and October. Once harvest is complete, soils are left mostly bare and exposed to the elements through the remainder of the Fall, Winter and Spring until crops are planted and begin to mature in late Spring or early Summer the following year. This extended period of barren, unprotected soils is the “Big Brown Spot” — millions of acres of croplands devoid of living vegetation for months at a time each year. This has serious environmental consequences for Minnesota and downstream states.

Bare soil doesn’t typically exist in healthy, natural systems in Minnesota, and during the “Big Brown Spot” (See Figure 3), our natural resources are especially vulnerable. Unprotected soils expose the landscape to increased erosion and runoff pollution from manure and farm fertilizers. Nitrate, other fertilizers, pesticides, and particulates can runoff into surface waters and leach into groundwater resources, including public and private drinking water supplies. Bare soils can also exacerbate cropland greenhouse gas emissions while negatively impacting soil health, wildlife habitat and pollinator health.

Figure 3.

The 'Big Brown Spot' of Upper Midwest Crop Production

Brown shaded areas indicate lack of living vegetation in winter months



(Source: Adapted by Friends of the Mississippi River from the USDA VegScape tool using 2021 data)

1.E Project Scope: CLC Crops and Cropping Systems Examined

Phase 1 of this project entailed a detailed review of the different crops studied by Forever Green (FG) and/or included as CLC crops that could be implemented in Minnesota. To better manage the number of potential crops, six crop categories were developed, as denoted as the column headers of Table 1.

These crop categories group the crops by key characteristics whether that is if the crop is a winter annual or perennial, a cereal or legume, or how the crop is used. Table 1 shows the various crops that were included in the literature review and were the subject of interviews with experts. While there are multiple crops within each crop category, the amount of information on each can vary significantly, with some crops being studied in great depth due to the stage of commercialization they are at, the potential scale of their implementation, and the market opportunities they present, among other factors.

Due to the varied amount of information available, not every crop included in Table 1 is highlighted in subsequent tables and figures in this report. The wedge charts showing the environmental impacts of these crops, grouped into the above categories, and at times highlight specific crops within categories that contribute a larger amount of impact. For example, within the perennial grains crop category, Kernza® will often be highlighted individually due to the amount of research it has garnered relative to the other perennial grains, which are all in the pre-commercial phase.

Importantly, all crops studied can exist in a variety of cropping systems. The cropping system into which a given crop is implemented can have a significant impact on the environmental and economic value proposition. Similarly, forage and pasture systems can be a part of different grazing systems that have their own environmental and economic implications. This analysis is focused on the crops themselves and made some assumptions about what these cropping systems consist of; see the technical appendix for further details.

Table 1 .
CLC Crops Included in this Analysis

Perennial Grains	Perennial Oilseeds	Winter Annual Oilseeds	Other Winter Annuals	Pasture/Forage/Biomass	Woody Perennials

· Kernza/IWG
· Perennial cereal rye
· Perennial wheat
· Perennial oat
	· Perennial sunflower
	· Silphium
	· Perennial flax
		· Winter camelina
		· Pennycress
			· Hybrid winter rye
			· Spring and winter pea
			· Winter barley
			· Winter wheat
				· Perennial legumes
				  · Alfalfa
				  · Other legumes such as clovers
				· Cool season grasses
				· Warm season grasses
				  · Switchgrass
				· Prairie
					· Hazelnut
					· Elderberry
					· Aronia
					· Willow and poplar

CLC Crop Commercial Pathways

Each of the CLC crops included in this analysis have multiple potential market opportunities. Table 2 shows the key commercial pathways for each crop. The market size of these commercial pathways serves as a key signal of the potential demand and with it, the acreage scenarios for each crop.

While many factors such as yield, price points, state of value chain development, public policies, and access to financing influence each crop's ability to take advantage of commercial pathways, this table helps convey overall market alignment. Additional consumer uses include fiber, cosmetics, pharmaceuticals, cut flowers and more.

Key:
X = definite use.
m = possible potential use.

These crops are in various stages of commercial readiness across different users and categories, from early R&D to product testing to initial market penetration. The speed at which each of these crops progresses toward wide availability depends on a number of factors.

Table 2 . Commercial Applications for CLC Cropping Systems

Crop Category	Crop Name	Food Products	Alternative Protein	Animal Feed / Forage	Grazing	Edible Oil	Oil-derived Biofuels	Cellulosic Biofuels
Perennial Grains	Kernza®	X		X	X			m
	Perennial cereal rye	X		X	X			m
	Perennial wheat	X		X	X			m
	Perennial oat	X		X	X			m
Perennial Oilseeds	Perennial sunflower	X	X			m	X	
	Silphium	m	X	X			X	
	Perennial flax	X					X	
Winter Annual Oilseeds	Winter camelina	m	X	m		X	X	
	Pennycress	m	X	m		m	X	
Other Winter Annuals	Hybrid winter rye	X		X	X			
	Winter pea	m	X	X	X			
	Winter barley	X		X	X			
	Winter wheat	X		X	X			
Pasture/ Forage/ Biomass	Alfalfa (perennial legumes)		m	X	X			m
	Other legumes	X	X	X	X			
	Cool season grass			X	X			m
	Warm season grass (switchgrass)			X	X			m
	Prairie restoration			X	X			m
Woody Perennials	Elderberry	X						
	Hazelnut	X				X		
	Aronia	X						
	Willow and Poplar							m

Box 2: A Market Opportunity for Winter Annual Oilseeds

Winter annual oilseeds present a significant opportunity in the sustainable aviation fuel (SAF) market. As the aviation industry seeks to reduce its carbon footprint and transition towards more sustainable fuel sources, winter annual oilseeds offer a promising solution. These oilseeds, winter camelina and pennycress, have several characteristics that make them well-suited for SAF production. They have high oil content, making them good sources of feedstock for biofuel production. The oil extracted from these seeds can be converted into renewable jet fuel through various processing techniques, including hydroprocessing and hydrotreating. This process results in a drop-in replacement for conventional jet fuel, meaning it can be used directly in existing aircraft engines and infrastructure without requiring modifications. By utilizing winter annual oilseeds, the production capacity for SAF can be expanded beyond the limitations of traditional summer oilseed crops.

Ecosystem services from CLC cropping systems

CLC cropping systems can provide a multitude of ecosystem services that are important for maintaining the health and sustainability of the state's agricultural landscapes and beyond.

These services can include nutrient loss reduction, soil erosion control, soil formation and regulation of nutrient cycling in agroecosystems, greenhouse gas emissions mitigation, climate resilience, pollinator support, and wildlife habitat.

Soil health

A key ecosystem service offered by CLC crops in Minnesota is the enhancement of soil health. Winter annuals and perennial crops can improve soil structure, increase organic matter content, and enhance soil fertility (Forever Green Initiative, 2021). The continuous living vegetation helps to prevent soil compaction, increase water infiltration, and promote beneficial soil microbial activity (Chamberlain et al., 2022). This, in turn, contributes to improved nutrient cycling and nutrient availability and leads to increased agricultural productivity and resilience (Land Stewardship Project & Green Land Blue Waters, 2020). Foliage "canopies" also reduce the physical impact of precipitation on the soil and mitigate soil crusting (Glover et al., 2010).

Nitrogen and phosphorus runoff reduction

CLC crops can play a role in minimizing agricultural nutrient loss by acting as natural filters, capturing excess nutrients such as nitrogen and phosphorus over a larger part of the year that could otherwise leach into water bodies and contribute to water pollution (Reilly et al., 2022), reducing the risk of harmful algal blooms, ecosystem degradation and drinking water contamination.

Erosion reduction

CLC crops serve as a valuable tool for erosion control. The continuous vegetative cover provided by these crops acts as a protective layer, safeguarding the soil from erosion caused by wind and water. The living root systems of winter annuals and perennial crops help stabilize the soil, preventing its displacement and preserving valuable topsoil (The Land Institute, 2022). This not only helps to maintain agricultural productivity but also mitigates the sedimentation of water bodies and supports the long-term sustainability of the ecosystem (Reilly & Cates, 2022).

Water storage

CLC crops, with their extensive root systems and ability to improve soil structure, enhance water infiltration and water holding capacity. Foliage "canopies" also reduce the impact of precipitation on the soil and mitigate soil crusting These attributes help mitigate the risk of flooding by reducing surface runoff and improving water retention in the soil. Communities benefit from reduced flood damage to infrastructure, improved water availability during dry periods, and overall more resilient water management.

Climate resilience and adaptation

Year-round living roots and extensive vegetative cover can improve soil health and help make farms more resilient to climate change (Gutknecht & Jungers, 2021). CLC crops, particularly perennials with their more substantial root structure, can also have greater resiliency to temperature, moisture and weather extremes, helping to protect against our shifting climate and reducing the risk of losing a crop in any given year.

Habitat and pollinators

The presence of CLC crops in Minnesota provides habitat for pollinators and other wildlife (MDA, 2023). Flowering winter annuals and perennial crops offer nectar and pollen sources, attracting and sustaining a diverse range of pollinators including bees, butterflies, and other beneficial insects. This, in turn, aids in the pollination of certain agricultural crops and enhances their productivity. The different plant species associated with CLC systems also provide habitat and food sources for wildlife, contributing to the preservation of biodiversity and the overall health of the ecosystem (Eberle et al., 2015).

Greenhouse gas (GhG) mitigation and sequestration

CLC cropping systems have the potential to mitigate greenhouse gas (GhG) emissions. Perennial systems can support reduced use of farm machinery and reduced tillage or no-till practices, which minimize soil disturbance and subsequent greenhouse gas emissions (Abdalla et al., 2019). Some CLC systems can reduce nitrous oxide (N2O) emissions by supporting reduced use of nitrogen fertilization (Cecchin et al., 2021; Meehan et al., 2013), although research around N2O emission reductions is still new and developing.

CLC crops also have the potential to actively sequester carbon dioxide in the soil or their own biomass (such as woody perennials) by pulling it from the atmosphere through photosynthesis. As highlighted by Gutknecht and Jungers (2021), certain CLC systems may have the potential to sequester up to 0.34 US tons of carbon per acre per year. Perennial systems such as grasslands have some of the greatest sequestration potential, while annual CLC systems such as those with winter annuals tend to have a lower per-acre potential (Crews et al., 2018). This is highly dependent on the management of those systems - see Box 3 for details.

Box 3: Uncertainty in Greenhouse Gas Estimates

The science behind carbon sequestration, nutrient cycling, and other GhG emission topics – and the practices that can be employed to achieve GhG reductions – remains uncertain and requires significant additional study before solid claims of efficacy can be made (Gutknecht & Jungers, 2021). As a result, the evidence base for on-farm GhG performance estimates is evolving and subject to change.

The relationship between changes in soil organic carbon (SOC) and net GhG mitigation effects is complex. As highlighted by Moore et al. (2023), management strategies that lead to increased SOC do not necessarily guarantee a net GhG mitigation effect. Factors such as the long-term maintenance of SOC gains and the consideration of other potential emission sources in agricultural production need to be accounted for. Given this complexity, there is a need for improved sampling methodologies and monitoring tools as well as enhanced models to better estimate the overall net GhG impacts of soil carbon changes. To manage this uncertainty, this report uses conservative estimates of potential carbon sequestration and GhG benefits more broadly.

1.F Project Parameters

Based on the CLC crops outlined, their commercial pathways, and their ecosystem services, this project developed a series of evidence-informed scenarios for the future of continuous living cover cropping systems in Minnesota. In particular, this work entailed creating projections of both the environmental and economic impacts based on realistic acreage adoption scenarios. Low, medium and high adoption scenarios were developed for each crop and/or crop category. Values for each scenario were derived from a combination of any pre-existing estimates, subject matter expert opinion, acres that are considered high priority for their environmental attributes, current crop development status, market opportunities, among other criteria (See Technical Appendix 8).

As a result, the findings communicated in this report are not forecasts of what will come to be, but are scenarios that may occur based on an anticipated range of market conditions and crop development over the coming decades.

Limitations

The project scope has three important limitations that shape the final results.

1. Assessment approach: This project is not a watershed-by-watershed modeling exercise for the entire state and does not utilize a watershed modeling tool such as the soil and water assessment tool (SWAT). Instead, this project relied on conservative, literature-derived assessments of the environmental impacts per acre of CLC crop regardless of the location of that crop within Minnesota. This approach applies the same impact per acre (e.g. % of soil erosion mitigated per acre) to each acre of the given CLC crop adopted relative to the "business as usual" scenario. As a result, this analysis does not make assumptions about where a CLC crop is being placed on the landscape and therefore does not assign benefits to specific watersheds or - in the case of avoided nitrogen loss - differentiate between benefits to surface water and groundwater resources.
2. Conservation technology forecasting: We recognize that farmers will also continue to adopt conservation "best management practices" (BMPs) over time. To account for this likely change, the environmental performance wedges include a conservative estimate of the environmental benefit of ongoing BMP adoption over time. However, we note that numerous farm innovations may emerge in the coming decades (like next-generation precision farming and farm robotics) that could in turn influence the environmental and economic impacts of both CLC and conventional cropping systems in Minnesota. Such innovations are not included in this analysis.
3. Climate forecasting: Lastly, while climate change and extreme weather conditions will likely impact farm productivity and economic performance over time, specific assumptions about climate impacts are not embedded in this assessment.

As a result, the findings of this report provide a strong indication of the potential environmental and economic impacts of implementing CLC cropping systems in Minnesota but should not be considered a comprehensive prediction of future conditions.

Environmental variables analyzed

To analyze the environmental benefits of CLC crops in Minnesota, it was necessary to identify metrics that have been studied across most of the CLC crops in the Forever Green portfolio as well as metrics that would align with the use of a wedge analysis format.

We reviewed 60+ articles and resources, mapping the relevant environmental metric(s) studied to the corresponding crop and/or crop category (see Bibliography in section 6). This gave us a clear understanding of the extent to which each metric has been studied for each crop. Where gaps existed, we interviewed subject matter experts to get their perspectives on strategies for filling those gaps. At the close of this process, three environmental metrics were identified as both being studied sufficiently for each crop category and being measured in a way that would fit with a wedge analysis format. The three metrics were nitrogen loss, soil erosion, and greenhouse gas emissions.

1. *Nitrogen loss:* Avoided nitrogen loss is widely studied as a metric. As a result, the potential impact of CLC cropping systems on nitrogen loss is reasonably well understood. Where CLC cropping systems benefit from detailed nitrogen loss research, those results were used as performance assumptions. Where such data is not yet available, surrogate crop performance metrics were used based on individual crop characteristics.

2. *Soil erosion:* Given that cropland is often bare for a significant portion of the year, (see 'The Big Brown Spot' in Figure 3), soil loss can be substantial, sometimes as high as multiple tons of soil loss per acre annually. Many CLC cropping systems have been studied for their ability to reduce soil erosion, and as a result, this metric was included in this report. This metric includes both loss to surface water as sediment and loss to the air as dust/particulate matter.

3. *Greenhouse gas (GhG) emissions:* Studies of the impact of CLC crops on GhG emissions are growing. While, as previously described, there is considerable uncertainty, the amount of studies to date was considered sufficient to include in this analysis.

Environmental variables not analyzed

While three environmental variables were included in this analysis, several others were reviewed and excluded. Three of the primary metrics of interest that were ultimately not included were pollinator and wildlife habitat, phosphorus loss, and climate resilience. However, we do want to highlight their importance here.

1. *Pollinator and wildlife habitat:* The benefits of increased groundcover, crops flowering at different times of year, and increased crop diversity all provide potential benefits to pollinators and wildlife. However, consistent data was not readily available across CLC crops, and the metrics applied to pollinator and wildlife habitat quality are not as readily incorporated into a wedge chart as nitrogen loss, soil loss, and GhG emissions.

2. *Phosphorus loss:* Phosphorus, while a significant pollutant of concern for surface waters, was not included in this project due to the limited extent it has been studied for each of the CLC crops. However, this should not minimize the importance of considering the reduction of phosphorus in Minnesota waterways. Many practices that reduce soil erosion and nitrogen loss can likewise reduce phosphorus pollution to surface waters.

3. *Climate resilience:* Given that CLC cropping systems have the ability to often perform better in extreme weather events, particularly in the case of perennials, this can result in improved yield stability, reduced risk of loss of crop, among other resilience metrics. Research in this topic however is varied and not readily incorporated into a single metric for a wedge analysis.

Economic variables analyzed

When analyzing the economic impacts of CLC crops, there were two primary categories of impacts to consider: (1) on-farm economic impact and (2) off-farm economic impact. On-farm economic impacts consider farm profitability and all the costs and revenues that drive it. Off-farm impacts factor in the economic 'ripple effects' from farm operations including jobs supported, supply chain linkages, and household incomes from non-farm labor.

For this report, we focus on the on-farm economic impacts of CLC cropping by comparing enterprise budgets for different cropping systems in order to evaluate per-acre revenue and per-acre net returns. This focus was established by reviewing existing resources and the extent data on crops was available and/or if an appropriate proxy value existed (for example, if a perennial crop would be accessing similar value chains to an annual counterpart). FINBIN and pre-existing analyses developed by Forever Green were pooled and reviewed for completeness of data and to determine which crops had data. This generally included CLC crops that were either already commercialized, are near commercialization, or had a relevant proxy value. As a result, not all CLC crops included in the environmental analysis appear in the economic analysis. Economic assumptions were based on peer-reviewed research, best available data and expert interviews.

Importantly, this analysis does not forecast economic impacts - it creates scenarios of on-farm economic impacts based on varying levels of adoption of CLC crops using 2023 dollars and 2023 pricing and cost estimates. The scenarios developed are based on the 2035 and 2050 acreage scenarios used for the environmental impacts for those CLC crops with sufficient economic data.

Economic variables not analyzed

There are four primary elements of economic performance that are not fully assessed in this report - each with significant economic implications for Minnesota's agricultural economy.

1. *Transition costs:* The adoption of CLC crops and cropping systems may require time, labor, inputs and technological changes to be made by farmers. The scope of these potential costs is not accounted for in the review of on-farm economics, although it is an important consideration and area for future research.

2. *Ecosystem service markets:* This analysis does not include the potential economic benefits of markets for carbon and other ecosystem services.While the value of these payments for ecosystem services is not currently a part of the on-farm revenues or net returns for this analysis, they may impact these values if the markets are implemented at a large enough scale.

3. *Off-farm regional economic impact:* In addition to on-farm economics, there is a vision for increased regional economic impact that extends off-farm due to the adoption of CLC crops and cropping systems. This would in theory show increases in economic activity, in value add, in jobs, and in labor income for Minnesota. This topic was found to be understudied and deserving of future attention. Technical appendix 14 includes an example of what this analysis could consist of using Kernza® flour produced in Minnesota as a brief case study.

4. *Grazing operations' costs and revenues:* We note that several CLC crops are "dual use" meaning that they can be harvested as seed, grazed or cut as forage. In some cases, such as Kernza®, the forage value can be as great as the value of the seed (as included in Section 2.C economic impact analysis). However, this analysis does not holistically consider the economics of grazing operations. It does not consider the costs to implement grazing of a crop such as Kernza® such as fencing, labor and water costs nor does it consider the benefits it may provide to animal or dairy production. Instead, it focuses solely on the cash value of a given crop whether through its value as forage, as grazed vegetation, and/or as a harvested crop. Details on the additional economic arguments in favor of increased perennial forage as a part of a grazing operation are available with groups such as Green Lands Blue Waters and Grasslands 2.0.

Acreage, Environmental and Economic Impact Results

2.A CLC Acreage Scenarios

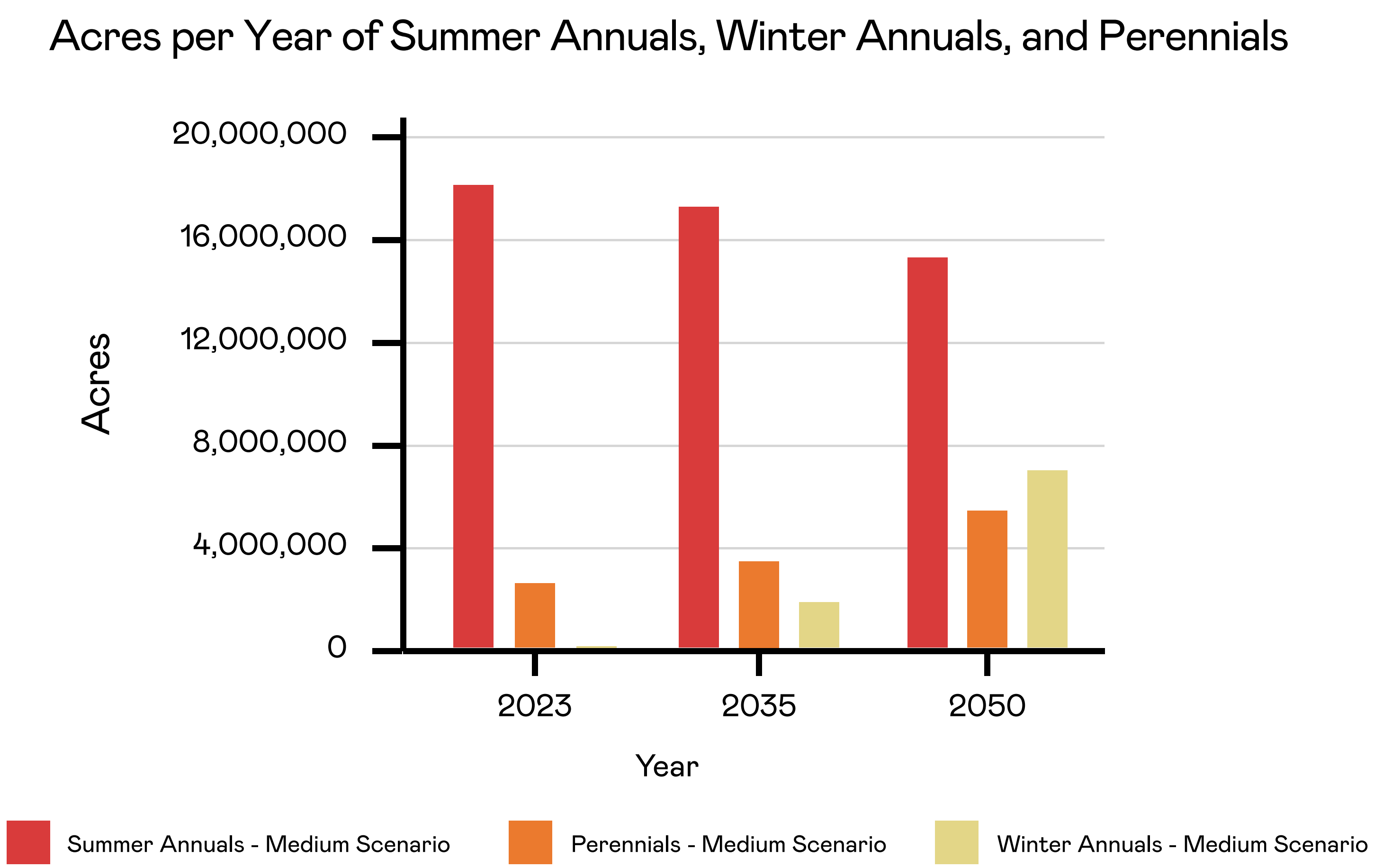
Based on an extensive literature review (in total over 100 published resources) and dozens of subject matter expert interviews, Ecotone developed evidence-informed scenarios of the potential adoption rates of CLC crops in Minnesota. Despite the scope of our search, there was limited available data to project the potential growth in the adoption of CLC crops without myriad assumptions. However, in addition to any pre-existing estimates and feedback from expert interviews, several acreage reference points could be developed from the identification of high-priority land areas, state initiatives such as the Nutrient Reduction Strategies, estimated acres of marginal lands that could feasibly be transitioned, existing crop acreages (i.e. how many acres of corn are there for winter annuals to be integrated with) and corporate goals focused on regenerative agriculture that include benefits aligned to CLC crops. Together, these helped inform the scale of acreage on which CLC crops are likely to be deployed.

For example, in 2022 there were a total of 115,000 acres of row crops in Minnesota's Wellhead Protection Areas. These are high-priority acres due to their importance for protecting drinking water from excess nutrients. As a result, they are well-suited for perennials that will take up excess nutrients before it reaches the groundwater.

Each crop or crop category analyzed was assigned a low, medium, and high acreage adoption scenario based on perceived level of conservatism or optimism in rates of adoption. In all scenarios, it is assumed that CLC acreage increases over time due to the assumption that existing barriers to adoption will be reduced going forward.

The scenarios in this document do not encompass the full range of possible futures for crop production in Minnesota. Still, they describe how CLC crop adoption could benefit Minnesota environmentally and economically. Throughout this document, the medium scenario is utilized to communicate a middle ground based on the range of values either seen in the literature or identified through interviews. See Technical Appendix 8 for the low and high scenarios and further discussion around the identification of acreage values.

Figure 4.
Acreage by Crop Type



Note: Not every summer annual grown in Minnesota is included in this analysis in order to draw bounds about what the business as usual consists of. However, major crops representing over 98% of summer annual acreage in Minnesota are accounted for.

Figure 4 shows the envisioned transition from predominantly summer annuals (e.g. corn, soybeans) to the increased integration of perennials and winter annuals into Minnesota crop production through 2050 under a medium adoption scenario. Perennials show a steady increase from 2023 (primarily perennial forage and pasture) to 2050 (an expanded portfolio of perennials). Winter annuals see the most significant increase, going from tens of thousands of acres in 2023 to several million by 2050.

Given the assumption that the total number of acres in production will remain constant over time, the increased acreage for perennials necessitates the reduction in summer annuals grown at any given time (although perennials may be integrated into longer rotations with summer annuals), hence the reduction in summer annual acres. The increase in acres envisioned for winter annuals comes entirely from integration into summer annual acreage.

Figure 5 provides a more detailed view of the specific summer annuals and CLC crops for the same three benchmark years: 2023, 2035, and 2050. Across all three milestones, corn and soybeans continue to be the leading crop by acreage in Minnesota, although they experience a decline from 2023 due to the envisioned expansion of perennials. It is assumed that the perennials primarily replace corn and soybean acres, resulting in constant spring wheat and other short-season crop acreage.

Total CLC acres under this medium adoption scenario, combining winter annuals and perennials, amount to over 12 million acres by 2050. The two leading CLC crop categories are expected to be 1) Winter Annual Oilseeds with over 5 million additional acres by 2050 and 2) Perennial Forage and Pasture with about 1.7 million additional acres by 2050. Perennial Forage and Pasture starts out as the leading CLC crop category, given the millions of acres already active in Minnesota.

Any winter annuals adopted would be integrated into summer annual acres such that an increase in winter annuals grown does not contribute to a net increase in total acres of cropland in Minnesota. Crop categories such as winter annual legumes (winter pea), perennial grains, woody perennials, and perennial oilseeds have greater uncertainty at this time around their development and/or market opportunities. As a result, the acres envisioned for those crops are kept conservatively low, but with future crop and market development, these figures may be revised.

Box 4: Building the Winter Annual Oilseed and Perennial Forage Acreage Scenarios

Winter annual oilseeds and perennial forage & pasture are the two leading CLC crop categories by acreage under each scenario included in this analysis. This is due to a few reasons outlined below. In the case of both crop categories, these acreage scenarios are considered to be possible visions for Minnesota's future, but will take effort to be realized. See the technical appendix for further details on acreage reference points and specific low, medium and high acreage scenarios used for each CLC crop in each scenario.

Winter annual oilseeds:

Winter annual Oilseeds such as winter camelina and pennycress have the opportunity to take advantage of a large market opportunity as a feedstock for sustainable aviation fuel (SAF). Mousavi-Avval and Shah (2020) note that about 40% of corn/soybean acres in the Midwest are suitable for pennycress each year (about 30 million acres) and could replace about 4.3% of annual fossil jet fuel demand in the U.S. If we take this same ratio and apply it to Minnesota corn/soybean acres, that means there is the potential for 6.2 million acres of pennycress in Minnesota. Assuming similar acres are suitable for both winter annual oilseeds, this provides us with a reference point for the crops potential in Minnesota today. Related, winter annuals more generally have been projected by the GHG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team in Minnesota (2022) to be grown on up to 12 million acres by 2050. While many of these may not be winter annual oilseeds, it provides us with another upper bound figure to consider.

Lastly, the SAF market opportunity and state agency projections loosely align with corporate regenerative agriculture goals that heavily feature cover crops and, by default, winter annuals. For example, the Midwest Row Crop Collaborative, consisting of various private and nonprofit stakeholders, has a goal of 30 million acres of regenerative agriculture in the Midwest by 2030. If even 5 million of those, or about 17%, occur in Minnesota, we would expect many of those to have cover crops on them.

Based on these different reference points as well as expert interviews on the topic, we set a target of just over 5 million acres of winter annual oilseeds by 2050, with the adoption rate following an S-curve such that the rate of adoption is greatest between now and 2035 before slowing and eventually plateauing in acreage in the late 2040's.

To integrate the winter annual oilseeds into the existing summer annuals, we assume that, until 2035, the winter annuals will be grown following short-season annual crops such as spring wheat, oats, corn silage, etc. This is because it is currently challenging to establish winter annuals following longer-season crops such as corn and soybeans without making adjustments to the management of those crops—such as using shorter-season varieties—that reduce the yields of those crops. However, we assume that it will be more economically feasible to grow winter annuals after corn and soybeans as of 2035. This is based on the assumption that the lengthening growing season, improved crop genetics, and improved agronomic practices will allow winter annuals to be grown following corn and soybeans with minimal impact on the yields of the summer annuals. This staged integration of the winter annuals is not necessary in states further south, where the growing season is already long enough that winter annual oilseeds can be integrated with corn and soybeans.

Perennial forage and pasture:

Unlike winter annual oilseeds, the market for perennial forage and pasture is well established. Crops such as alfalfa and perennial grasses are already grown on close to 2 million acres each year in Minnesota. And related hay from alfalfa and grasses can often be sold at a profit, with alfalfa hay often being more profitable than corn and soybeans over the past decade. The market opportunities, however, for these crops tend to be limited to forage and feed for animals - particularly dairy and beef operations. Recent years have seen a decline in acres of alfalfa due to various reasons such as reduced demand for alfalfa by dairy and beef producers who prefer corn silage instead, an often localized market, the need for improved insurance products to be competitive with corn and soybeans, potentially greater labor and equipment needs to grow alfalfa compared to other crops, among other barriers.

Despite these barriers, perennial forage and pasture is assumed to increase in this analysis for several key reasons. These include increased demand for grass-fed livestock (primarily cows), reduced demand for corn-fed cows, increased conversion of marginal croplands to forage/pasture as the aforementioned barriers are reduced, potential relocation of cattle based on drought conditions in the Western U.S. in coming decades, and continued increase in demand for plant-based proteins for humans, of which alfalfa could play a role.

For example, within Minnesota, a significant number of corn/soybean acres are considered marginal and are often unprofitable. These are acres that may be more readily transitioned to perennial crops due purely to economics. However, as described in the body of the report, not all marginal acres may be readily repurposed due to their location within fields. Thus if we assume half of marginal acres may be more readily transitioned to perennials, that would leave us with about 1.5 million acres potentially available today.

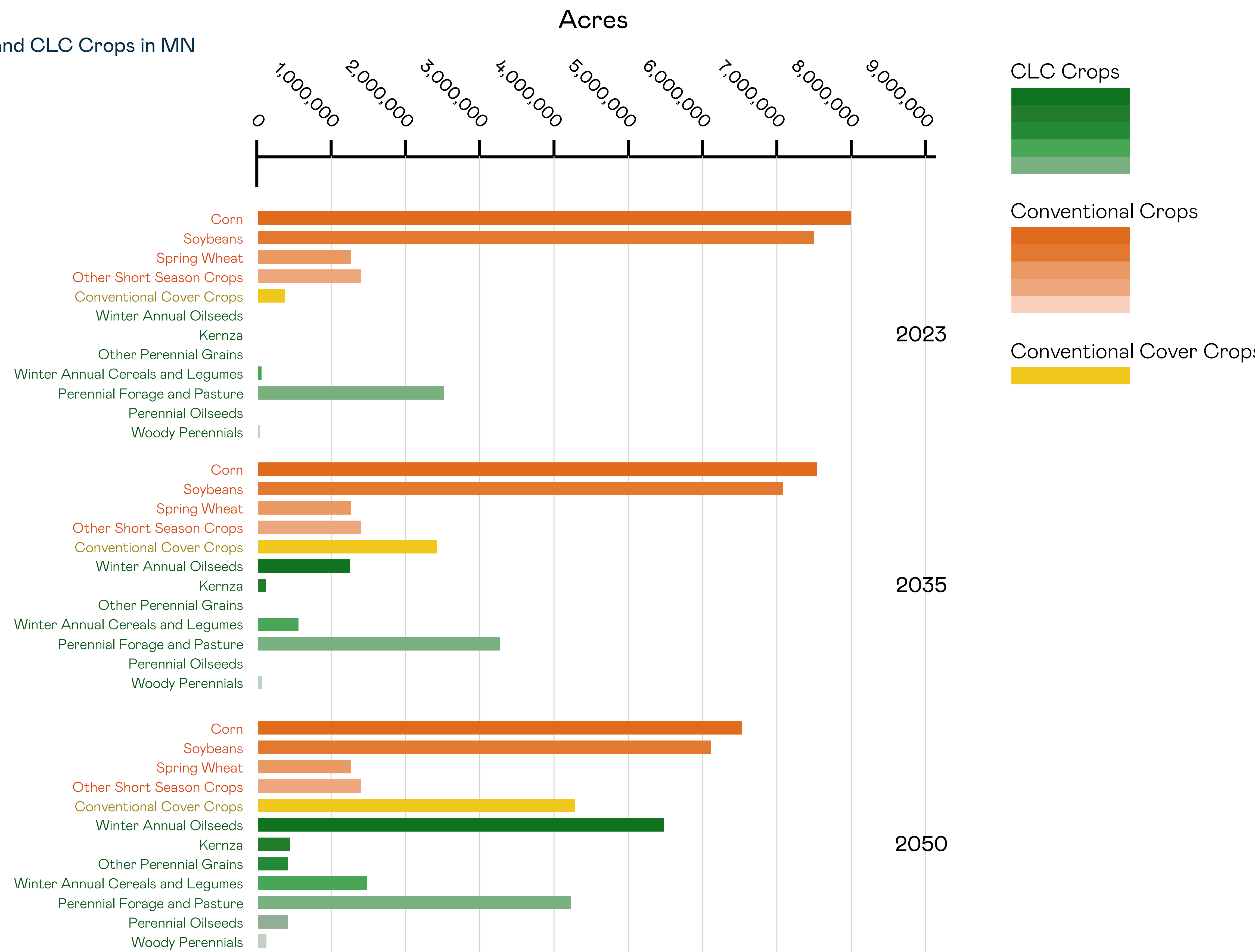
Related, the GHG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team in Minnesota (2022) estimated that perennial legumes could see an increase of 700,000 acres by 2050 and perennial grasses/pasture could see an increase of 800,000 acres by 2050 for reasons similar to those outlined above.

This collection of factors, along with expert interviews, led to the medium adoption scenario of an additional 1.5 million acres of perennial forage and pasture, beyond those already in production, by 2050. Given the already established markets for livestock feed that these crops serve, the expected steady growth in the demand for grass-fed livestock (Future Market Insights, 2023), and the uncertainty in when other innovations such as the use of alfalfa for human-consumption, we utilized a linear growth rate in acres adopted between now and 2050.

Figure 5.

Medium Acreage Scenario for Major Crops and CLC Crops in MN

Acreage projections in this section are particularly important for this analysis, as subsequent estimates of Minnesota's 'CLC score' (Section 2.B), environmental impact wedge analysis (Section 2. C), and economic analysis (Section 2.D) are tied to per-acre impact estimations.



Box 5: Views on the Future Acreage of Corn

Corn is clearly a major crop for the state of Minnesota. However, there are differing views on the future of corn acreage. Those who are bullish on corn's future see several factors that contribute to its positive outlook. Thanks to advancements in genetics, agricultural practices and technology, corn is increasingly productive and resilient. This resilience ensures a consistent and reliable supply of corn, even in the face of potential challenges such as climate change (particularly drought and high-temperature stress) or pests. Additionally, proponents point out that there is continued demand for corn-based ethanol, paired with opportunities for bioplastics, aviation and marine fuels and other crop utilization strategies that may contribute to the overall demand for corn and support its future prospects.

On the other hand, those with a bearish stance on the future of corn highlight the potential reduction in demand due to the increased adoption of electric vehicles (EVs). As EVs become more prevalent, the demand for traditional gasoline decreases. As ethanol is primarily used as a blending component in gasoline, a decline in gasoline consumption could lead to reduced overall demand for corn.

These differing viewpoints reflect the complexity of the factors influencing the future trajectory of summer annual cropping systems and the need for ongoing analysis and evaluation of the market dynamics. To account for the expected increase in perennials on current Minnesota cropland, however, this analysis assumes a reduction in corn acres. See Section 8 in the Technical Appendix for further details on corn acreage scenarios.

2.B Estimating Minnesota's "CLC Score"

For this report, we developed a "continuous living cover (CLC) score" that measures the percentage of the year that soils are protected by living roots and vegetation. This score excludes the period of the year with frozen ground, since the risks of nutrient loss, soil erosion, and GhG emissions from soils are greatly mitigated when soil is frozen.

Based on the "medium acreage adoption" scenario, this report used three snapshots in time (2023, 2035, and 2050)[3] and identified the proportion of the year that Minnesota's crop portfolio is providing living vegetative cover on the landscape (excluding those months when the ground is frozen and accounting for a delay from planting date to establishment of living cover)[4]. These scores are depicted in Figure 6.

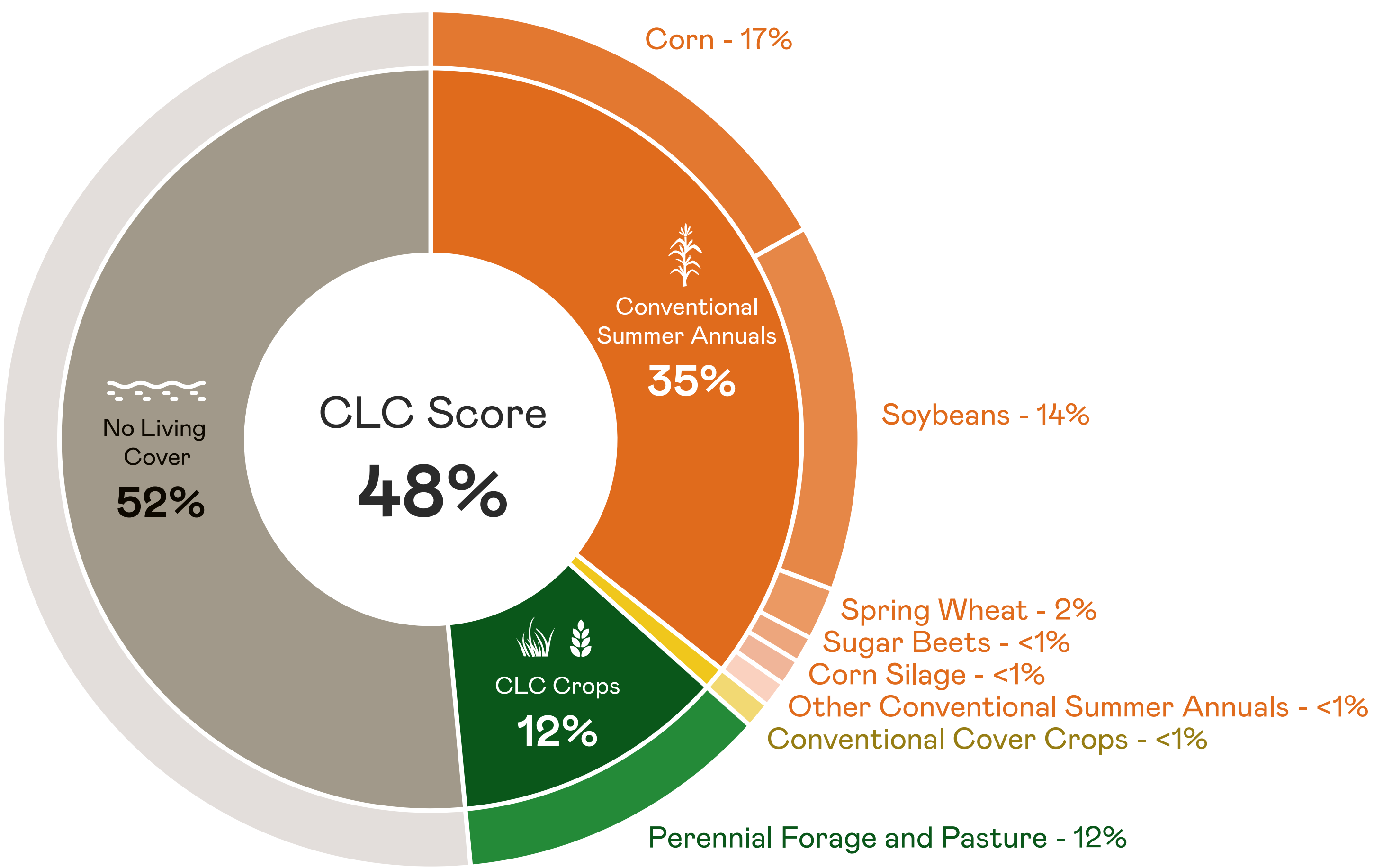
[3] Of note, it is expected that with climate change, the amount of time the ground is frozen each year is likely to reduce as we approach 2050. This potential reduction in the amount of time the ground is frozen is not currently considered.

[4] To build these estimates, we assigned an estimated average proportion of the year that each crop or crop category will provide ground cover. This includes a 2 week delay between when a crop is planted and when it will begin to provide the ecological benefits of ground cover. This was applied to all crops equally.

Figure 6.
Minnesota CLC Score from 2023 to 2050

Minnesota CLC Score for 2023

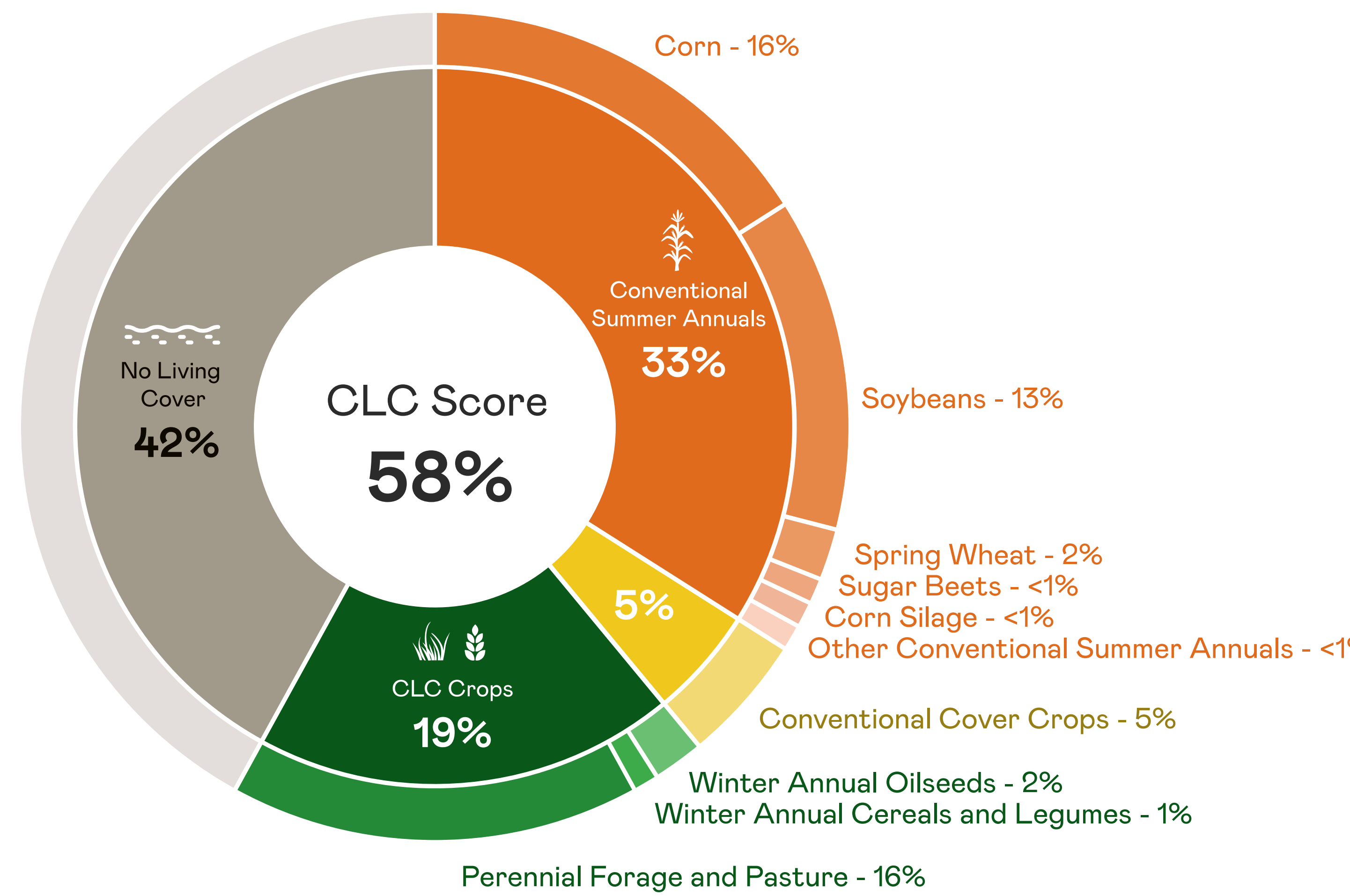
Scenario: Medium Acreage Adoption
Average proportion of the year that Minnesota cropland has vegetative cover (excluding when ground is frozen)



Figures are rounded and may not sum

Minnesota CLC Score for 2035

Scenario: Medium Acreage Adoption
Average proportion of the year that Minnesota cropland has vegetative cover (excluding when ground is frozen)

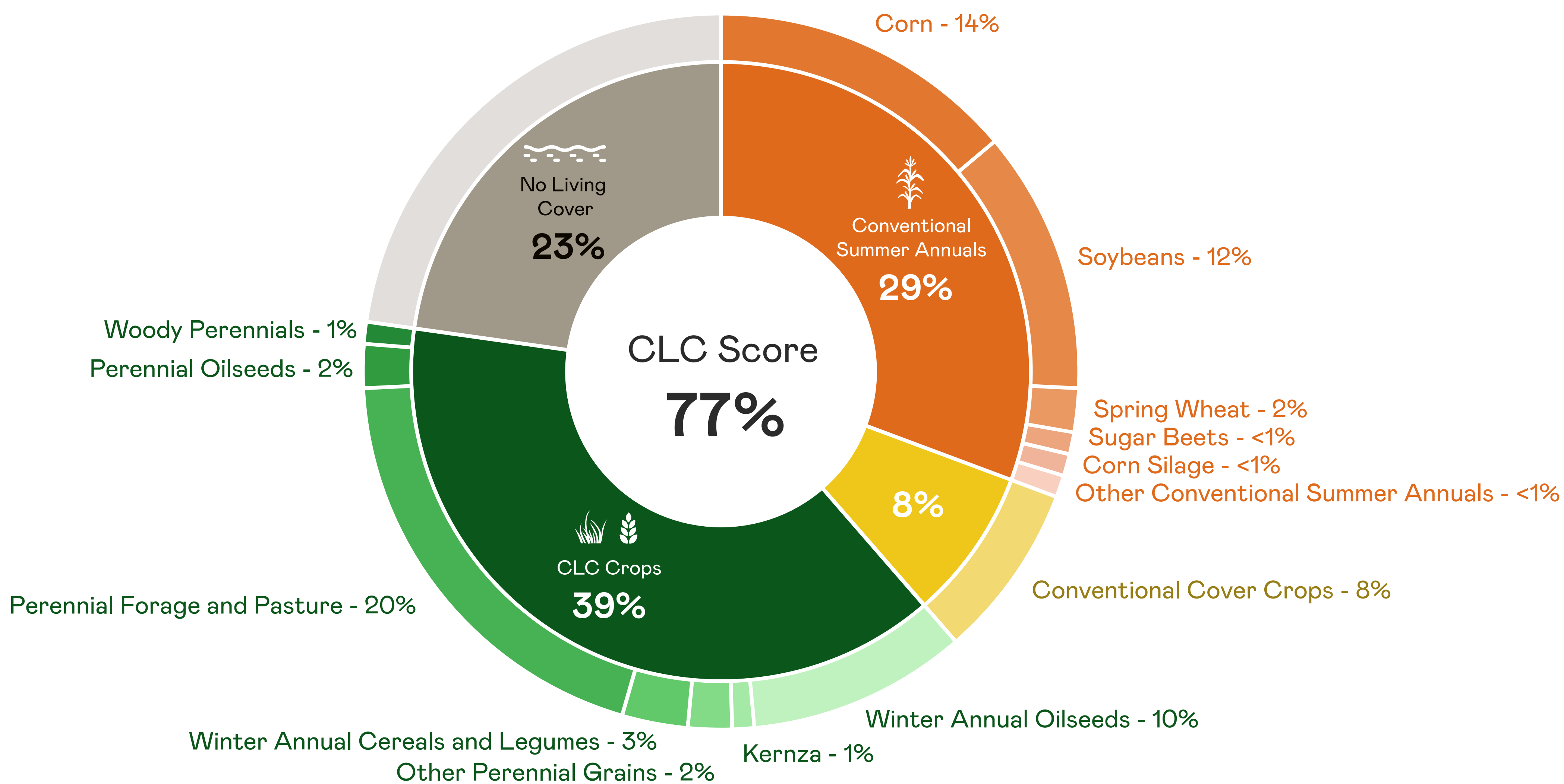


Figures are rounded and may not sum

Figure 6. (continued)
Minnesota CLC Score from 2023 to 2050

Minnesota CLC Score for 2050

Scenario: Medium Acreage Adoption
Average proportion of the year that Minnesota cropland has vegetative cover (excluding when ground is frozen)



Figures are rounded and may not sum

Figure 6 shows that Minnesota's 2023 CLC Score is estimated at 48%. This means that with our present crop portfolio, the average acre of agricultural land has living vegetative cover just 48% of the time (excluding the time the ground is frozen). The most likely crops on any given acre are corn (17%) or soybeans (14%). In addition, perennial forage/pasture (12%) provides crop coverage year-round - but is deployed on fewer acres. This figure shows that 52% of the time there is no living crop on the land.

In some cases there may still be crop residue such as corn stover, left on top of the soil following harvest. Crop residue can provide benefits of reduced soil erosion (see Box 6 for details), although this score is focused on living vs. non-living cover. The current low amount of living cover is the product of our reliance on summer annual crop rotations that are planted in late spring or early summer and harvested in the fall. As a result, our soils are left unprotected by living vegetation ("no living cover" in the graphic).

These soils without living cover are at heightened risk of erosion (either from rainfall, heavy winds, or snowmelt) and nutrient loss. As will be shown in later sections of this analysis, there are variations in the size of the benefit provided by the different types of living cover. For example, the amount of benefit from winter annuals will depend on how well they establish prior to winter.

Moving to 2035, the number of acres of winter annuals and perennials begins to increase, driving up the average proportion of time any given acre has living vegetative cover on it. As a result, Minnesota's CLC score improves to 58%, while the portion of the year where there is no living cover is reduced to 42%. Also noticeable is the slight decline in corn or soybeans as all perennials and, particularly, perennial forage/pasture are assumed to replace corn and soybean acres. Winter annuals are integrated into short-season summer annuals initially (as previously described) and, by 2035 are integrated into corn and soybean acres. Together the increase in these crops alters Minnesota's overall crop portfolio. In addition, we assume an increase in the rate of conservation practice adoption over time, resulting in an increase in conventional (non-harvested) cover crops. These also contribute meaningfully to an improvement in the CLC score.

By 2050, Figure 6 shows the rate of CLC adoption has increased significantly, and Minnesota's CLC score jumps to 77%. As such, the average proportion of time an acre of agricultural land in Minnesota has no living cover is only about 23%. This is driven primarily by large increases in perennial forage and pasture, and winter annuals (particularly winter annual oilseeds). Smaller changes, including further adoption of conventional (non-harvested) cover crops, contribute to the score improvement.

As demonstrated in the following sections, this increase in average CLC score over time can produce significant environmental and economic benefits.

Box 6: Crop Residue Cover Supports Reduced Erosion

The CLC score is focused on isolating the proportion of time on average that cropland has living cover or not. This means it does not control for whether there is crop residue on the field (non-living material left on the field after a crop has been harvested) or if the field is bare. This is important to note because crop residue, when left on the field, can provide some similar types of benefits as living cover, such as reduced wind erosion and increased water infiltration (Blanco-Canqui and Wortmann, 2017; He et al., 2017; Mulla et al., 2019). While crop residue does add organic matter to the soil it doesn't take up nutrients or actively photosynthesize the way living cover does.

2.C Environmental Impact Wedge Analysis

The environmental impact analysis included in this report is modeled on the example of well-known GhG reduction 'wedge models' that marry the expected market growth of renewable technologies and practices with associated GhG reductions. Such models help us understand the percentages (or 'wedges') of change provided by a future portfolio of activities over time. The size of the wedge shows the relative size of the benefit from each CLC crop category.

These wedge graphs depict the outcomes under the "medium" adoption and "medium" impact scenarios to describe the environmental outcomes we could reasonably envision from a future portfolio of CLC cropping systems. We include the upper and lower boundary scenarios in Technical Appendices 10-14.

Acreage is the leading lever for determining how much impact will be generated, given that the environmental impacts are derived from per-acre values. The impact per acre is the extent that the crop helps/hurts the environment in terms of how its effect differs from the business-as-usual condition. Establishing the impact per acre was based on a literature review of 60+ resources documenting the effects of different CLC crops compared to a given counterfactual (which varied by study). We reviewed those measurements that are from the most robust studies (see Bibliography in Section 6), that used the appropriate counterfactual (i.e. comparison against corn/soybeans) and that were aligned to the context of Minnesota. Within these measurements, there were ranges of values, which were then used to establish our upper and lower bounds of impact. For example, studies of Kernza® show it reduces nitrogen leached compared to corn (Jungers et al., 2019). The proportional reduction compared to corn is not a static value and will vary depending on multiple factors - soil, weather, slope, rainfall, time of year, etc. As a result, the benefit per acre from Kernza® exists within a range. As mentioned, the medium value is used for wedge graphs. The annual acreage scenario for each crop is then multiplied by the corresponding impact per acre of that crop.

There may also be variation within the crop category that informs the upper and lower bounds of potential impacts per acre given the breadth of crops included in the category. For example, perennial forage and pasture can range from a monoculture of alfalfa to a polyculture of grasses and legumes. The implications of this variation is that the impact relative to a counterfactual of corn/soybeans will differ, with polycultures of grasses and legumes informing the upper bound of impact per acre, and monocultures of alfalfa (for example) informing the lower bound. Given the body of this report focuses on the medium impact per acre, we arrive at this by taking an average between upper and lower bounds. Future analysis may take a more specific approach to estimating values by each of the different crops within the perennial forage and pasture category.

Each environmental wedge graphic also includes an additional wedge depicting the supplemental impacts of Best Management Practice (BMP) adoption on conventional summer annual acreage, including cover crops, no-till, and nutrient management. More information about this methodology is available in Technical Appendix 9.

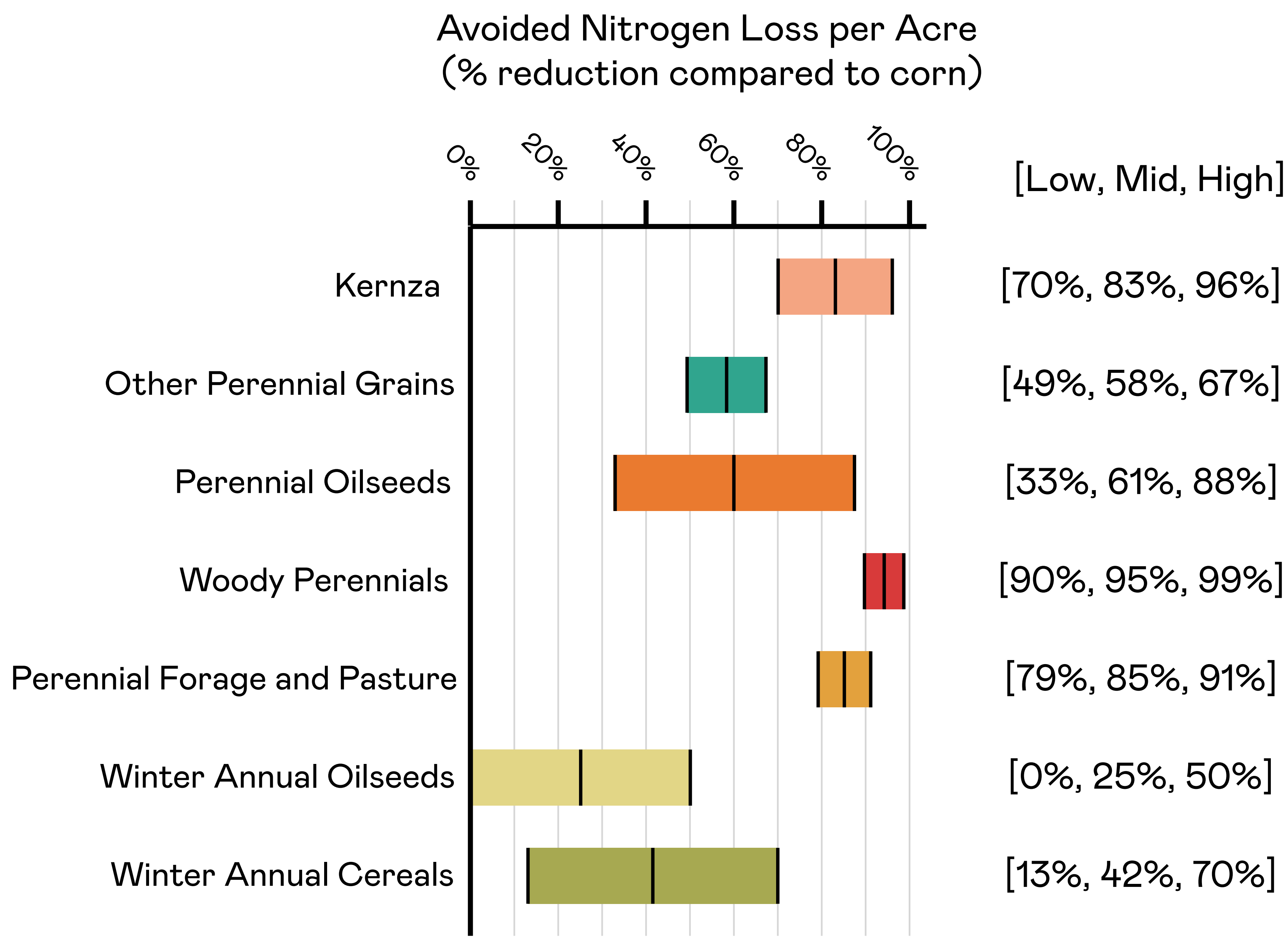
Box 7: Interpreting Wedge Graphics

The y-axis of each figure below (8, 10, and 11) shows the total estimated nitrogen loss, soil eroded or GhG emissions and the starting point in 2020 represents the business as usual scenario. This business-as-usual scenario, as estimated in 2020-2023, is assumed to be static going out to 2050 to create a constant baseline the CLC crops can be measured against. When reviewing the scale of the y-axis, it is important to note that not all crops in Minnesota are accounted for (although 99% of acres of row crops are accounted for, very minor row crops and horticultural crops were not included) and the impacts from livestock that may be on the land are not included. However, both of these can and do impact the total nitrogen loss, soil erosion or GhG emissions for Minnesota. Thus, the total values used in the business-as-usual scenario should not be considered the total value for all agricultural activities in Minnesota. They serve as a benchmark to gain a sense of the scale of impact that can be achieved by CLC crops. To complement the role of CLC crops, BMPs are included in the environmental wedge analysis to help communicate the additional role those practices can play in achieving improved environmental outcomes (See Technical Appendix 9 for details).

Nitrogen loss wedge analysis

Reducing the amount of nitrogen lost to either surface waters or groundwater is an important component of achieving the state's water quality and drinking water goals. Each of the CLC crops and crop categories contributes to a reduction in nitrogen lost to water as maintaining living roots in the ground reduces runoff and leaching. Further, some CLC crops have lower nitrogen fertilizer requirements reducing the amount of nitrogen that could be lost. Figure 7 shows the range of impacts per acre for each crop category. The medium value is used in calculating the figures for Figure 8. Crops like woody perennials, perennial forage and pasture, and Kernza tend to have the highest rates of avoided nitrogen loss compared to corn/soybean rotations.

Figure 7.

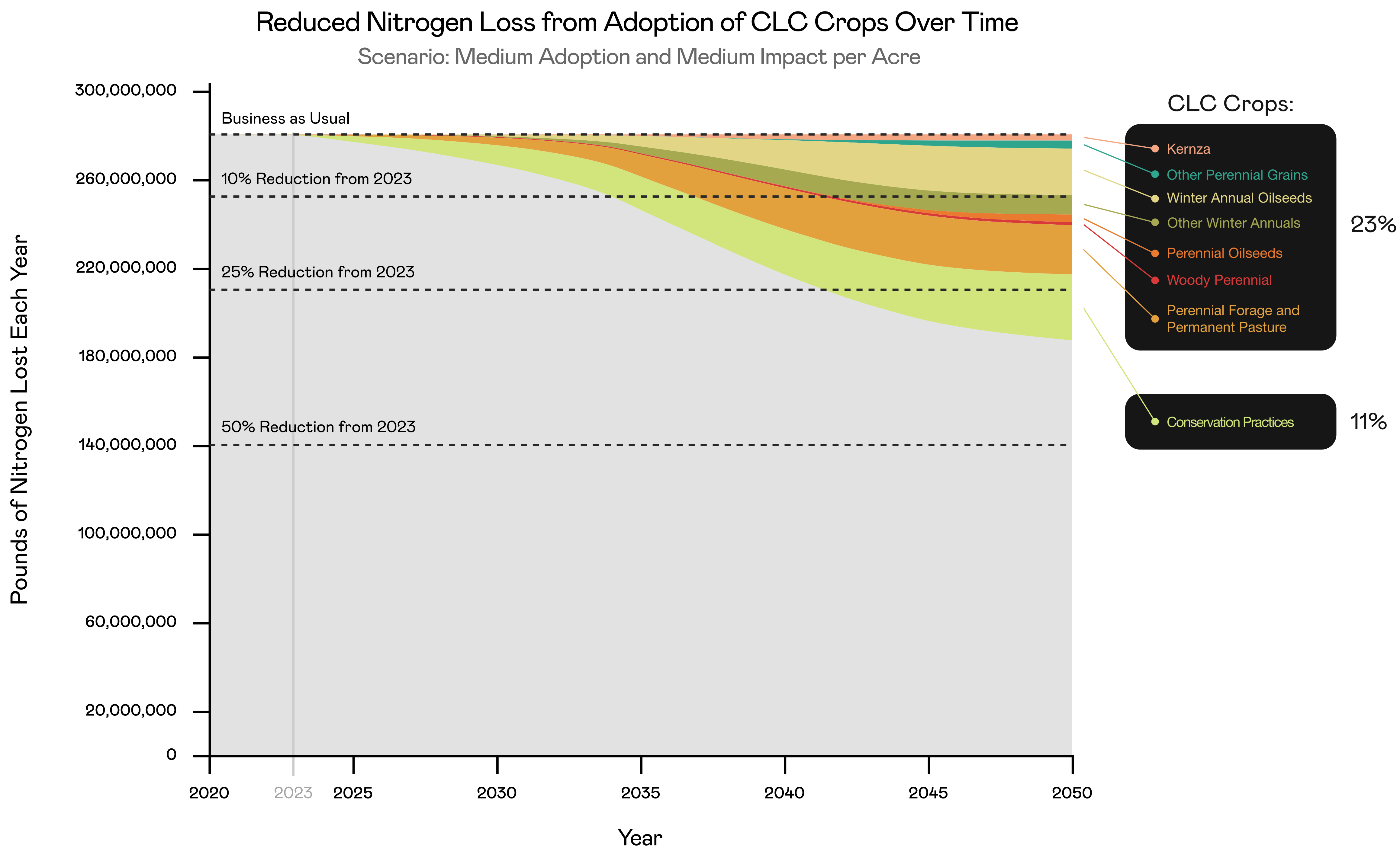


Note: The pounds of nitrogen lost per acre are contingent on the counterfactual used. Comparison against corn/soybean is used for all perennials and for winter annuals after 2035. Prior to 2035 the benefit per acre of winter annuals is applied to short-season crops where it is assumed they would not otherwise have a cover crop. Certain crops such as Perennial Grains and Perennial Oilseeds have little existing evidence and as a result rely on proxy values from other crops. See the technical appendix for details.

Referencing the benchmark lines included in Figure 8, CLC crops can reduce nitrogen loss by 23% by 2050. With the inclusion of conservation practices deployed on conventional summer annual acreage, the reduction could be over 34%.

As Figure 8 demonstrates, perennial forage and pasture is the most impactful crop category, followed closely by winter annual oilseeds. This is because these two crop categories have the largest potential increases in acreage by 2050 (about 1.7 million for perennial forage and 5.5 million for winter annual oilseeds) while having a significant impact per acre. In particular, perennial forage and pasture can reduce nitrogen loss by up to 90%, over twice as effective as winter annual oilseeds (compared to corn production).

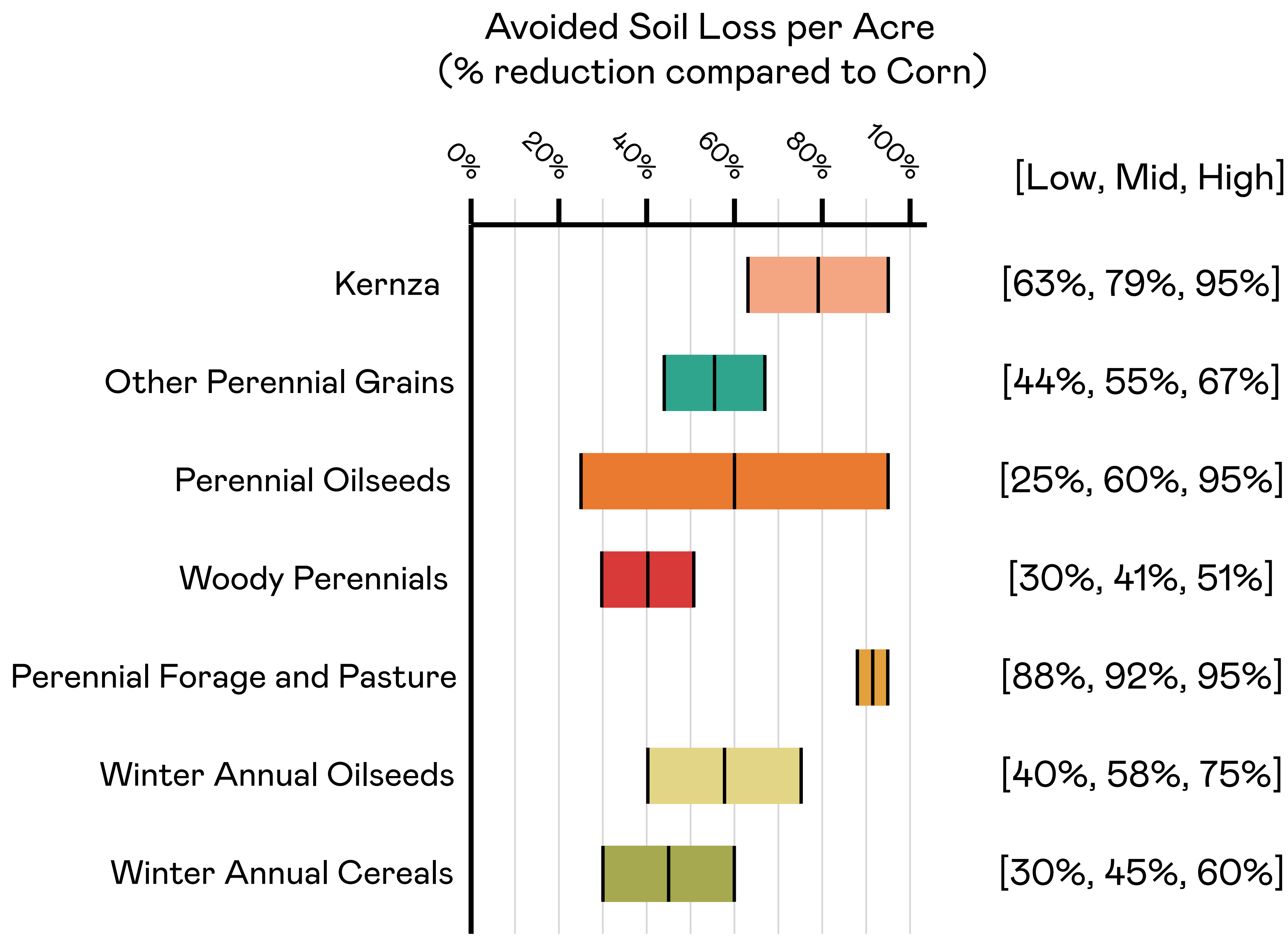
Figure 8.



Soil erosion wedge analysis

The second environmental wedge looks at changes in rates of soil erosion from increased CLC crop adoption. Not surprisingly, we see that CLC crops have great potential to reduce soil loss, due to the combination of both increased ground cover and increased proportion of the year with live roots in the ground. Figure 9 shows the impact per acre from each crop category with the medium value being used to calculate the values in Figure 10. Crops such as perennial forage and pasture, as well as Kernza tend to be particularly effective at reducing soil erosion.

Figure 9.



Note: The upper bounds of impact are generally from studies that are making a comparison against a cropping system with little to no crop residue left on the field after harvest, while lower bounds of impact may include a mix of crop residue amounts on the field. See Technical Appendix for specific citations referenced for each. Similarly, certain crops such as Perennial Grains and Perennial Oilseeds have little existing evidence and as a result rely on proxy values from other crops.

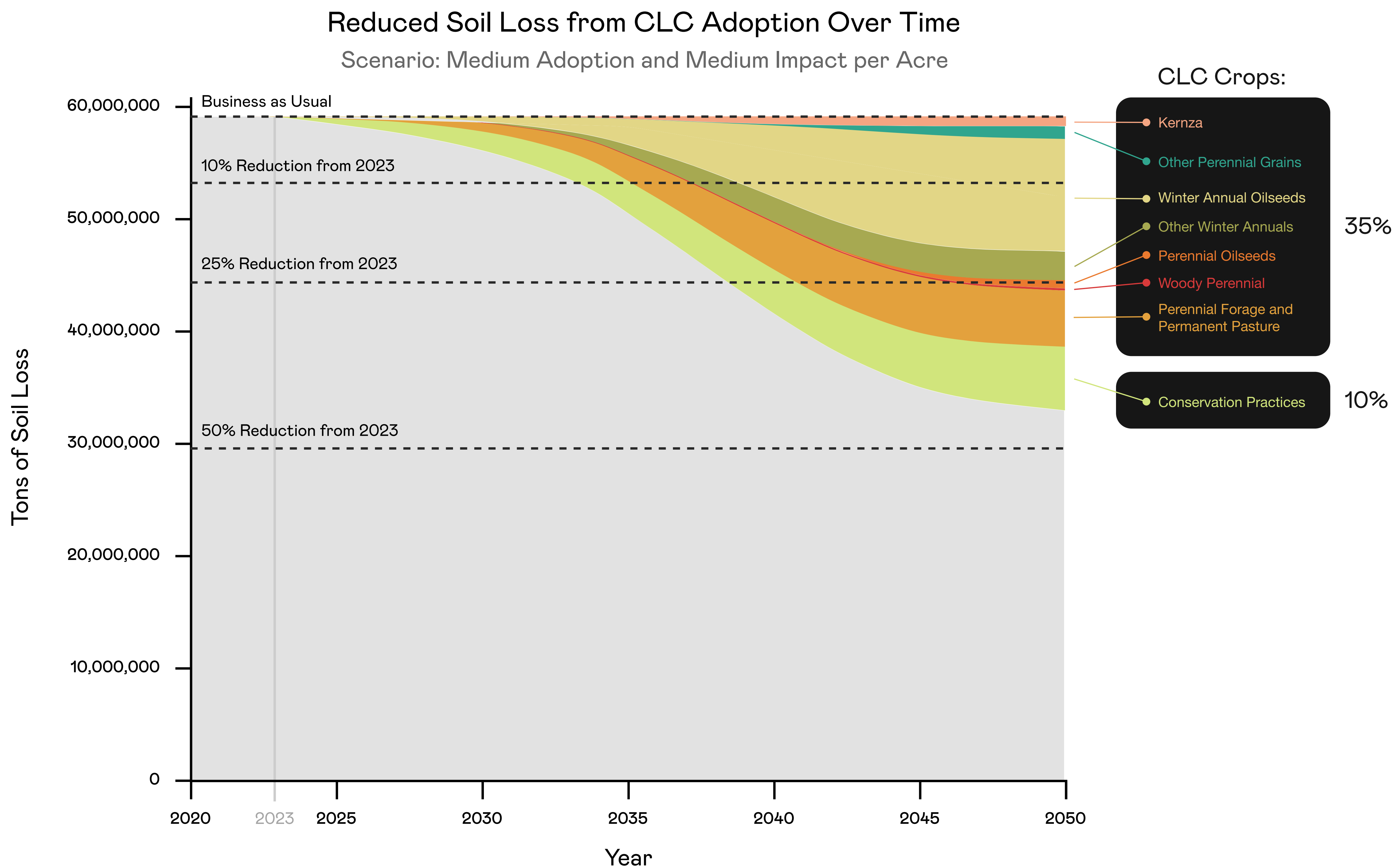
Referencing the benchmark lines included in Figure 10, the adoption of CLC crops can support a 35% reduction in soil loss under the current medium adoption and medium impact scenario. With the inclusion of the increased adoption of conservation practices on conventional summer annual acreages, the reduction can reach over 45% by 2050.

Winter annual oilseeds have the greatest projected impact in this scenario. This is due to both the expected scale of adoption (over 5 million acres by 2050) and their ability to provide ground cover during a time period when the soil would otherwise often be bare.

Perennial forage and pasture also perform well. While their per-acre impact is higher than winter annuals (since they provide greater year-round benefits), we anticipate a smaller net increase in new acres (1.7 million additional acres) and therefore their overall contribution to reduced erosion is less than that of winter annuals.

Other winter annuals come in third, due to the relatively large number of acres of adoption envisioned while providing a similar benefit per acre, often in line with conventional cover crops given some of the winter annuals, such as rye can be used as an unharvested cover crop as well.

Figure 10.



Greenhouse gas emissions wedge analysis

The third environmental wedge analysis examines on-farm greenhouse gas emissions. Before describing the results, it's important to note two key elements of this analysis:

1. Scientific uncertainty: The science of on-farm GhG emissions assessments is subject to significant uncertainty as methods are revised, new monitoring tools are developed, new cropping systems are studied in new contexts, and scopes of analyses are continually updated. As a result, the evidence base for on-farm GhG performance estimates is evolving and subject to change (See Box 3).

2. On-farm vs lifecycle emissions: It is important to distinguish on-farm and lifecycle GhG emissions in cropping systems. The cropping systems described in this report are integrated into a variety of food, feed, fuel and consumer goods supply chains. However, this analysis focuses only on the on-farm emissions and does not account for post-farm-gate emissions (or emissions reductions) associated with the full lifecycle of those end-use products (See Box 9 for an example).

CLC crops in Minnesota, particularly perennials, have the potential to support GhG reductions through on-farm emissions reductions and through reduced nitrous oxide (N2O) emissions through reduced use of nitrogen fertilization compared to conventional summer annual crops such as corn. Some systems have the potential to increase carbon sequestration and carbon storage in biomass. However, CLC crops can also contribute to increased agricultural emissions - as some CLC crops may require additional fertilizer application for desired yields. In the case of winter annuals, this may result in increased per-acre N2O emissions.[5]

Two figures detail the greenhouse gas potential of CLC crops in Minnesota. Due to the unique characteristics of the winter annual oilseeds, Figure 11 excludes them and Figure 12 depicts their results in detail. Both figures depict changes in net CO2 and N2O emissions reported as CO2 equivalents (CO2e). CH4 is a third greenhouse gas that is important in the agricultural sector however it does not factor into this analysis given the bulk of these emissions come from animal production rather than crop production (e.g. enteric emissions from ruminants such as cows).

This analysis makes two primary assumptions as a part of the approach to projecting the rate of carbon sequestration. The first is that it assumes that the carbon initially sequestered remains in the ground, although future management practices, such as tillage of fields, may end up releasing previously sequestered carbon. The second is that rates of sequestration will diminish to zero over a 10 year time period as the amount of carbon that can be stored in the soil will reach its maximum (See Box 8 for additional details). This is a conservative time frame to help manage for the uncertainty in future management practices. Gutknecht and Jungers (2021) for example, summarize that the highest rates of sequestration are likely to occur for the first 10-20 years assuming no change in practice occurs during that time period that could release the soil carbon. The amount of time the soil will continue to accumulate carbon depends on how depleted the soil was to begin with. More aggressive analyses may extend the currently used 10 year time frame to be 20+ years. The result of our conservative time frame is a reduced amount of GhG being mitigated by years 2045 and beyond under current model assumptions. This is why the wedge chart begins to curve upward at that point (see Box 8 for further explanation).

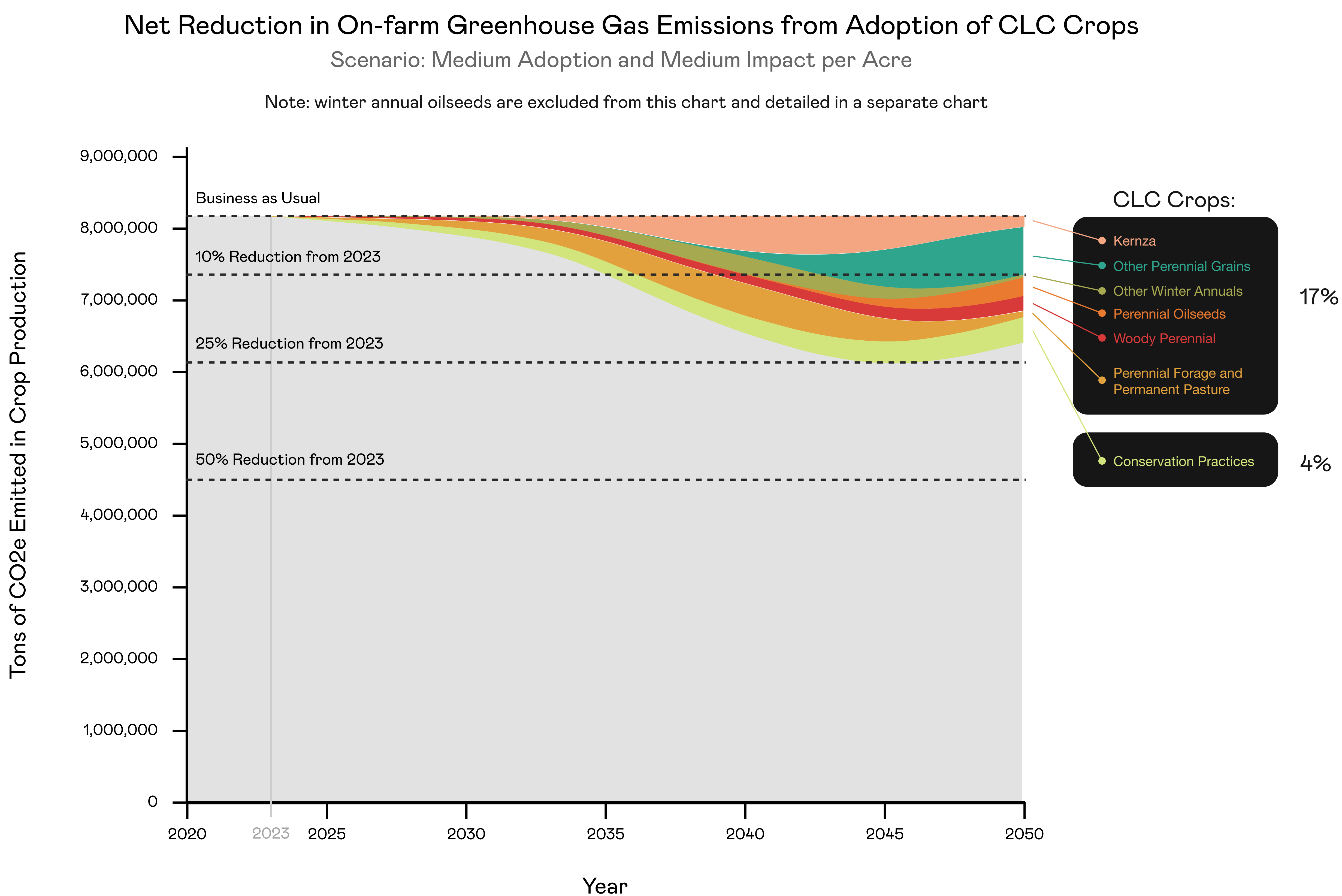
Figure 11 depicts how the increased adoption of CLC crops (excluding winter annual oilseeds) can lead to a reduction in emissions over time, with 17% lower emissions in 2050 compared to the business-as-usual. Due to shifting rates of envisioned adoption and reduced rates of carbon sequestration following adoption, different crops provide the greatest benefit at different times. In the near term, perennial forage and pasture is the leading crop category driving GhG reductions.

This is due to the combination of sheer number of acres in the medium adoption scenario, and the relatively large impact per acre. However, as time goes on, Kernza and other perennial grains provide the greatest benefit due to the combination of delayed adoption, sizable number of acres adopted following the delay (over 600,000 for all perennial grains by 2050), and large emission reduction potentials.

Other crop categories such as winter annual cereals and legumes, woody perennials and perennial oilseeds provide GhG reductions but they are not adopted at a scale that provides the same level of impact as other CLC crops.

[5] Nitrous oxide has a Global Warming Potential approximately 295 times greater than carbon dioxide.

Figure 11.



Net Reduction in On-farm Greenhouse Gas Emissions from Adoption of CLC Crops
Scenario: Medium Adoption and Medium Impact per Acre
Note: winter annual oilseeds are excluded from this chart and detailed in a separate chart
Tons of CO2e Emitted in Crop Production
9,000,000
8,000,000
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Business as Usual
10% Reduction from 2023
25% Reduction from 2023
50% Reduction from 2023
2020
2023
2025
2030
2035
2040
2045
2050
Year
CLC Crops:
Kernza
Other Perennial Grains
Other Winter Annuals
Perennial Oilseeds
Woody Perennial
Perennial Forage and Permanent Pasture
17%
Conservation Practices
4%

Box 8: Interpreting Figure 11

Figure 11 shows that, while CLC crops can each contribute to a reduction in on-farm GhG emissions, the rate of reduction diminishes over time each year as the amount of additional carbon that can be sequestered in the soil each year is less and less.

Figure 11 can be read in the same way as Figures 8 and 10, however, it requires some additional interpretation to understand why it looks different. As CLC crops are adopted they can reduce the net GhG emissions from crop production relative to the BAU, similar to how CLC crops can reduce nitrogen loss and soil erosion. In Figures 8 and 10 however, the benefit per acre per year is assumed to be constant (e.g. Kernza provides the same benefit relative to corn/soybeans every year). So as more acres of the CLC crops are adopted, a proportional increase in benefits is realized.

With GhGs however, the benefit per acre per year is not assumed to be constant - the amount of additional carbon that can be sequestered is limited by what the soil can absorb and as has been described, the amount of carbon sequestered will decline over time. As a result, the GhG benefit per acre relative to the BAU scenario becomes smaller over time.

This is reflected in Figure 11 by the upward slope of the graph in the out years. This does not indicate an increase in emissions, but rather that the potency of year-over-year GhG emissions reductions declines slightly over time (assuming the CLC crop is being grown on the same acres). This reduced rate of sequestration is coupled with the plateauing of additional acres adopted each year. As fewer acres are added each year and as the amount of carbon that the soil can absorb diminishes, the additional carbon stored each year will diminish as well.

In order for the wedges to continue to grow out to 2050 and beyond, the number of acres of CLC crops adopted would need to grow at a rate fast enough to counteract the reduced net GhG benefit of the previously planted CLC crops. This is important because some estimates show the carbon sequestration can offset up to half of the total GhG emissions profile of each crop although there remains significant scientific uncertainty in this measure (Berti et al., 2017; Cecchin et al., 2021). As a result, a potentially large portion of the net GhG benefit of CLC crop adoption will be lost over time.

When reviewing Figure 11, the area of each wedge is the cumulative emissions avoided since 2023 compared to the BAU. In all years, the CLC crop portfolio outperforms the BAU.

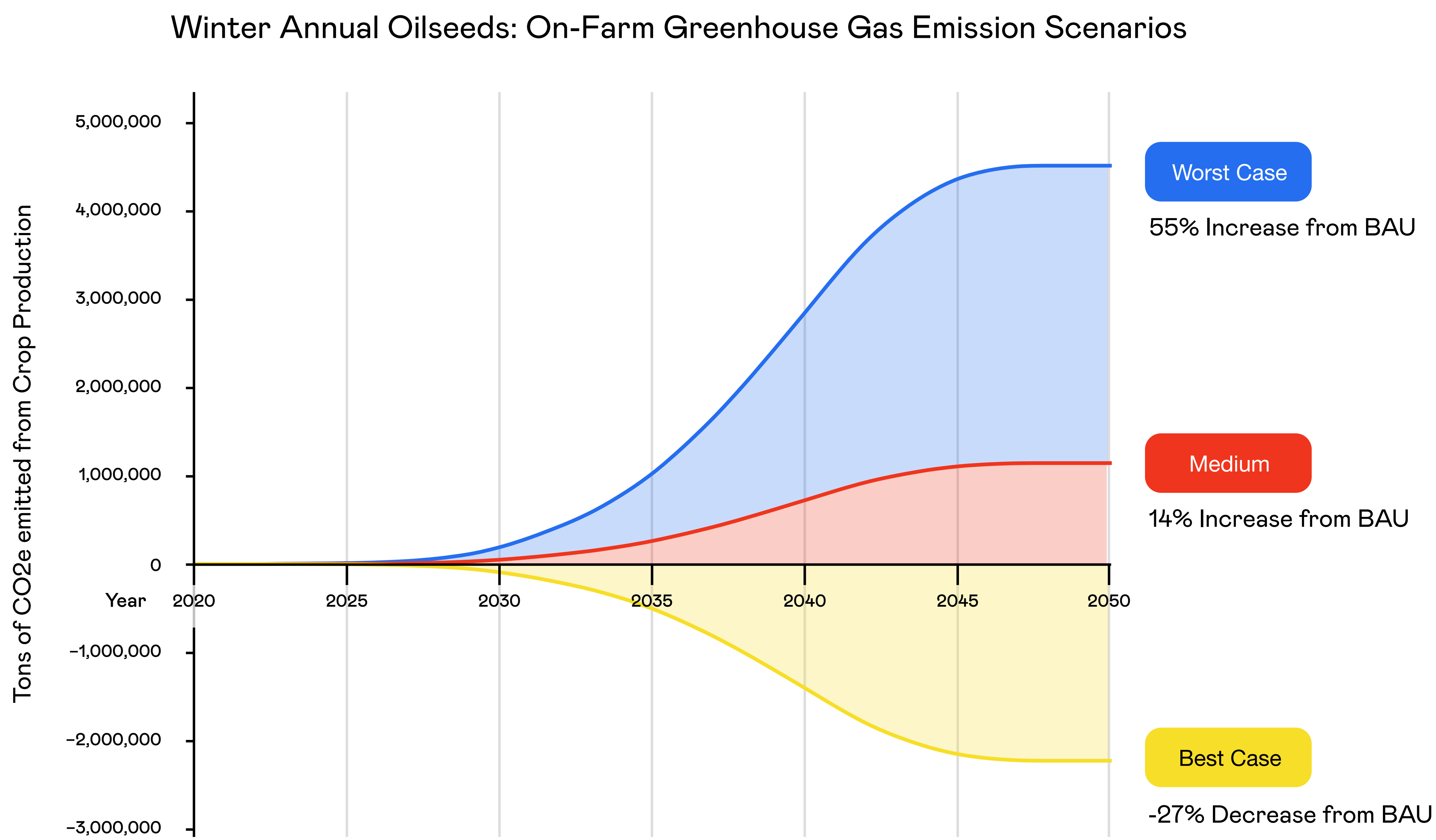
Notably, winter annual oilseeds are excluded from this wedge chart (Figure 11). This is because there is an exceptionally wide range of estimated greenhouse gas emissions changes from winter annual oilseed production, ranging from a net increase in on-farm emissions to a net decrease in on-farm emissions. Given the potential for these cropping systems to be deployed on millions of acres in Minnesota, we separate winter annual oilseeds to examine this uncertainty more closely.

Figure 12 depicts the on-farm GhG emissions performance of winter annual oilseeds under worst-case, medium-case and best-case impact scenarios. The best-case scenario provides a net reduction in emissions, while medium-case and worst-case scenarios have a net increase in emissions. However, the winter oilseeds hold great potential to reduce emissions from the transportation sector if they are used as a biofuel feedstock (see Box 9).

This variation in GhG emissions is due primarily to the management practices utilized, such as the number of passes on the field, fertilizer usage and tillage methods. Additional fertilizer applications carry the potential for additional nitrous oxide emissions (N_2O), a potent greenhouse gas. Additional tillage has the potential to release carbon previously stored in the soil. In all cases, not just winter annual oilseeds, farming practices play an important role in managing on-farm GhG emissions from both conventional and CLC cropping systems. Additional research into strategies for optimizing winter annual oilseed production is warranted.

When combining the estimated 17% reduction in emissions from CLC crops (from Figure 11 and excluding winter annual oilseeds) with the estimated 14% increase in emissions from the medium scenario of winter annual oilseeds (Figure 12) the result is a net 3% reduction in on-farm GhG emissions relative to the business as usual row crops in Minnesota. When adding in the benefit from conservation practices applied to summer annual acres, there is a net reduction of about 8%. Using the winter annual oilseeds to mitigate transportation emissions could substantially improve the net lifecycle GhG emissions from CLC agriculture (Box 9).

Figure 12.



Note: These emissions are in addition to those of Figure 11.

Box 9: Accounting for Winter Annual Oilseed Lifecycle Greenhouse Gas Emissions

When included as a feedstock for transportation fuels, winter annual oilseeds like camelina and pennycress result in significant lifecycle greenhouse gas reductions compared to conventional fossil fuels and biofuels (including from summer annual oilseeds like soybeans). Studies have found that pennycress and camelina-based aviation fuel and biodiesel can reduce greenhouse gas emissions relative to petroleum-based fuels by 63-92% and 40-60% respectively (Fan et al., 2013; Shonnard et al., 2010; Li and Mupondwa, 2014). Since they increase the amount of oil that can be produced in a given year, rather than taking oil off the market as soybean biofuels do, they do not incentivize new oilseed production. This production often occurs on natural land that is converted to agriculture, such as tropical rainforests, which has huge implications for GhG emissions and biodiversity (Zanetti et al., 2021). In this analysis, these "downstream" GhG reductions are not included in the on-farm GhG performance wedges but should be taken into account when evaluating the overall climate impacts of CLC systems.

While on-farm emissions may increase with the adoption of winter annual oilseeds, preliminary analysis shows that the GhG emissions reductions from replacing fossil transportation fuels outweighs, on average, potential on-farm emission increases. The average emission reduction equates to approximately 14.9 lbs of co2e per Mj for biodiesel and 25.5 lbs of co2e per Mj for jet fuel. As a result, even under the high on-farm emission scenario (10.5 lbs of co2e per Mj) the net savings from replacing petroleum-based fuels outweigh the potential increase in on-farm emissions. (See Ecotone estimation in Technical Appendix 15 for further details)

Given the scale of this emission reduction, there is expected to be significant demand from the major airlines as they seek to reduce their carbon footprint. In addition, residual seed material available after oil extraction is rich in protein, which has many potential uses as animal feed and direct human consumption.

2.D Economic Impact Analysis

Assessing the economic impacts of CLC cropping systems shows there is an opportunity for increasing both total on-farm revenues and total on-farm net returns.

- On-farm revenue: Revenues consist of the total income received from crop production. The scale of revenues generated is an important indicator for total (on and off-farm) economic impact.
- On-farm net returns: Net returns capture the profitability of the farm, calculated as revenues minus expenses. The scale of net returns is an important indicator for business health. This analysis excludes land rent from the expenses side of the equation to help make the comparisons between summer annuals and CLC crops less dependent on the rental price paid, if any, while also acknowledging that winter annuals will share the same acreage as summer annuals.

The CLC cropping systems detailed in this report are being developed to utilize agricultural land for greater portions of the year, either by maintaining a constant crop (perennials) or implementing a double cropping system (integrating winter annuals with conventional summer annuals). This may increase the productivity and potential per-acre profitability of the land.

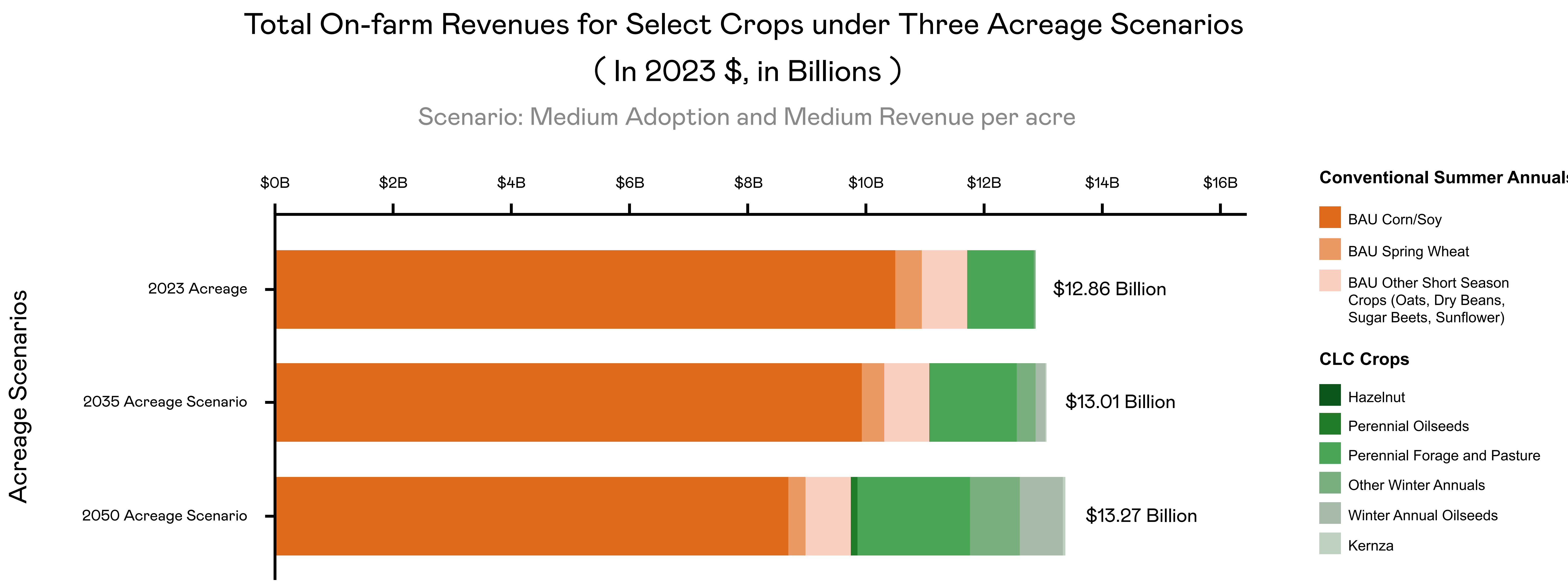
In order to estimate the economic impacts of CLC cropping systems in Minnesota, a different approach was needed than the environmental wedges previously detailed, due to the more limited data available on CLC economics as well as the significant market uncertainties associated with any market forecasts. Given several of the CLC crops of interest are pre-commercialization or very early in their commercialization, market prices are either non-existent or highly variable depending on the buyer. Similarly, market conditions are constantly shifting, making projections around crop supply and demand through 2050 a highly uncertain undertaking.

To manage these uncertainties, we utilize the acreage scenarios created in the medium-adoption scenario for 2023, 2035 and 2050, and apply the current pricing and/or recent historical average of on-farm revenues and net returns to a subset of CLC crops that have either existing financial data or expectations of financial performance. This serves to show what total revenues and net returns could look like holding current market conditions constant. These values can vary from year to year and farm to farm based on many factors - management practices, equipment used, inputs used, market prices, market accessibility, weather conditions, among others. Thus, revenues and net returns exist along a range. More information about the upper and lower bound assumptions for this range is available in the Technical Appendix in Tables 10 and 11. This does not include any financial effects from the adoption of BMPs nor does it account for the transition costs a grower may experience such as time spent learning about the new crop, any equipment modifications, etc.

On-farm revenues

As Figure 13 shows, under a medium adoption and medium revenue scenario, total on-farm revenues would increase from $12.86B to just over $13.27B were the 2050 CLC crop portfolio scenario in place on the landscape today. This represents an increase of 3%. In each scenario the total revenues are largest for corn/soybeans but when we increase the acreages of winter annuals and perennials, those bars (represented in green in Figure 13) grow and contribute more to the total revenue in Minnesota.

Figure 13.



Box 10: Valuing Perennial Forage and Pasture

We assumed that forage from alfalfa (as a proxy for perennial legumes) or perennial grasses produces net returns based on the market price of hay either specifically from alfalfa or hay generally. However, these crops are not necessarily sold as hay because in many cases the crop may be grazed or harvested and then used on-farm. We make the assumption that regardless of whether these crops are sold, the market value of it is still being captured. This is an important assumption because in doing so it supports a net increase in on-farm revenues in Minnesota, whereas there might otherwise be a slight decline by 2050.

Future analysis may conduct a review of crop by crop revenue and net returns (including the percent of crops that are sold vs. used on farm) including how the production of perennial forage and pasture influences the animal production operations that are the primary buyers of hay at this time. Organizations such as Grasslands 2.0 have built tools to help showcase the economics of a grazing operation that accounts for the animals themselves, something this analysis excluded.

On-farm net returns

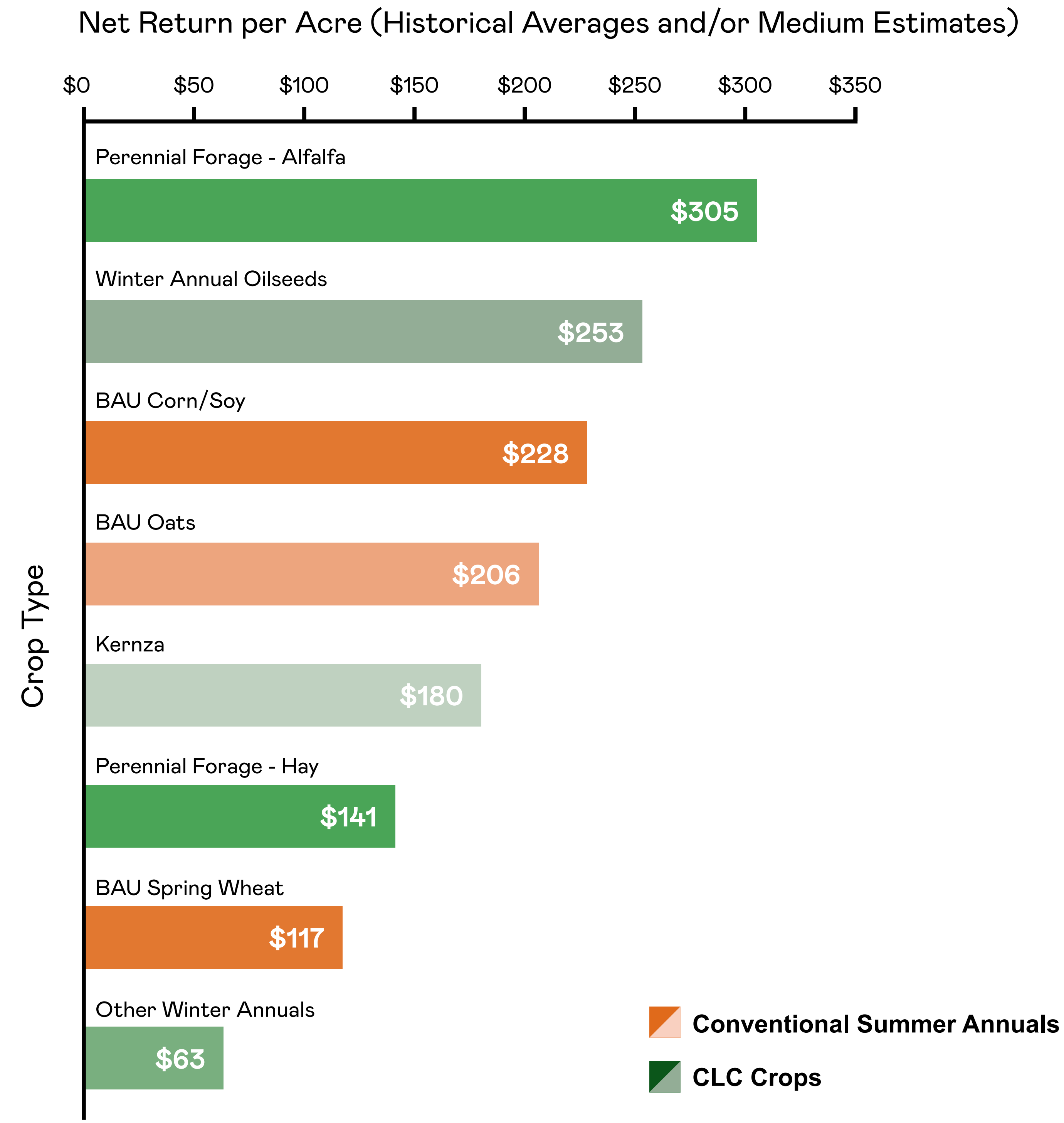
Figure 14 indicates that alfalfa hay has the potential to be the most profitable crop option when sold. However, it is not always sold, whether because it is being used on-farm or because the market to sell it is not accessible (See Box 10).

The next most profitable crops are the winter annual oilseeds, followed by two-year corn/soybean rotation, oats and Kernza®. Winter annual oilseeds are at early stages of commercialization, with relatively large market opportunities but also pricing uncertainties. When viewing the returns of just the winter annual oilseed crop and not accounting for returns of the entire cropping system they may be a part of, the net returns can be quite high, even with relatively conservative price points.

Kernza® has a relatively wide range of sale prices, which can significantly impact its profitability - with upper and lower bounds of prices making it either the most profitable or one of the least profitable crop options. Kernza is also a dual-use crop such that both its seed can be sold and it can also be used as forage. This is important because by year 3 when yield is lowest for Kernza, the forage value can make up more than half the revenue depending on seed prices. See Table 10 in the Technical Appendix for details on specific price points used.

Figure 14.

On-farm Profitability Comparisons for Select Crops



Note: Net-returns exclude land rent. See Technical Appendix 10 for details

However, the full picture of net returns can change when taking into account the full cropping system the CLC crops are a part of. For example, and as previously mentioned, preliminary trials of winter annual oilseeds in Minnesota lead to a reduction in soybean yields that follow winter annuals. This means that today, there is a potential reduction in soybean net returns that counters the revenues from the winter annual crop. Due to the assumed staged integration of winter annuals into corn/soybeans not occurring until 2035, we assume this issue is avoided.

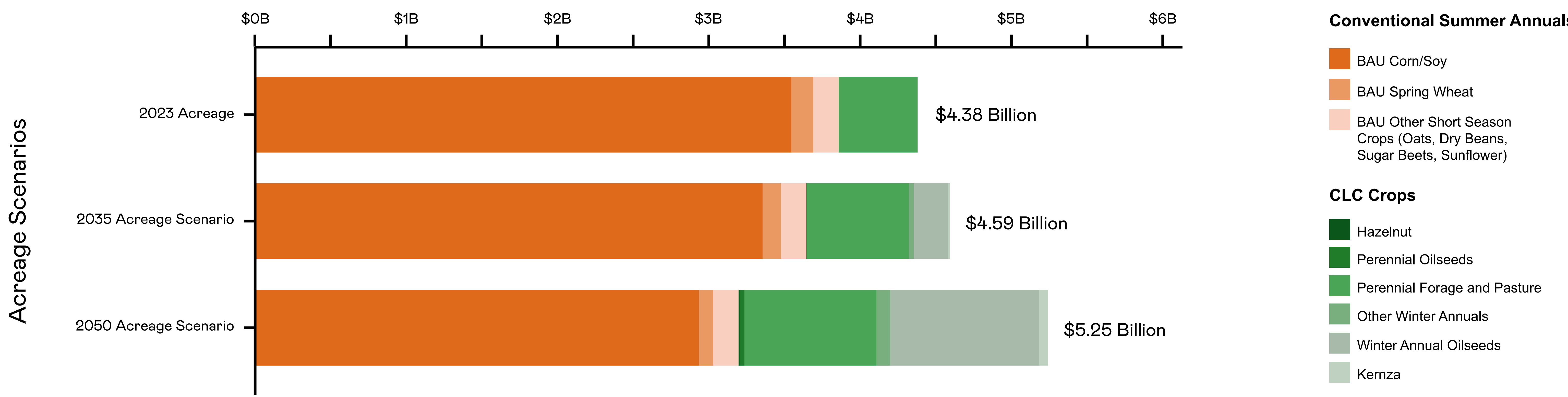
Similarly, profitably does not always align with acres grown. There may be other forces at play that influence the number of acres grown each year. For example, insurance policies may be less favorable to alfalfa and as a result, growers will be less likely to receive favorable financing to grow alfalfa in comparison to crops like corn or soybeans.

Figure 15 describes how present-day on-farm net returns might look with a different portfolio of conventional and CLC cropping systems. Under a medium adoption and medium revenue scenario, Figure 15 shows that total on-farm net returns would increase from $4.38B to just over $5.25B with a selection of the 2050 CLC crop portfolio in place on the landscape today. This represents an increase of 20%. When comparing against the 3% increase in gross revenues, this suggests that CLC crops are relatively low input for the output generated, as compared to the BAU.

Figure 15.

Total On-farm Net Returns (excluding land rent) for Select Crops under Three Acreage Scenarios
(In 2023 $, in Billions)

Scenario: Medium Adoption and Medium Net Returns



The total revenues and total on-farm net returns shown in Figures 13 and 15 are not meant to capture the total figures for all cropland in Minnesota. Data on CLC cropping systems is limited and as a result, multiple crops are not included. However, the chart is intended to capture the dominant crops, both conventional summer annuals and CLC crops.

The primary CLC crops excluded from these revenue and net return estimates are woody perennials (except for hazelnuts) and other perennial grains (except for Kernza). This means that about 22,000 acres are excluded under the 2023 revenue and net return estimates and upwards of 500,000 (largely perennial grains) are excluded from the 2050 revenue and net returns estimates, amounting to about 10% of all 2050 perennial acreage. This is due to the uncertainty around what revenues and net returns will look like for these crops given they are either expected to have a small number of acres or are still several years from commercialization. While a scenario of 500,000 acres for other perennial grains presumes the crop will be profitable, excluding them from these economic impact estimates helps support a more conservative estimate overall.

Similarly, for conventional summer annuals, some crops with smaller acreages are not included such as spring peas, canola and barley (amounting to about 300,000 acres in 2023) as well as horticultural crops such as apples and grapes (over 4,000 acres in 2023) amounting to about 2% of all 2050 summer annual acres being excluded from this estimate. These crops did not figure prominently into the BAU scenario of the environmental wedges and as a result, were not included in the economic impact estimate.

It is unclear the extent the revenues and net returns would change with the inclusion of all crops in Minnesota. However, given the greater number of CLC acres in 2035 and 2050 that are excluded from these projections, it is fair to expect the proportional increase in revenues and net returns from 2023 to 2050 is likely to be similar if not slightly larger to the currently estimated 3% and 20% increases. As CLC crops gain traction, particularly those that are still pre-commercialization, these figures will become much more clear.

Enhancing overall farm prosperity

The goal of these economic bar charts is to show that the adoption of CLC crops, while potentially reducing the number of acres of major crops such as corn and soybeans, does not have to come at the cost of reduced profitability for growers nor the annual crops used primarily for human food (e.g. wheat, oats, etc.).

Similarly, while revenues do not show as dramatic an increase as net returns, the stability of revenues under the different acreage scenarios shows that the downstream value chain as a whole does not have to lose income in the course of the adoption of CLC crops either.

While there will be transition costs experienced by growers that are not accounted for in the above figures, the potential for enhanced overall farm prosperity with a mature portfolio of CLC cropping systems in Minnesota is promising.

2.E Barriers to CLC Cropping System Adoption

Several factors can significantly influence the rate of CLC crop adoption in the future, and shape both environmental and economic outcomes. Some key factors include:

1. Crop development: The development and improvement of crop varieties through research and breeding programs can enhance yields and yield stability, disease resistance, drought resistance, and environmental adaptability, thereby positively impacting future crop prospects.
    a. Rate of yield increases: The rate at which crop yields increase due to advancements in technology, agronomic practices, and genetic improvements plays an important role in determining future crop prospects, as higher yields can lead to increased profitability.
    b. Agronomy of crops' integration into cropping systems: The successful integration of crops into the existing cropping system, considering factors such as crop rotation, pest management, and soil health, can optimize productivity, reduce risks, and improve sustainability, ensuring better crop prospects.
2. Marketability: The marketability of crops depends on factors such as consumer preferences, quality standards, and value-added opportunities. Crops with high marketability have better prospects for profitability and long-term viability.
    a. Market demand: The level of demand for specific crops, both domestically and internationally, can significantly impact their prospects. Anticipating and aligning with market demand trends can help farmers make informed decisions and maximize their returns.
    b. Market(s) accessibility: The accessibility of markets, including transportation infrastructure, processing facilities, distribution networks, and proximity to buyers, influences crop prospects. Easy access to markets facilitates efficient supply chains and reduces costs.
3. Ease of adoption: CLC crops need to be well-suited to local climate, soil conditions, and management practices to have better prospects for success. Ease of adaptation allows farmers to reduce risks and capitalize on the inherent advantages of their specific regions.
    a. Grower transition costs: The level of transition or changes required by growers to adopt new crops or practices can affect crop prospects. On-farm transition costs can be influenced by several variables, including the following:
        i. Upfront investment needed: The initial investment required for crop establishment, infrastructure, equipment, and inputs can influence crop prospects. Lower upfront costs or availability of financing options can make crop ventures more feasible.
        ii. Opportunity cost: The opportunity cost of choosing one crop over another or one agricultural practice over another affects farmers' decision to adopt a new CLC crop.
        iii. Time to achieve positive net income: The time it takes for a crop to generate positive net income is a crucial factor. Crops that offer shorter timeframes for profitability provide quicker returns on investment and may be preferred by farmers.
        iv. New learnings and practices: The adoption of new learnings, practices, and technologies can enhance crop prospects. Staying updated with innovative approaches to farming, such as precision agriculture or regenerative practices, can improve efficiency and sustainability.
    b. Access to equipment: The availability and suitability of on-farm equipment for specific crops can influence crop adoption. Equipment compatibility and availability of efficient machinery can streamline operations and reduce costs. This is especially important for certain crops like Hazelnuts that may need an entirely new piece of equipment to harvest the nuts.
4. Institutional support: Government policies, programs, and support services for farmers, such as technical assistance, training, subsidies, program qualifications and/or grants, can positively influence crop prospects. Such support can mitigate risks for growers who might not otherwise consider adopting a new crop.
    a. Policy support and public funding options: Favorable policies, incentives, and public funding options that promote sustainable agriculture, research, and innovation can stimulate crop prospects and encourage investment in the sector.
    b. Private co-investment (including the ability to leverage regenerative agriculture funding): Partnerships and private co-investment, particularly in the context of regenerative agriculture goals, can unlock additional resources, expertise, and funding, contributing to improved crop prospects.

3. Findings Summary

This analysis is the first of its kind, and serves to provide preliminary estimates of the benefits that could be derived from a portfolio of CLC crops in Minnesota. The authors expect the figures included in this report to be updated over time as research evolves, market conditions adjust, climate and technological changes emerge, and policies change. However, this analysis provides a benchmark of the value proposition of these crops over time.

The included acreage scenarios, developed through literature reviews, market assessments and subject matter expert interviews, provide a look into how cropland in Minnesota could be used by 2050. In particular, results show a significant increase in the amount of time per year the land has living ground cover. Under the medium acreage adoption scenario, Minnesota's CLC score increases from 48% to 77% between 2023 and 2050, with the average acre of cropland having living cover on it 77% of the time by 2050.

This improved CLC score has the potential to support the net reduction of nutrient loss, soil erosion and on-farm GhG emissions by 23%, 35% and 3% by 2050, respectively. When paired with a moderate increase in conservation practices for existing conventional summer annual crops, those values increase to 34%, 45% and 8.5%.

The adjusted crop portfolio also impacts on-farm revenues and net returns, which have the potential to rise by 3% and 20% by 2050. This does not include any potential changes to on-farm expenses and revenues due to transition costs of adopting a CLC cropping system nor does it include financial impacts of BMP adoption.

The largest expected contributors to soil and nutrient retention come from two crop categories: 1) winter annual oilseeds and 2) perennial forage and pasture. This is due to (1) the anticipated scale of adoption and (2) per-acre performance.

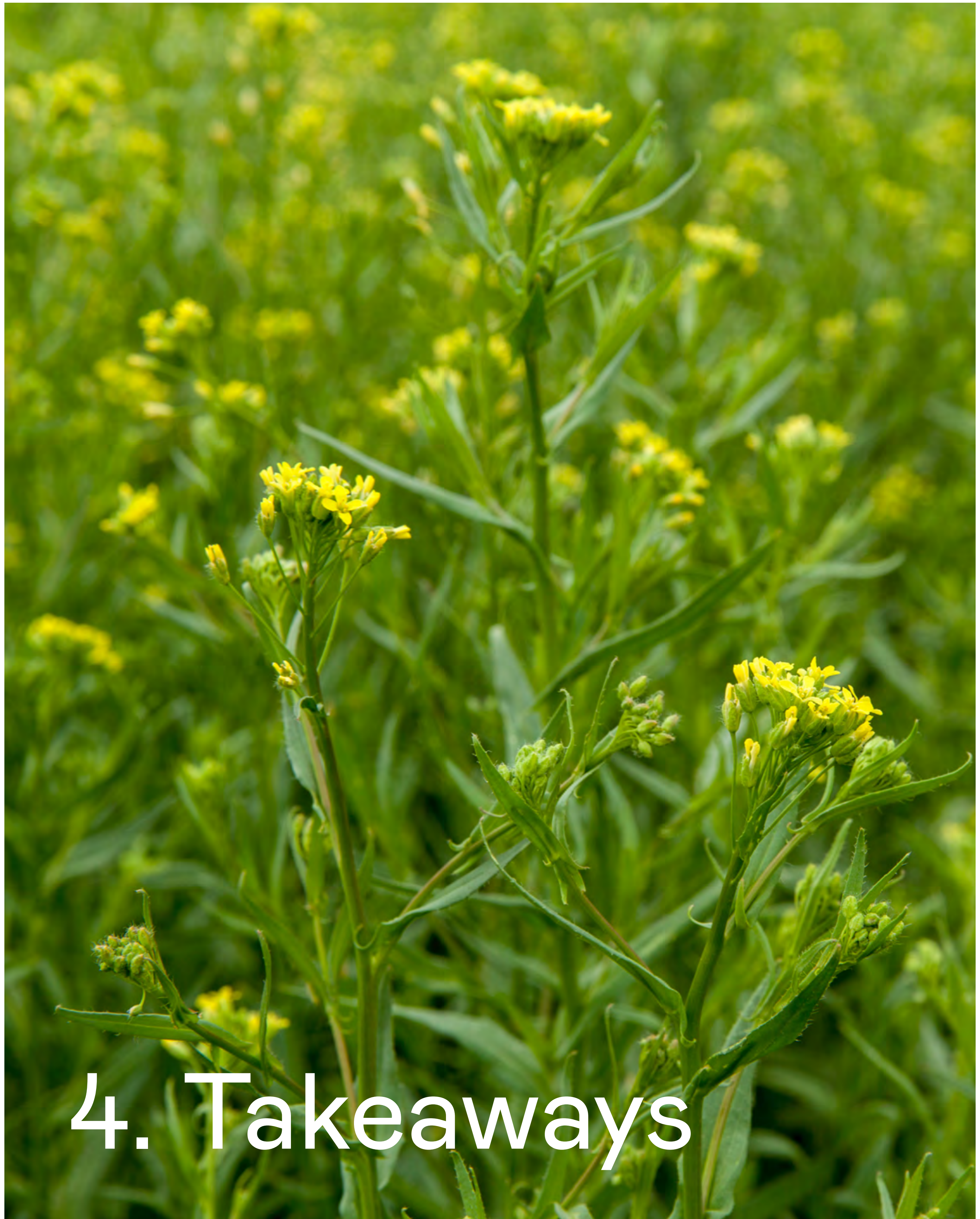
Winter annual oilseeds have the largest envisioned growth in acreage of any CLC crop category (5+ million acres by 2050 under medium adoption scenario) due in large part to the forecasted demand for sustainable aviation fuel (see Boxes 2 and 9) and sustainably-produced vegetable oil and protein.

Perennial forage and pasture is expected to expand by 1.7 million acres, somewhat less than winter annual oilseeds, but they are up to twice as effective at reducing erosion and runoff per acre.

Photo Credit: Dodd Demas for FMR

The story changes slightly when considering GhG emissions. Perennial forage and pasture is the leading contributor to emission reduction initially, and later surpassed by perennial grains, due to their scale of adoption and ability to sequester carbon while avoiding N2O emissions. The role of winter annual oilseeds is complicated by uncertainty in how the oilseeds will be produced. If grown in a manner utilizing additional fertilizer application and requiring additional passes on the field by farmers, they may actually increase the amount of GhG emissions from crop production in Minnesota. Conversely, with low nitrogen application and more efficient management practices, winter annual oilseeds can contribute slightly to a reduction in the GhG emissions on-farm. In either case, the non-farm GhG impacts of using winter annual oilseeds as a low-carbon alternative to fossil transportation, marine and aviation fuels must be considered.

Like the soil erosion and nutrient loss wedges, the major economic contributors of the CLC crops are the winter annual oilseeds and the perennial forage and pasture crops. Given their envisioned acreage and economic performance, these two crop categories play an important role in driving an increase in total on-farm revenues and profits in Minnesota.



This project has outlined the environmental and economic impacts of CLC cropping systems under different scenarios of future adoption rates. In each scenario, it is expected that CLC cropping system adoption will increase over time.

Importantly, these results suggest that the adoption of a portfolio of CLC crops over the coming decades can increase the productivity of Minnesota's agricultural lands, generate new economic opportunities and build and access new markets, all while protecting our water, improving air quality, furthering climate mitigation and climate resilience, and boosting biodiversity of pollinators and other wildlife.

Adoption rates for individual CLC cropping systems vary significantly due to many factors including plant genetics, market development, supply chain maturity and ease of integration, regulatory status, and more. Despite these varied challenges, the medium adoption scenario communicated here shows the dual economic and environmental benefits that can be achieved from CLC crop integration in Minnesota.

The winter annual oilseeds and the perennial forage and pasture crop categories were shown to be the two leaders in terms of environmental and economic impacts. This is not to say the other CLC crop categories are not contributing to the benefits in Minnesota, however. Each is playing a role in driving environmental benefits while supporting economic opportunities. Specific CLC crops are well-positioned to address specific environmental needs as well. For example, Kernza® (and potentially other perennial grains) is well-suited for plantings in Wellhead Protection Areas, as its extensive, perennial root systems reduce the amount of nutrients reaching drinking water sources. Similarly, crops like woody perennials (e.g. hazelnut, elderberry) can make for important additions to highly erodible lands by providing a positive economic return while making targeted reductions to soil loss and runoff pollution. The various CLC crops fit into a portfolio that serves as a toolkit for farmers to generate a profit and be stewards of their land in the way that best serves the context of their land. Certain tools may be used more than others, but that does not mean the rest of the toolbox is not valuable.

The increased adoption of CLC crops can serve as a means to increasing the extent the cropland of Minnesota is utilized, through an intensification of production, as is the case with the double cropping system supported by winter annuals, as well as increasing the extent the natural resources of Minnesota and downstream stakeholders are protected.

Photo Credit: Forever Green Initiative

While the scenarios included in this report do show a reduction in acres of conventional summer annuals such as corn and soybeans, the results do not show a loss of productivity or farm prosperity. As such, support for CLC cropping systems should not be framed as a tradeoff between environmental and economic agendas but as complementary agendas.

While CLC cropping systems are not the only means to achieve environmental and economic goals for agriculture in Minnesota, they can play a sizable role. Other options, such as conservation practices, are in part included in this analysis to show their potential environmental benefits. Still, other tools, such as precision technologies, are likely to also play a role in this space.

This analysis is a starting point for recognizing and communicating the importance of CLC cropping systems.

Community impacts

This analysis focused on select environmental and economic impacts due to the current state of evidence on those topics and the ability to create forward-looking projections of the impacts of more CLC crops on MN agricultural land.

However, these environmental and economic impacts exist within local communities, both where the crop production is taking place and downstream of crop production. Nitrogen lost to groundwater and surface water impairs local drinking water of local communities as well as hurting fishing, swimming, boating, wildlife, and property values. Soil erosion increases the sedimentation of waterways, impairs habitat, carries phosphorus among other pollutants into waterways, increases dredging costs, exacerbates flooding, and reduces the amount of topsoil growers have to work with in subsequent years. Greenhouse gas emissions, while generated locally and having potentially local impacts, contribute to global climate change impacting the likelihood and severity of weather events, changing precipitation patterns and growing seasons both locally and abroad.

On-farm economics have potentially many ripple effects on local communities and downstream supply chain partners. With the potential increase in profitability that CLC crops may provide, there are changes in farming practices, in equipment needs, in inputs required, and, correspondingly, changes in investment needed. Each of these impacts the on-farm labor needs, the value of labor provided, and the revenues and profitability of those supplying equipment, inputs, advice, insurance, etc. Changes in the spending made on-farm then have ripple effects off-farm. If more of the supply chain exists locally, more local supply chain jobs will be needed. With increased jobs in the local supply chain, there will be increased local spending of income.

This materializes in the form of additional people paying rent, paying mortgages, buying groceries, visiting doctors, visiting restaurants, etc. As demand for each of these changes, so too will their own needed labor supply. As jobs are created, and the value of those jobs increases, the amount of labor income occurring locally increases. This means reduced rates of unemployment, increased incomes, reduced rural poverty rates, increased demand for high-value jobs, and increased economic diversification that can then support increased economic resiliency in cases of economic downturns. Additionally, CLC crop adoption is likely to create increased recreational opportunities (fishing, hunting, birding, ecotourism, and agritourism) that can substantially benefit rural economies. These indirect changes (changes via the agricultural supply chain) and induced changes (changes from household spending) combine to magnify the effect of direct changes occurring to the on-farm economics included in this analysis.

Addressing equity & environmental justice

While not the subject of this analysis, it is important to acknowledge deep inequities embedded within Minnesota's current agricultural landscape. As a result, not all current or prospective farmers, ranchers, supply chain actors and entrepreneurs have an equal chance of success and prosperity.

Likewise, the costs and benefits of our current agricultural systems are not equitably shared across our communities.

As new CLC crops, supply chains and markets materialize, Minnesota has a unique opportunity to support emerging farmers, ranchers, supply chain actors, entrepreneurs and underserved communities by investing in efforts to build a more resilient, just and equitable agricultural system.

For a detailed exploration of potential strategies for embedding equity and environmental justice in the transition to CLC cropping systems, we urge readers to review the publication by Green Lands Blue Waters entitled 'Our Journey to a Transformed Agriculture through Continuous Living Cover.'

5. Implications for Policy and Investment

Achieving the economic and environmental outcomes described in this report can only be achieved with sufficient support for CLC agriculture on three fronts: Research, commercialization, and farmer adoption. None of these elements can stand independently, but must instead work in tandem to accelerate the adoption of CLC cropping systems at scale.

Research

America's public agriculture research institutions — foremost, land grant universities such as the University of Minnesota — have long delivered outstanding returns on state and federal investment. Such institutions are crucial drivers of a CLC transition because of their mandate to advance programs that are in the public interest, and sustained government funding is vital to maintaining long-term research projects, paying the salaries of graduate students and postdoctoral fellows who work to answer the most pressing questions in the CLC space, enabling programs to afford laboratory and field equipment, and much more. Funding for such activities, however, has been severely constrained in recent years.

The United States Congress must recommit to investing in research programs within the Department of Agriculture and other bodies whose remits touch on agricultural utilization, such as the Department of Energy. Key USDA programs that should be funded and directed to pursue CLC research and implementation include:

- AFRI Foundational and Applied Science Program
- NIFA Supplemental and Alternative Crops Program
- AFRI Sustainable Agriculture Systems - Coordinated Agricultural Projects
- Biomass Crop Assistance Program
- Foundation for Food and Agriculture Research
- Interregional Research Project No. 4 and other pesticide-related efforts
- Ad hoc efforts such as the Partnership for Climate Smart Commodities

State governments should fund research into regionally appropriate CLC systems and leverage existing programs — in procurement of agricultural products, municipal and rural water management, agricultural extension, and elsewhere — to encourage adoption of these systems.

Photo Credit: CFANS

Commercialization

Nascent industries are already growing in Minnesota and other states around CLC systems, but the markets and value chains for these crops need to grow — in some cases, need to be created — as does the critical infrastructure to support them. Substantial private investment will be needed to scale up the production of CLC crops, yet, despite the massive potential of some of these crops and systems, it can be difficult to overcome tendencies towards risk aversion, which understandably influences many corporations and individuals to seek the paths of least resistance and greatest support.

"De-risking" is a crucial concept in modern production agriculture; it refers to the suite of policies and programs that shift financial risk from individual farmers or businesses onto society writ large, such as federally subsidized crop insurance and commodity supports. It takes time, significant actuarial analysis, and political will to bring new crops and production methods under the protective umbrella of such programs, and most CLC systems do not yet qualify for such support.

On the commercial front, "de-risking" applies to numerous elements of supply chain development, including state and federal support for infrastructure, public/private collaboration on pilot research and implementation projects, and, indirectly, public support to underpin crop pricing and availability:

- There is a clear need for business capitalization grants to help entrepreneurs, cooperatives, and established businesses invest in equipment, storage, processing and distribution to help bring continuous living cover crops from the farm gate to the retail shelf or industrial end-user. The state of Minnesota piloted one such publicly-funded program beginning in 2023, investing $1 million in grants for CLC value chain operators.

- The University of Minnesota is partnering with corporations such as Cargill, Inc. on field-scale pilot implementation projects for energy crops like winter camelina. Pilot projects are useful both as working laboratories to test production methods and as "proof of concept" for corporate and government stakeholders. Close collaboration with federal agencies like the Risk Management Agency and the Natural Resources Conservation Service is important to ensure compliance with existing policies and regulations; and to gather data that informs future policies and regulations in order to de-risk future commercial-scale production.

- Beyond strictly agriculture-oriented grant/loan opportunities and other de-risking policies, policymakers can help to establish value chains for energy crops — particularly winter annual oilseeds and forage/pasture crops — within the framework of public and public-private initiatives to reduce greenhouse gasses.

Farmer adoption

Farmers are co-equal partners in research, development, and real-world implementation of CLC systems, but may face financial risks, particularly for early adopters. Policymakers can greatly reduce this risk pressure by leveling the playing field for CLC systems as compared to established commodity crops, whose market dominance has long been underpinned by taxpayer-subsidized crop insurance, price supports, and disaster payments. CLC systems' significant contributions to public health, climate adaptation, and other environmental benefits are core factors for adoption but are largely externalized by market forces.

Program areas to focus on could include:

- Support for pilot implementation projects that allow researchers, farmers, and supply chain actors to test and refine new cropping systems and their associated business models, while providing "proof of concept" for further build-out

- Inclusion of CLC systems within federal crop insurance and other risk-mitigation programs

- Compensation for ecosystem services

- Equipment and farm infrastructure grants and loans

- Farm-to-school and institutional procurement

- Farmer outreach and education, including via both public (e.g. university extension) and private agronomic services companies

On the following pages, specific sources referenced for this analysis are included - whether used as helpful context, as backing evidence or for the specific impact estimates made. Each study is ranked by its level of evidence. This helps to communicate the relative strength of the findings estimated and used. Whenever possible, the highest level of evidence is utilized.

Levels of Evidence of Causality

1 is Highest, 7 is Lowest

1 Evidence from a systematic review or meta-analysis of all relevant RCTs (randomized controlled trial) or evidence-based clinical practice guidelines based on systematic reviews of RCTs or three or more RCTs of good quality that have similar results.

2 Evidence obtained from at least one well-designed RCT (e.g. large multi-site RCT).

3 Evidence obtained from well-designed controlled trials without randomization (i.e. quasi-experimental).

4 Evidence from well-designed case-control or cohort studies.

5 Evidence from systematic reviews of descriptive and qualitative studies (meta-synthesis).

6 Evidence from a single descriptive or qualitative study.

7 Evidence from the opinion of authorities and/or reports of expert committees.

N/A N/A, Fact - Information provided in the source does not make casual claims. This includes statistics and other facts.

 Photo Credit: CFANS

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Section 7: Project Approach

Friends of the Mississippi River, in partnership with the Forever Green Initiative, put forth a two phase RFP to conduct a wedge analysis modeled on the example of well-known GhG reduction 'wedge models' that marry the expected market growth of renewable technologies with projected GhG reductions. Such models help us understand the percentage (or wedge) of change provided by a future portfolio of activities.

In this project, we aimed to create scenarios for the expected range of acreage of select continuous living cover crops (perennial and winter annual crops) in Minnesota under a given time frame with low, medium and high adoption scenarios. From there, this project calculated the coefficient-derived expected ecological services from that scale of activity in Minnesota as well as the on-farm economic effects of that activity. The ecological services were modeled in the wedge analysis format while economic effects were showcased in various scenarios due to the more limited evidence and significant future market uncertainties.

The two phases of work were:
Phase 1: A scoping exercise to determine which CLC crops were best positioned for inclusion in a future wedge analysis including a detailed literature review and subject matter expert interviews.

Phase 2: Assessed, compiled, refined and published a report summarizing the potential economic and environmental benefits of a future CLC crop portfolio under varying adoption scenarios.

Outcomes-focused logic model

To help build an evidence-based understanding of the value proposition of the CLC crops and cropping systems, this analysis constructed a partial logic model, mapping the linkages between the crops themselves and the flow of short, intermediate, and long-term outcomes from those crops. This served to identify the pool of potential environmental metrics and economic metrics that have been at least acknowledged in the literature. It also shows how the different concepts of ground cover, nutrient runoff, and water quality, for example, are linked together. Table 3 thus serves to highlight both the varied value propositions of CLC crops but also how those values

Table 3.

Outputs	Short-term Outcomes	Intermediate Outcomes	Long-Term Outcomes	Impact
· Number of acres of CLC cropping systems · Number of acres of each in high priority areas · % of agricultural land with a CLC cropping system · Number of acres of CLC cropping systems (disaggregated by type of CLC system) · Acres of increased crop diversity · Number of crop types · Number of crop types with market	**Positive Environmental Outcomes**			· Water Quality and Quantity · Soil Health · Climate adaptation and climate change mitigation · Rural economic/social vitality · Landscape resiliency · Enhancing justice, equity, and inclusion in food and agricultural systems · Healthy People · Biodiversity · Air Quality
	· Increased crop diversity · Increased continuous cover · Increased root structure · Increased soil health · Increased soil porosity · Increased soil texture (particularly for sandier soils) · Reduced energy consumption · Increased biomass · Increased wildlife and pollinator habitat	· Reduced soil erosion from water and wind · Increased water infiltration, retention and flood resiliency · Moderated soil temperature · Reduced nutrient runoff · Increased carbon sequestration · Interrupted disease, pest, and weed cycles · Increased productivity/land intensification · Reduced ecotoxicity	· Improved air quality from reduced particulate matter · Improved water quality · Improved drinking water quality, reduced water treatment, and improved community health · Increased wildlife and biodiversity · Reduced global climate risks · Increased water conservation, efficiency, water supply stability and flood cost reduction · Reduced eutrophication, hypoxia and sedimentation	
	Negative Environmental Outcomes			
	· Increased fuel usage from intensification	· Potential increased on-farm GHG emissions		
	Positive Financial and Economic Outcomes			
	· Increased income diversity	· Increased and/or more stable crop yields across weather conditions · Reduced input application (pesticide, herbicide, fertilizer, etc.) · Potential increased net income · Increased economic value add in rural areas and MN generally	· Reduced risk and crop insurance payments · Increased property values · Increased long-term productivity (including on marginal lands) · Increased area recreation · Increased economic diversification in rural agricultural areas	
	Negative Financial and Economic Outcomes			
	· Potential decreased yield in cash crop · Potential market fluctuations - uncertain incomes year to year · Opportunity cost of investment - particularly in crops that take years to mature or have variable yields · Potential increase in labor	· Potential decreased net income · Potential decreased yield over time		

Description of impact estimation methodology

Following the establishment of the logic model, the impact estimation process involved two primary tasks: 1) Establish a Business as Usual scenario to serve as the counterfactual against which the CLC crops would be compared, and 2) Estimate the benefit of each CLC crop or crop category relative to that counterfactual.

To conduct these two tasks several steps were needed as outlined below.

1. Establish a Business As Usual scenario(s)
    a. Identify the major conventional annual crops in Minnesota through data review and subject matter expert interviews based on the extent of acreage they are grown on.
    b. Review existing individual crop acreage projections (if any) and engage subject matter experts to determine reasonable ranges of future acreages and their rationale for why they expect change or no change going forward.
    c. Future acreage scenarios are developed and include a low, medium and high scenario based on literature and expert opinion.
    d. Review literature on the environmental impact and economic data per acre for major conventional summer annuals.
    e. Assess the quality of this evidence and organize high quality data points for each conventional summer annual crop. In particular, leverage per acre estimations developed in the literature.
    f. Establish a range of potential values per acre to show both the range of existing estimates as well as to understand how the impact per acre may vary based on contextual factors such as soil type, land slope, cropping system, management practices, etc.
    g. Combine the environmental and/or economic data per acre with the number of acres expected of that crop in Minnesota for every year from 2023 to 2050.
    h. Sum the environmental and economic data for each conventional annual row crop to create an aggregate Business as Usual data point for every year (e.g. Total Nitrogen Loss in 2023).
    i. Identify the major conservation practices in use and/or being advocated for
    j. Review existing literature on the costs/benefits associated with each conservation practice as well as the projected change in adoption of conservation practices going forward.
    k. To show the aggregate potential benefit of conservation practices, apply their per acre benefit to the conventional summer annual acres.
2. Estimate the impact of each additional CLC crop or crop category relative to a Business as Usual scenario.
    a. Identify CLC crops in development by the Forever Green Initiative that are intended to be grown in Minnesota.
    b. Group CLC crops by their characteristics to create crop categories - a tool to both manage the number of crops being reviewed as well as manage data limitations for specific crops (for example, perennial oilseeds in Minnesota have not been studied directly for their soil erosion benefits, and as a result a proxy value from a European perennial oilseed - cup plant - with similar characteristics is used and applied to all perennial oilseeds planned for Minnesota).
    c. Review the existing state of development of each CLC crop and crop category as each crop is at a different stage of development, some being already commercialized and some being years away from commercialization.
    d. Review existing environmental and economic data for each crop to determine their inclusion in an environmental wedge chart or economic bar chart. Since some crops have not been studied as much, there may be little data to inform what the economics of the crop production could look like or their environmental impacts. In those cases, it may not be prudent to include such large uncertainties in the estimates.
    e. Review existing crop acreage projections (if any) and engage subject matter experts to determine reasonable ranges of future acreages and their rationale for why they expect change or no change going forward.
    f. Review literature on the environmental and economic data per acre for that individual crop or crop category relative to a counterfactual crop/cropping system. This step identifies specific values to use whereas step d. was a preliminary review to identify the inclusion of environmental and economic metrics.
    g. Identify what counterfactual scenario makes sense for each CLC crop category each year from 2023 to 2050. For example, winter annuals are assumed to be integrated first with shorter-season crops until in 2035 they are also integrated with corn/soybeans. This is important in Minnesota because of the relatively short growing seasons, integration of winter annuals today may lead to competition with some summer annuals that use more of the growing season than other summer annuals that use less of the growing season.

h. Combine the environmental impact and/or economic data per acre with the number of acres of that CLC crop in Minnesota for every year from 2023 to 2050 and do this for every CLC crop or crop category.

i. Subtract the benefit of each CLC crop or crop category from the Business as Usual to show the resulting environmental impact per CLC crop category.

j. Sum the total on-farm revenues and total on-farm net returns for both conventional summer annuals and CLC crops to estimate the statewide change in on-farm revenue and on-farm net returns.

Key Overarching Assumptions

Many assumptions are required to build the wedge projections and economic impact scenarios. Below are high level assumptions used across crop categories. Additional assumptions unique to the projections of each crop are detailed in Technical Appendix 9, 10 and 11.

Overall

1. S-curve adoption rates are used for CLC crops that are in earlier stages of commercialization, assuming there will be an initial period of slow growth, followed by an increased growth, before plateauing. Crops that are still pre-commercialization may not plateau by 2050 while others, such as Kernza® that have been on the market for multiple years, are assumed to plateau before 2050. Other crops use linear acreage increases either due to their already widespread commercialization (such as alfalfa) or due to lack of information to suggest what a fair adoption trajectory may entail.

2. CLC crops are integrated into existing row crop acres in MN - no additional acres of row crops are assumed to be included in this analysis.

3. It is assumed that genetic, agronomic, economic and policy barriers are reduced over time to support the increased adoption of CLC crops. The extent these barriers need to be reduced will vary from crop and crop; this does impact the expected acreage values used for each crop. This analysis does not go so far as to say that specific reductions in barriers will lead to specific increases in acres adopted. Across the board, increases in acreage of CLC crops are expected to some extent.

4. This analysis is not making forecasts - it is creating future scenarios to convey the potential benefit of CLC crops. Avoiding forecasts is particularly important in the case of economic impacts where the amount of uncertainty around future market conditions is profound. Scenarios are however meant to be realistic.

5. Proxy values of similar crops are assumed appropriate. This is done to manage both the lack of information on specific crops as well as to simplify the potential complexity of agricultural systems. For example, perennial oilseeds in Minnesota have little to no evidence regarding their environmental impacts. However, the cup plant, a perennial oilseed used in other geographies, has very similar characteristics and has a greater evidence base attached to it, allowing us to leverage those studies and transfer the values seen for the cup plant to the perennial oilseeds of Minnesota. See Technical Appendix 10 and 11 for details on when proxies were utilized for certain crops for proxies.

6. We are assuming yields of CLC crops are increasing enough to avoid significant displacement of conventional crop production to other states and that there is negligible net loss of total food/feed/fuel output. This is a potential risk as many of the CLC crops come with a yield tradeoff, like Kernza®, which has a yield much lower than spring wheat currently. This matters when we get to large acreages because CLC crops may be displacing more productive crops and sending a market signal to produce more of them elsewhere (i.e. indirect land use change).

7. There is the potential for a tradeoff that as yields increase, the number of acres of the crop may not be needed if demand stays constant. As a result, we assume demand is increasing at a rate sufficient to offset any downward pressure on acreage needed. Similarly, increasing yields should also reduce prices which will support higher demand.

8. In order to facilitate the adoption of perennials onto the landscape that will replace annuals, there will need to be a decrease in demand for some annuals so that the prices for products derived from existing annuals is not pushed up too high to negatively impact communities reliant on the products. In addition, food, feed, and forage products from CLC crops may also serve as substitutes for conventional crop products in the market, relieving some of the price pressure that would result from reduced production of summer annual crops.

Environmental

1. The production of CLC crops co-exists with no-till practices in perpetuity to avoid risk of releasing carbon otherwise sequestered. This is a potentially large assumption but as is discussed in the main report, the GhG benefits are contingent on farming practices as much as on the crops being grown.
2. A constant rate of avoided N loss and avoided soil loss across all acres where CLC crops are planted is assumed. This value will in reality vary by the conditions of each acre.
3. Mitigated GhG emissions have a decay rate tied to diminishing rates of carbon sequestration, such that over time less and less additional carbon will be sequestered in the soil.
4. CLC crops are being integrated into acres that were not previously using conservation practices. This maximizes the environmental benefit of CLC crop integration.
5. The wedge charts show the total estimated nitrogen loss, soil eroded, or GhG emissions for major conventional annual row crops in Minnesota. Not all crops in Minnesota are represented, but the major row crops are captured, such as corn, soybeans and spring wheat. As a result, the total values included on the y-axis of the wedge charts are not the total nitrogen loss, soil eroded, or GhG emissions for all annual row crops in Minnesota, but they are expected to be strong approximations since the crops included make up the vast majority of total row crop acres. These summed values also do not account for animal production (other than producing pasture and other forages), another source of agricultural environmental impact in the state, nor do they account for year over year variations that may occur from droughts, heavy rains in spring, heat, severe weather, etc. - each of which will impact the environmental impacts of both conventional summer annual crops and CLC crops.

Economic

1. On-farm net returns follow historical averages for conventional summer annuals and for those CLC crops that are already commercialized, such as alfalfa.
2. On-farm revenues and net returns for other CLC crops are estimated as a range, and the middle value is used in visualizations.
3. Constant net returns on-farm is assumed as adoption of CLC crops increases. This will vary in practice as market conditions and crop development changes over time, each impacting profitability.
4. Importantly, there is the assumption that markets exist for each CLC crop, allowing for the market value of the crop to be realized no matter the acreage adopted.
5. To avoid potentially many assumptions required for forecasting economic outcomes, we use the acreage scenarios to highlight how the on-farm economics would look different today with increases in CLC crops on the landscape.
6. Any economic effects from BMP adoption such as cover crops are not included in the economic impact scenarios.
7. Transition costs of adopting CLC crops and cropping systems are not accounted for.

Counterfactuals

In order to determine the marginal benefit of the adoption of CLC crops, we have to determine what the counterfactual is - what would otherwise be happening were it not for the CLC crops being adopted. While there are many possible futures, Table 4 below provides details on what crops and cropping systems the new CLC crops are assumed to be either integrated into and/or partially replace.

This is a simplistic view of the counterfactual - by assuming the business as usual (BAU) crops will all continue in use and there are no other competing crops that are seeking to enter Minnesota acres. Given there is some expectation of change in cropping practices going into the future, this analysis does incorporate the change in use of conservation practices as an additional environmental wedge, as previously described. However, the analysis does not consider other structural or technological changes that could impact what crops are grown and how they are grown. Precision agriculture technologies are rapidly developing and changing how farming is conducted. Similarly, food production methods are being developed that alter the means of production such as increased reliance on plant protein (potentially causing a shift in demand for forages), indoor farming facilities, lab grown meats, among others. These each have a place in the market.The scope of their impact on the future trajectory of Minnesota acres is not included here, but could be in the future with more information.

Table 4: Counterfactuals:
Where CLC Crops Are Assumed to Be Integrated into MN Agriculture

CLC Crop Category	CLC Crop	Replaces and/or is integrated into systems of:
Winter Annuals	Winter Annual Oilseeds	Now thru 2035: Short-season crops - small grains, silage corn, sunflower
		2035 thru 2050: Target marginal/unprofitable corn/soy-bean acres
	Winter Annual Cereals	Now thru 2035: Short-season crops - small grains, silage corn, sunflower
		2035 thru 2050: Target marginal/unprofitable corn/soy-bean acres
	Winter Pea	Short-season crops - small grains, silage corn
Perennial Grains	Kernza®	Preceded by a short-season crop or winter annual, and replacing corn/soybean acres
	Other Perennial Grains	Target marginal/unprofitable corn/soybean acres
Perennial Oilseeds	Perennial Oilseeds	Target marginal/unprofitable corn/soybean acres
Perennial Forage	Perennial Legumes	Target marginal/unprofitable corn/soybean acres
	Perennial Grasses	Target marginal/unprofitable corn/soybean acres
Woody Perennials	Hazelnut	Target marginal/unprofitable corn/soybean acres
	Perennial Berries	Target marginal/unprofitable corn/soybean acres
	Short-rotation Woody Biomass	Target marginal/unprofitable corn/soybean acres
	Windbreaks/ Woody Riparian Buffers	Target marginal/unprofitable corn/soybean acres

Box 11: Benefits of Diversification

Crop diversification in Minnesota offers numerous benefits for agricultural systems and the environment. While diversification specifically was not a focus of this analysis, it is an important effect of adopting CLC crops and cropping systems that can have a slew of its own positive benefits.

By incorporating multiple crop species, farmers can reap several advantages, including enhanced ecosystem services, improved resilience, and increased economic value. For example, Hungate et al., (2017) highlights the economic value of grassland species for carbon storage in Minnesota. According to their research, the marginal value of gaining one additional species in a Conservation Reserve Program (CRP) grassland area, increasing species richness from S = 6 to S = 7, amounted to approximately $722 million. This underscores the significant economic benefits associated with biodiversity and emphasizes the potential economic gains that can be achieved through crop diversification efforts.

Diversified cropping systems contribute to increased resilience in the face of climate variability and changing environmental conditions. Different crops have varying tolerance levels to drought, heat, pests, and diseases. By diversifying the crop portfolio, farmers can minimize the risks associated with climate-related challenges. If a particular crop suffers from adverse conditions, other crops in the rotation may thrive, supporting a more stable yield and income.

Crop diversification also opens up opportunities for market diversification and value-added products. By growing a range of crops, farmers can tap into various market niches and meet the diverse demands of consumers. This reduces reliance on a single crop and expands income potential. Related, diversified cropping systems can provide feedstock for bioenergy production, adding value to the agricultural enterprise and promoting renewable energy sources.

Section 8: Acreage Estimations

For this analysis, acreage scenarios are the key lever for driving environmental and/or economic impacts in Minnesota. Generating acreage scenarios relied on a combination of identification of the status quo of the crop, the key headwinds and tailwinds facing the crop such as market opportunities or lack thereof, crop development trajectories, and the sentiment towards the crop based on interviews with growers, NGOs, state agencies, and private industry players. Based on these inputs, low, medium and high scenarios were created. These acreages are scenarios for the future and should not be considered forecasts due to the significant uncertainty around each crop's prospects and the many variables that can have a dramatic effect on each crop's adoption rate This analysis does rely on pre-existing crop acreage estimates wherever possible (See Table 7). A recent report (2022) from the GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team for the State developed GhG reduction estimates going out to 2050. A major component of this work included estimating the future acreages of perennials and winter annuals on the Minnesota landscape. These estimates were usable for a few crop categories in this analysis, although given the different objectives of the two projects, our analysis required more detail on specific crops and crop categories, necessitating the prior mentioned approach to understand crop potentials. In sum, these scenarios are meant to be realistic visions for 2035 and 2050 crop production in Minnesota.

Acreage scenarios were needed for both the CLC crops as well as existing conventional summer annual row crops in Minnesota. Two approaches were utilized for the conventional summer annuals: 1) an 'independent' scenario, where scenarios were developed independent of what happens with CLC crops, based on pre-existing estimates and/or feedback from stakeholders that was specific to corn and soybean prospects, and 2) a 'dependent' scenario, that is dependent on CLC acreage scenarios, with corn and soybeans losing the necessary amount of acreage to maintain a constant total number of acres of cropland in production in Minnesota. This is important because the vision for CLC crops does not expect any additional acreages of farmland to be put into production that weren't already. No land conversion from prairie or forest to crop production is included in this analysis.

The 'dependent' scenario for corn and soybeans are utilized in the wedge charts to ensure a constant total acreage for Minnesota. When considering the 'independent' corn and soybean scenario, there are multiple combinations of CLC crop and summer annual crop scenarios that cannot exist in practice. For example, the high acreage scenario for perennials and the high acreage scenario for conventional summer annuals would lead to an additional 7 million acres of land entering into crop production in Minnesota beyond those already used. This analysis focuses on communicating the results of the 'dependent' acreage scenarios that have a constant total acreage for Minnesota. Still, we feel it important to acknowledge there may be differing views on the future acreages of crops in Minnesota and this can lead to competition between crops.

A part of developing scenarios of CLC crop acreages involved aggregating and assessing different acreage benchmarks that correspond to opportunities for CLC crop integration (see Table 5). For instance, in Minnesota, the Department of Health has identified Wellhead Protection Areas of 360,000 acres of land at high risk of drinking water pollution, with 115,000 acres currently used for row crops. The state has also implemented laws like the Buffer Strips requirement, which mandates buffer strips on approximately 110,000 acres statewide to improve water quality. Additionally, the Minnesota Agricultural Water Quality Certification Program has certified over 700,000 acres, including 110,000 acres dedicated to cover crops, with a goal of certifying 6.5 million acres by 2030. The Minnesota Nutrient Reduction Strategy aims to increase and target living cover solutions, with targets set at 440,000 acres for perennials and 1,900,000 acres for cover crops. These acreage values provide a sense of the scale of acres that are likely to be early adopters of CLC cropping systems.

Another consideration is land classification. About 20% of corn and soybean fields in the state (upwards of 3 million acres) are considered "marginal" due to consistently low yields and low profitability (Basso et al., 2019). Land considered marginal may have the greatest opportunity for realization of the environmental value proposition of CLC crops, although like most summer annuals, many CLC crops are unlikely to prosper on marginal lands. Further, while 20% of corn and soybean acres may be considered marginal, in many cases those acres are found in sub-field areas that would be logistically difficult to plant to another crop while continuing to grow corn and soybean in the profitable part of the field. As a result, the actual portion of corn and soybean fields that can realistically be repurposed is expected to be significantly less than 20%. If we assume half of marginal acres are more readily transitioned to CLC crops, that would leave us with about 1.5 million acres available to CLC crops, with the bulk of these being perennials since adding winter annuals would not remove the summer annuals from those marginal acres.

Corporate goals related to regenerative agriculture also provide insights. The Midwest Row Crop Collaborative (MRCC) aims to achieve 30 million regenerative agriculture acres in the Midwest by 2030. General Mills has set a goal of 1 million acres of regenerative agriculture by 2030, and Cargill aims for 10 million acres of regenerative agriculture in North America by the same year. Winter annuals are well aligned to regenerative agriculture goals given the current emphasis on cover crops. If 5 million acres of regenerative agriculture practices (17% of the total Midwest goal for MRCC) are implemented in Minnesota as a part of these corporate goals, much of those are likely to be winter annuals.

Table 5.

High Priority Benchmarks		Acres
DWSMAs	All Agriculture DWSMA acres	450,000
	High and Very High Vulnerability DWSMA acres in agriculture	240,000
Wellhead Protection Areas	Wellhead Protection Areas in row crops in 2022	115,000
MN Nutrient Reduction Strategy Goal by 2040	Increased perennials (non-CRP land - grass, pasture, hay) - acres in 2022	65,000
	Increased cover crops - acres in 2022	580,000
	Increased perennials (non-CRP land - grass, pasture, hay) - targeted acres in 2025	440,000
	Increased cover crops - targeted acres in 2025	1,900,000
Marginal Lands	All (20% of corn and soybean acres)	3,000,000
	Feasibly repurposed (10% of corn and soybean acres)	1,500,000

Taking these values together it is reasonable to suggest an additional 500,000 acres of perennials and 4+ million acres of winter annuals would be needed to reach 2030 State and corporate goals. Our scenarios use these values as reference points.

In addition to these reference points, other important factors included market sizing, ease of adoption on-farm, and current rates of crop development. For example, while winter annual oilseeds have few acres in Minnesota in 2023, the scale of the opportunity is very large and major agribusiness companies in the region are investing heavily in the opportunity. For this reason, acreage scenarios for winter annual oilseeds are quite large. On the flip side, some crops such as perennial oilseeds are years, sometimes several years, away from commercialization, in which case there is an assumed lag in when adoption begins. However, these crops also potentially benefit from being perennialized versions of already well established annuals - such as sunflower and flax. This means, they may be able to access an already existing value chain once developed, thus making the adoption relatively more straightforward than other crops, such as Kernza®, that require building new portions of the value chain.

Table 6 shows the 2023 starting point acreage values used for this analysis. Given the early stages of many of the CLC crops of interest, there was often uncertainty around just how many acres were in production. As a result, those in Table 6 should be considered conservative estimates.

Table 6.

		2023 - Acres in Minnesota	Source
Winter Annual Oilseed		5,000	Approximate value expected in 2023 based on interviews. No known published figures yet.
Kernza®		1,000	Approximate value expected in 2023 based on FGI interviews and The Land Institutes's 2022 Kernza® Planting and Harvest Report.
Other Perennial Grains		0	No acres in production other than potential research plots.
Winter Annual Cereals		50,000	Winter Wheat: ~40,000 USDA NASS 2022. Hybrid Winter Rye (harvested): 10,000 - estimated. not always clear when it is harvested vs. used as a cover crop per FGI research team interview. USDA NASS 2022 shows approximately 11,000 acres previously harvested in MN.
Winter Pea		0	No acres in production other than potential research plots.
Perennial Legumes		1,000,000	Approximated value in: Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022. Hay value from USDA NASS 2022 shows 640,000 acres of alfalfa hay (the most common hay legume) harvested in 2022 for example.
Perennial Cool and Warm Season Grasses (including pasture)		1,500,000	Approximated value in: Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
Perennial Oilseeds		0	No acres in production other than potential research plots.
Hazelnuts		200	Approximate value expected in 2023 based on interviews.
Short-rotation Woody Perennials	Low	2,000	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
	Medium	12,500	Middle of upper and lower figures reported.
	High	25,000	Hybrid Poplar Acres in MN estimated in Lazarus et al., (2011). Estimates for SWPs vary by accounting method.
Windbreaks and Woody Riparian Buffers		10,000	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.

Given the 2023 starting point values used, Table 7 shows the 2035 and 2050 acreage snapshots used for both the conventional summer annuals and the CLC crops. The adoption of perennials does reduce the acreage of corn and soybeans, as there is no net increase in cropland acreage assumed in this analysis.

Table 7.

Acres per year in Minnesota	Scenario	2023	2035	2050	Notes
Corn - Independent	Medium	8,000,000	8,000,000	8,000,000	Status Quo - USDA, NASS.
	Low	8,000,000	6,666,667	5,000,000	2050 figure reported in: Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
Corn - Dependent	Low	8,000,000	7,506,580	4,742,922	These values are the needed change in acreage based on projected acreage for perennials (assuming winter annuals are integrated into remaining summer annual acres).
	Medium	8,000,000	7,545,865	6,522,144	
	High	8,000,000	7,620,973	7,048,810	
Soybean - Independent	Medium	7,500,000	7,500,000	7,500,000	Status Quo - USDA, NASS.
	Low	7,500,000	6,833,333	6,000,000	2050 figure reported in: Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
Soybean - Dependent	Low	7,500,000	7,037,419	4,446,489	This is the needed change in acreage based on projected acreage for perennials (assuming winter annuals are integrated into remaining summer annual acres).
	Medium	7,500,000	7,074,248	6,114,510	
	High	7,500,000	7,144,662	6,608,260	
Corn and Soy - Independent Scenario	Medium	15,500,000	15,500,000	15,500,000	Status Quo - USDA, NASS.
	Low	15,500,000	13,500,000	11,000,000	Reduction reported in: Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.

Acres per year in Minnesota	Scenario	2023	2035	2050	Notes
Corn and Soy - Dependent Scenario	Low	15,500,000	14,543,999	9,189,412	This is the needed change in acreage based on projected acreage for perennials (assuming winter annuals are integrated into remaining summer annual acres).
	Medium	15,500,000	14,620,113	12,636,653	
	High	15,500,000	14,765,636	13,657,070	
Spring Wheat	Low	1,250,000	1,050,000	800,000	Reduction scenario based on wheat demand being partially met by perennial wheat and Kernza by 2050.
	Medium	1,250,000	1,250,000	1,250,000	Status Quo - USDA, NASS.
	High	1,250,000	1,405,556	1,600,000	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
Sugar Beets	Medium	455,000	455,000	455,000	Status Quo - USDA, NASS.
Corn Silage	Medium	400,000	400,000	400,000	Status Quo - USDA, NASS.
Dry Beans	Medium	200,000	200,000	200,000	Status Quo - USDA, NASS.
Spring Peas	Medium	90,000	90,000	90,000	Status Quo - USDA, NASS.
Sunflower	Medium	75,000	75,000	75,000	Status Quo - USDA, NASS.
Oats	Medium	165,000	165,000	165,000	Status Quo - USDA, NASS.
Winter Annual Oilseed Acres per year in Minnesota	Low	5,000	580,646	2,178,144	Low-High range based on interviews with growers, industry players, and Wedge Analysis project team. Industry players provided detailed acreage goals through 2030 which served as the benchmark for the medium adoption scenario with a continued increase in acreage based on market opportunity.
	Medium	5,000	1,233,611	5,468,953	
	High	5,000	3,071,045	9,436,458	
	Mirroring Canola's growth rate	5,000	600,000	1,500,000	Applying the annual growth rate of canola from 1990-2020 to the acreage starting point of the winter annual oilseeds. This puts all three of the winter annual oilseed adoption scenarios above canola.
Kernza® - Acres per year	Low	1,000	30,592	122,753	Low-High range based on interviews with growers and Forever Green team and uses an S curve adoption rate, noting that Kernza is well-suited to be grown on wellhead protection areas although has not experienced significant growth in acreage over the past 5 years.
	Medium	1,000	54,162	217,330	
	High	1,000	119,392	534,346	

Acres per year in Minnesota	Scenario	2023	2035	2050	Notes
Other Perennial Grains - Acres per year (assumes adoption begins in 2030)	Low	0	2,694	173,526	Uses the same S curve adoption rates as Kernza® but adoption is delayed to 2030. Total acreage surpasses Kernza due to the ability of other perennials to access already existing wheat, cereal rye and oat value chains.
	Medium	0	3,715	409,629	
	High	0	8,008	1,687,075	
Winter Annual Cereal Acres per year in Minnesota	Low	50,000	270,420	878,916	Low-High range based on interviews with growers, industry players, lit review and Wedge Analysis project team. Assuming harvested winter annuals, excluding winter annual oilseeds and all other cover crops, make up about 10% of all cover crops. This would amount to 1.2 million acres based on a total of 12 million acres projected by: Methodology and Assumptions for Greenhouse Gas (GHG) Reduction Estimates for Natural and Working LandsPrepared by GHG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022. The 1.2 million is used as a benchmark and for which the medium adoption scenario roughly aligns.
	Medium	50,000	545,487	1,447,762	
	High	50,000	759,994	3,072,226	
Winter Pea Acres per year in Minnesota	Medium	0	500	20,000	Adoption is delayed until 2030 due to additional crop development needed with rapid adoption after that due to growth in demand for pea-based products.
Perennial Legumes - Acres per year in Minnesota	Low	1,000,000	1,206,811	1,386,250	Low-High range based on interviews with growers, industry players, and Wedge Analysis project team. Medium adoption scenarios are based on figures projected by: Methodology and Assumptions for Greenhouse Gas (GHG) Reduction Estimates for Natural and Working LandsPrepared by GHG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
	Medium	1,000,000	1,304,918	1,685,304	
	High	1,000,000	1,369,637	2,066,237	
Perennial Cool and Warm Season Grasses - Acres per year in Minnesota	Low	1,500,000	1,810,217	2,079,375	
	Medium	1,500,000	1,957,377	2,527,955	
	High	1,500,000	2,054,456	3,099,355	
Perennial Oilseeds	Low	0	2,694	173,526	Adoption is delayed until 2030 due to additional crop development needed. Growth rates of adoption follow that of perennial grains given that the perennial oilseeds will be accessing existing markets, similar to perennial wheat and cereal rye, but in this case will be perennial sunflower and flax.
	Medium	0	3,715	409,629	
	High	0	8,008	1,687,075	

Acres per year in Minnesota	Scenario	2023	2035	2050	Notes
Hazelnuts	Low	200	300	1,000	Low-High range based on interviews with researchers and resources discussing market opportunities and current crop development obstacles.
	Medium	200	500	2,000	
	High	200	1,000	5,000	
Short-rotation Woody Perennials	Low	2,000	5,000	15,000	Estimates of current acreages vary by source. Hybrid Poplar Acres in MN estimated in Lazarus et al., (2011) serve as a high point. Estimates for SWPs vary by accounting method however. A lower starting point is used by the Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022. This impacts the trajectories of acreages in 2035 and 2050.
	Medium	12,500	25,000	50,000	
	High	25,000	45,000	80,000	
Windbreaks and Woody Riparian buffers	Low	10,000	20,000	40,000	2050 acreages based on estimates used in Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
	Medium	10,000	30,000	60,000	
	High	10,000	50,000	100,000	
Perennial Berries	Medium	50	500	1,500	Minimal information was available around future prospects of perennial berries although multiple market opportunities are noted, so the acreage is expected to increase.

The range of projected acres adopted for continuous living cover (CLC) crops can be influenced by various factors that play a critical role in farmers' decision-making and overall feasibility. These factors include:

1. Financing: Access to financing options, such as loans, grants, or cost-sharing programs, can significantly impact the adoption of CLC crops. Farmers may be more inclined to adopt CLC practices if they have access to financial resources that help cover initial investment costs, such as seed purchases, equipment, or labor. The availability and terms of financing options can influence the range of projected acres adopted, as more favorable financial support can incentivize farmers to implement CLC systems on larger areas.
2. Insurance: The availability and terms of insurance coverage for CLC crops can affect farmers' decisions to adopt and expand CLC practices. Insurance that provides adequate coverage and risk mitigation for CLC systems, including protection against yield losses, pest and disease damage, or extreme weather events, can enhance farmers' confidence in adopting CLC crops. The existence of insurance tailored specifically for CLC systems can increase the projected acres adopted by reducing the perceived risks associated with transitioning from conventional annual crops.
3. Public policy: Supportive public policies, such as conservation programs, incentives, or regulatory frameworks, can significantly influence the range of projected acres adopted for CLC crops. Policies that promote environmental conservation, sustainable agriculture practices, and provide financial incentives for CLC adoption can encourage farmers to allocate more acres to CLC systems. The strength and effectiveness of public policies can shape the projected acres adopted by creating a favorable environment for CLC practices.
4. Market access for crops: The availability of well-established and accessible markets for CLC crops can influence farmers' decisions to adopt and expand CLC practices. If farmers have reliable market access for their CLC products, including well-functioning supply chains, established buyer relationships, and competitive pricing, it increases the likelihood of adopting CLC crops on a larger scale. The existence of strong market demand for sustainable and lower greenhouse gas (GhG) intensity food, feed, and fuel sources can also drive the projected acres adopted, as farmers respond to consumer preferences and market signals.
5. Profitability: The financial viability and profitability of adopting CLC crops compared to conventional annual crops play a crucial role in farmers' decisions. Factors such as input costs, potential yield gains, cost savings from reduced inputs, and premium prices for CLC products influence the economic attractiveness of CLC adoption. Higher projected profitability associated with CLC crops can incentivize farmers to allocate more acres to CLC systems.
6. Market demand for lower GhG intensity food, feed, and fuel sources: Growing market demand for sustainable and lower GhG intensity food, feed, and fuel sources can influence the adoption of CLC crops. If consumers and industries increasingly prioritize products with lower carbon footprints and sustainable sourcing, farmers may respond by expanding CLC acreage to meet this demand. The projected acres adopted can be influenced by the level of market demand for such products and the premium prices offered for CLC crops.
7. Crop genetics and agronomics: Advances in crop genetics and agronomic practices specific to CLC crops can impact the range of projected acres adopted. Improved varieties that are well-adapted to CLC systems, exhibit desirable traits (e.g., nutrient use efficiency, weed suppression), and provide reliable yields can increase farmers' confidence in adopting CLC practices on a larger scale. Furthermore, agronomic knowledge and practices that optimize CLC crop performance, such as planting techniques, nutrient management, and pest control strategies, can enhance the feasibility and success of CLC adoption, potentially influencing the projected acres adopted.
8. Competition with annuals: The competition between CLC crops and conventional annual crops for land, resources, and market share can influence the range of projected acres adopted. Farmers may be more likely to adopt CLC practices if they perceive a competitive advantage over annual crops or if they can effectively integrate CLC systems within their existing cropping rotations. The level of competition and the perceived benefits of CLC crops compared to annual crops can impact the projected acres adopted.

The interplay of these factors shapes the incentives, risks, and opportunities associated with adopting CLC practices, ultimately influencing the extent to which CLC systems are adopted on agricultural lands.

See Figures 16, 17, 18, 19, 20, and 21 for examples of environmental wedges and on-farm economics under alternative scenarios.

Section 9: Conservation Practice Estimations

This is particularly important as the state of Minnesota's environmental and climate goals and agribusiness corporate sustainability goals include incentivizing increased adoption of conservation practices such as cover cropping, no-till/reduced tillage, nutrient management, among other practices. In this analysis, it is assumed that conventional BMPs are implemented on a greater scale over time, and applied to those summer annual acres that do not adopt CLC crops.

To help better show the contribution of BMPs, a separate environmental performance wedge has been added to the wedge analysis graphs. This allows us to both show a static business-as-usual scenario to better visualize the contribution of the CLC crops, while also providing a reference point of how the crops compare to conservation practices implemented on conventional summer annual acreages.

Table 8 shows the various adoption scenarios for a selection of conservation practices that are applied to the BAU. Wedges featured in this report utilize the medium adoption scenario. Adoption rates highlighted as 'low' are maintaining the status quo - which assumes that major regenerative agriculture goals have little effect on adoption rates. Adoption rates considered 'high' are those used as assumptions in 'Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands' - Prepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.

While there are many possible scenarios of the impact of conservation practices, and various estimates have been modeled in Minnesota, the wedge charts show a single middle ground point estimate aligned with the Minnesota Pollution Control Agency's 2013 report 'Nitrogen in Minnesota Surface Waters'. Within this report, a modeled 30% reduction of Nitrogen could be achieved with a series of BMPs that inform this assessment found in Table 9, Appendix F1.

For example, the 30% nitrogen reduction scenario assumes cover crops are adopted on 70% of cropland acres. We take this value, and subtract the proportion of summer annuals acres that will include winter annuals based on this analysis (42%). That leaves another 28% of summer annual acres to adopt cover crops to reach a total of 70% of summer annuals having either cover crops or winter annuals. As a result, that value is utilized in the estimated benefit of the conservation practice wedges. It is assumed that the 28% figure is not reached until 2050, but a linear increase in cover cropping occurs from 2023 to 2050 (this is the medium adoption scenario in Table 8). Similarly, nutrient management practices featured prominently in the MPCA scenarios, and as such those practices were utilized in this analysis as well, using a medium adoption rate (see Table 8 - bolded values were used to populate the BMP environmental wedges in Figures 5, 6, and 7). Lastly, no-till is also assumed to increase in adoption over time reaching 20% of conventional summer annual acres by 2050 under the medium adoption scenario (this is the scenario used in the BMP wedge of the environmental wedge charts). While no-till is also assumed as a part of the adoption of CLC cropping systems, those acres are not included in the 20% of conventional summer annuals so as to isolate the additional benefits of the BMPs beyond those indirectly achieved from CLC adoption. Reduced tillage can also provide benefits of reduced erosion, however the benefits of reduced tillage are less than no-till and are already much more widely implemented in Minnesota. The aforementioned report 'Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working Lands' projects a reduction in the use of reduced tillage out to 2050. As a result, given the environmental wedges of this analysis are focused on additional change beyond what is achieved today, reduced tillage is not included in forward looking projections, instead assuming that those acres of reduced tillage that are lost by 2050 (projected to be over 2 million acres) are either replaced with perennials or are make up a part of the acres that transition to no-till.

Isolating the impact of conservation practices and CLC crop adoption is a hard to untangle undertaking given that CLC crops are a market-based conservation practice that in many ways, serve a similar function as many of the conservation practices. CLC cropping systems serve a similar ecological function to cover crops, are not necessarily tilled annually, particularly if they are perennials, and often reduce the scale of fertilizer needed each year. Thus, different assumptions can be made around the extent the CLC cropping system scenarios included in this analysis effectively already account for BMP adoption.

Table 8 shows the full collection of conservation practices reviewed for this analysis and the varying adoption scenarios studied. However, only cover cropping, no-till and nutrient management were used in the BMP wedge estimations. Crop rotations, a practice already widely used, is an outcome effectively realized through the envisioned medium adoption of CLC crops. Conservation Reserve Program (CRP) acres, while providing significant environmental impact, are envisioned to have minimal change over time and provide negligible additional benefit beyond what they already achieve, thus providing little change to the business as usual scenario. Cover cropping and nutrient management practices were the most important practices used for estimating the size of the conservation practice impact using the medium adoption scenarios from Table 8 (bolded values were used).

The increased adoption of BMPs on conventional summer annual acres does not have the same impact per acre across the three environmental wedges included in this analysis. This is because those practices accounted for - namely nutrient management, no-till, and cover cropping, do not have the same proportional benefit per acre across nitrogen, soil erosion, and GhG emissions. Similarly, the simultaneous delivery of these three practices will not provide benefits equivalent to the sum of if each practice were delivered individually. To manage this, the practice that generates the highest impact per acre, whether it be nutrient management, no-till or cover cropping is utilized in the model. This is expected to be a conservative approach.

Table 8. Conservation Practice Adoption Over time for BMP Environmental impact

		Adoption Scenario	2023	2035	2050
Adoption of conservation practices in % of acres	Cover Cropping	Low - Status Quo	2%	2%	2%
		Medium	**2%**	**14%**	**28%**
		High	2%	28%	60%
	No-till	Low - Status Quo	5.88%	5.88%	5.88%
		Medium	**5.88%**	**12.16%**	**20%**
		High	5.88%	17.93%	33%
	Crop Rotations (at least corn/soy)	Low - Status Quo	70%	70%	70%
		Medium	70%	74%	80%
		High	70%	83%	100%
	CRP	Low	6.00%	5.11%	4%
		Medium - Status Quo	6.00%	6.00%	6.00%
		High	6.00%	6.89%	8%
	Nutrient Management	Low - Status Quo	10%	10%	10%
		Medium	**10%**	**19%**	**30%**
		High	10%	46%	90%

Carbon sequestration over time

As has been discussed in the main report, estimating the greenhouse gas emissions from crop production can be a complex undertaking. A component to estimating the greenhouse gas emissions or mitigation potential of CLC crops is their carbon sequestration potential. There is considerable uncertainty in the measurement of carbon sequestered in the soil, but it is generally accepted that rates of sequestration will diminish over time. The specific rate of decline of sequestration and the period of time over which that decay occurs have varying estimates and will be specific to soil conditions. For this analysis, a conservative timeline of 10 years is utilized with a diminishing rate of sequestration projected for years 2-10. As a result, it is only the first year of the crop's time in ground that its measured carbon sequestration is applied (see Table 11 for specific values used for each crop). This approach is taken due to the large uncertainty both in the rate of sequestration that will occur but also the risk that changes in practices in the years following the establishment of a CLC crop may lead to eventually releasing the very carbon that was sequestered. Future analyses may consider greater sequestration rates over a longer period and incorporate estimates of the rate of change of management practices that would lead to releasing the previously stored carbon.

Table 9. Diminishing Rates of Carbon Sequestration Over Time

Year from planting	1	2	3	4	5	6	7	8	9	10
Proportion of max sequestration occurring each year	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Average proportion of max sequestration occurring up to that year	1	0.95	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.55

Section 10:
Crop-specific Model Inputs

The following tables show the per acre values and impacts used for each crop across environmental and economic topics. The values in these tables are combined with the acreage values and conservation practice values to generate the aggregate impacts shown in the wedge and bar charts.

Table 10. Crop-specific Model Inputs

Crop	Wedge		Scenario	Figure in Year 1	Sources
BAU - Corn/ Soy rotation	Nutrient loss	% nitrogen loss per year on average - corn		20-25%	The Nature Conservancy, (2016).
		pounds of nitrogen applied per acre of corn in MN		146	Minnesota Ag News – Chemical Use: Corn: Fall 2021, USDA.
		pounds of nitrogen loss per acre - corn		29.2 - 36.5	Calculated.
	Soil erosion	tons of soil loss per acre in MN on average		3.2	DeJong-Hughes et al., (2014); BWSR, (2002).
	GhG emissions	Co2e emission per acre of annuals per year (tons/ac/year)		0.42	Field to market study found a national average for Corn (grain) of about 1800 lb co2e per acre in 2020. Potential to sequester 0.20 to 1.05 Mg of CO2 equivalents per year under perennials, while annuals are likely to emit 0.41 to 1.14 Mg/ha/yr (Robertson et al., 2000).
	On-farm economics	Revenue per acre	Low	$623.85	Average of historical corn and soy values 2017-2021.
			High	$676.20	Average of FINBIN corn and soy values 2012-2021.
		Net return per acre (excluding land rent)	Low	$228.39	Average of historical corn and soy values 2017-2021.
			High	$241.80	Average of FINBIN corn and soy values 2012-2021.

Table 10. Crop-specific Model Inputs

Crop	Wedge		Scenario	Figure in Year 1	Sources
Spring Wheat	Nutrient loss	% nitrogen loss per year on average		20%	The Nature Conservancy, (2016).
		pounds of nitrogen applied per acre in MN		65	Median value contingent on target yield. (Kaiser and Piotrowski, UMN Extension, 2023).
		pounds of nitrogen loss per acre		13	Russ Gesch - Winter Camelina & Pennycress Dual Cropping: Agronomics (n.d.).
	Soil erosion	tons of soil loss per acre in MN on average		1	Used as a proxy: Ton/acre erosion losses in 2, 3, and 4-year rotations (corn-soybean, corn-soybean-oat/red clover, and corn-soybean, and corn-soybean-oat/alfalfa-alfalfa) were 1.36, 1.08, and 0.88, respectively; the three and four year rotations resulted in 20.5% and 35.3% reductions (Lazicki and Wander, unpublished data).
	GhG emissions	Co2e emission per acre of annuals per year (tons/ac/year)		0.16	This translates to a potential to sequester 0.20 to 1.05 Mg of CO2 equivalents per year under perennials, while annuals are likely to emit 0.41 to 1.14 Mg/ha/yr (Robertson et al., 2000).
					Global Meta Analysis: Results show that the GWP of CH 4 and N 2O emissions from rice (3757 kg CO 2 eq ha -1 season -1) was higher than wheat (662 kg CO 2 eq ha -1 season -1) and maize (1399 kg CO 2 eq ha -1 season -1). (Linquist et al., 2012).
	On-farm economics	Revenue per acre	Average	$362	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
		Net return per acre (excluding land rent)	Average	$117	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).

Table 10. Crop-specific Model Inputs

Crop	Wedge		Scenario	Figure in Year 1	Sources
Oats	Nutrient loss	% nitrogen loss per year on average		20-25%	The Nature Conservancy, (2016).
		pounds of nitrogen applied per acre in MN		60	(Kaiser, UMN Extension, 2018).
		pounds of nitrogen loss per acre		12	Calculated.
	Soil erosion	tons of soil loss per acre in MN on average		1	The 3 year rotation may be a proxy value: Ton/acre erosion losses in 2, 3, and 4-year rotations (corn-soybean, corn-soybean-oat/red clover, and corn-soybean, and corn-soybean-oat/alfalfa-alfalfa) were 1.36, 1.08, and 0.88, respectively; the three and four year rotations resulted in 20.5% and 35.3% reductions (Lazicki and Wander, unpublished data).
	GhG emissions	Co2e emission per acre of annuals per year (tons/ac/year)		0.16	This translates to a potential to sequester 0.20 to 1.05 Mg of CO2 equivalents per year under perennials, while annuals are likely to emit 0.41 to 1.14 Mg/ha/yr (Robertson et al., 2000).
	On-farm economics	Revenue per acre	Average	$400	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
		Net return per acre (excluding land rent)	Average	$206	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
Pea	On-farm economics	Revenue per acre	Low	$342	Average from FinBin 2020. Field Pea.
			High	$453	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
		Net return per acre (excluding land rent)	Low	$127	Average from FinBin 2020. Field Pea.
			High	$253	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).

Table 10. Crop-specific Model Inputs

Crop	Wedge		Scenario	Figure in Year 1	Sources
Flax (all FINBIN states)	On-farm economics	Revenue per acre	Average	$259	Average 2013-2022 FINBIN.
		Net return per acre (excluding land rent)	Average	$80	Average 2013-2022 FINBIN minus land rent.
Rye (harvest & sold)	On-farm economics	Revenue per acre	Average	$273	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
		Net return per acre (excluding land rent)	Average	$63	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
Hay on Cash Rent	On-farm economics	Revenue per acre	Average	$342	Average 2013-2022 FINBIN.
		Net return per acre (excluding land rent)	Average	$141	Average 2013-2022 FINBIN minus land rents.
Dry Beans	On-farm economics	Revenue per acre	Navy Beans	$693	FINBIN average 2013-2022.
			Pinto	$519	FINBIN average 2013-2023.
		Net Return per acre (excluding land rent)	Navy Beans	$283	FINBIN average 2013-2022 minus land rent.
			Pinto Beans	$284	FINBIN average 2013-2022 minus land rent.
Sugar Beets	On-farm economics	Revenue per acre	Average	$1,163	Average 2013-2022 FINBIN.
		Net return per acre (excluding land rent)	Average	$151	Average 2013-2022 FINBIN minus land rents.
Winter Wheat	On-farm economics	Revenue per acre	Average	$311	FINBIN average 2013-2022.
		Net return per acre (excluding land rent)	Average	$63	Average 2013-2022 FINBIN minus land rents.

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Kernza®	Nutrient loss	% reduced nitrogen loss against corn	Low	70%	Jungers et al., (2019); Reilly et al. in prep.
			High	96%	Jungers et al., (2019).
	Soil erosion	% reduced soil erosion against corn	Low	63%	Switchgrass proxy. Reduced soil loss of 1.8-4.9 t per year against conventional corn.
			High	95%	Cup plant proxy. Reduced soil loss by nearly 99% against corn in Germany. (Grunwald et al., 2021).
	GhG reduction	Carbon sequestration (tons per acre per year)	Low	0	"In one study, researchers who attempted to measure increases in SOM under the perennial grain Kernza® could not detect significant differences after four years since crop establishment. In another study, researchers measured the carbon balance of a Kernza® field over five years using eddy covariance observations and found an average net ecosystem carbon accumulation of 3.7 t ha−1 yr−1" (Crews et al., 2018; Oliveira et al., 2018).
			High	1.6	It was observed that the perennial Kernza® was a strong carbon sink on a long-term basis (~−370 g C m−2 per year). (Crews et al., 2018; Oliveira et al., 2018).
		N2O mitigation	Low	34%	Miguez, (2016); Gelfand et al., (2016) - cover crop effect when integrated with corn/soy.
			High	84%	Meehan et al., (2013) - switching from continuous corn to perennial grass, using this figure as an upper bound.
	On-farm economics	Revenue per acre per year	Low	$360	Assuming average yield is low over 3 productive years (yield is highest in year 1 before declining) and priced at $1 per pound. Secondary product (forage) priced at $40 per unit - with 4 units per acre.
			High	$960	Assuming average yield is high over 3 productive years (avg 400 lbs/acre) and priced at $2 per pound. Includes forage value of $40 per unit and 4 units per acre.
		Net Return per acre per year	Low	$253	Kernza® perennial grain yields range from ~200-500 lbs / acre / year of clean, dehulled grain (or saleable grain) for 1-4 years and the IWG can be used for forage for several additional years. Grain pricing in 2021 ranges from approximately $1.00 - $6.00 per lbs depending on grain condition (farm gate vs. cleaned and dehulled) and organic certification.
					Net return based on $200 revenue from grain and $160 revenue for forage per acre; $106 per acre in costs (Based on FG Spreadsheet: Returns Costs Net Returns CC v5).
			High	$853	Net return based on $800 revenue from grain ($2/lb and average 400lbs/acre and $160 revenue for forage per acre; $106 per acre in costs.

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Kernza®	Regional Economic Contribution (from more localized supply chain between grain production and final product stages)	Economic multiplier	Low	2.62	IMPLAN's Grain Farming sector Type SAM multiplier for all of MN: 2.13.
			High	2.62	Total production and supply chain costs w/ a markup are about equivalent to the on-farm revenue (Colin Cureton's Kernza® supply chain model v.4). As a result, total value chain output per acre (including on-farm revenue) is about $400 - $2000. This effectively assumes all components of the value chain exist within MN. Flour milling result: When purchasing all grain from within MN - the economic multiplier increases from 2.56 to 2.62.
			Low	$1,326	Calculated.
			High	$4,470	Calculated.
		Jobs multiplier	Low	8.24	IMPLAN's Grain Farming sector Type SAM multiplier for all of MN: 3.1
			High	8.24	Flour milling result: When purchasing all grain from within MN - the jobs multiplier increases from 7.99 to 8.24.
		Labor Income multiplier	Low	4.92	IMPLAN's Grain Farming sector Type SAM multiplier for all of MN: 2.93.
			High	4.92	Flour milling result: When purchasing all grain from within MN - the jobs multiplier increases from 4.82 to 4.92.
Perennial Cereal Rye / Perennial Barley / Perennial Wheat / Perennial Oat	Nutrient loss	% reduced nitrogen loss - corn	Low	49%	Kernza® proxy, reduced to 70% effectiveness - Jungers et al., (2019); Reilly et al. in prep.
			High	67%	Kernza® proxy reduced to 70% effectiveness - Jungers et al., 2019.
	Soil erosion	% reduced soil erosion - corn	Low	44%	Switchgrass proxy. Reduced soil loss of 1.8-4.9 t per year against conventional corn.
			High	67%	Cup plant proxy. Reduced soil loss by nearly 99% against corn in Germany. (Grunwald et al., 2021).
	GhG reduction	Carbon sequestration (tons per acre per year)	Low	0	Assumes similar lower bound to Kernza® (Crews et al., 2018).
			High	6.3	Assumes at least 70% as effective at carbon sequestration as Kernza® (Oliveira et al., 2018).
		N2O mitigation	Low	24%	Miguez, (2016); Gelfand et al., (2016) - cover crop effect when integrated with corn/soy.
			High	59%	Meehan et al., (2013) - switching from continuous corn to perennial grass, using perennial grass as an upper bound proxy.

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Biomass, Bioenergy	Nutrient loss	% reduced nitrogen loss - corn	Low	79%	Syswerda et al., (2014).
			High	91%	Francesconi et al., (2015).
	Soil erosion	% reduced soil erosion - corn	Low	88%	Francesconi et al., (2015).
			High	95%	Asbjornsen et al., (2014) - for perennial strips.
	GhG reduction	Carbon sequestration (tonnes per acre per year)	Low	0.08	Yang et al., (2019).
			High	0.24	Yang et al., (2019).
		N2O mitigation - in comparison to less diverse monocultures	Low	30%	Yang et al., (2019).
			High	40%	Yang et al., (2019).
		Global Warming Potential (t CO2e / ha)	Low	0.133	Crews et al., (2018).
			High	1.21	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
	On-farm economics	Pasture - Revenue per acre	Average	$30	Average from FINBIN 2012-2021.
		Pasture - Net return per acre (excluding land rent)	Average	$10	Average from FINBIN 2012-2021 - Net Return over Lbr and Mgmt minus land rent.
		Alfalfa, hay - Revenue per acre	Average	$615	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
		Alfalfa, hay - Net return per acre (excluding land rent)	Average	$306	Average from 2017-2021 (from FG spreadsheet - Returns Costs Net Returns CC).
		Hay - Revenue per acre	Average	$342	FINBIN average 2017-2022.
		Hay - Net return per acre (excluding land rent)	Average	$38	FINBIN average 2017-2022.

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Winter Annual Cereals	Nutrient loss	% reduced nitrogen loss - corn	Low	13%	Strock et al., (2004); Qi et al., (2011).
			High	70%	A meta-analysis by Tonitto et al. (2006) found that non-legume cover crops, on average, reduce nitrate leaching by 40–70% when compared with a winter bare fallow soil. (Cecchin et al., 2021).
	Soil erosion	% reduced soil erosion - corn	Low	40%	Pratt et al., (2014); SARE, (2019); Daryanto et al., (2018).
			High	75%	Francesconi et al., (2015). Daryanto et al., (2018) note reductions up to 75% from cover crops generally.
	GhG reduction	Carbon sequestration (tons per acre per year)	Low	0.29	Daryanto et al., (2018); Lewandrowski et al., (2004).
			High	0.6	SARE, (2019).
		Global Warming Potential (tons CO2e / acre)	Low	0	Abdalla et al., (2019). Use of fertilizer with cover crops appears to impact GWP: when the cover crops were fertilized with N, the control (i.e. no cover crop) had lower GWP than the other treatments, due to a higher contribution of N-fertilizer production to the GWP of the sequences with cover crops. (Cecchin et al., 2021).
			High	0.75	.75 is the average net greenhouse gas balance value based on meta-analysis by Abdalla et al., (2019). Their upper bound estimated was approximately double this value, but we'll use .75 to stay more conservative in the estimate given the uncertainty in alignment with these specific winter annuals vs. cover crops generally.
	On-farm economics	Revenue per acre per year - Rye ($/acre)	Average	$273	From FG Returns_Costs_Net Returns spreadsheet. Also referenced were Covercress' publicized figures. https://www.covercress.com/farmers.cfm FINBIN Average 2013-2022.
		Revenue per acre per year - Winter Wheat	Average	$311	
		Net Return per acre per year - Rye ($/acre)	Average	$63	
		Net Return per acre per year - Winter Wheat	Average	$34	

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Winter Annual Oilseeds	Nutrient loss	% reduced nitrogen loss - corn	Low	0%	If the Camelina or Pennycress is being fertilized they may even lose more N than if the field were fallow in winter. The assessment results suggest that the 78 kg ha-1 of N-fertilizer provided to camelina and pennycress in Year 2 were partially used by these cover crops. The M/Cam-S and M/Pen-S sequences had slightly greater nitrate leaching than the control in both Ames and Morris locations. (Cecchin et al., 2021).
			High	90%	A meta-analysis by Tonitto et al., (2006) found that non-legume cover crops, on average, reduce nitrate leaching by 40–70% when compared with a winter bare fallow soil. (Cecchin et al., 2021). "50% Adoption of WC Relay-Soybean on Wheat Acres with ~90% Reduction Nitrate Nitrogen by WC for Spring N loss (Gesch, n.d.).
	Soil erosion	% reduced soil erosion - corn	Low	40%	The M/Pen-S sequence reduced the soil losses by almost half when compared with the control (50% in Prosper, 43% in Ames and 45% in Morris), while the sequences M/Cam-S and M/Rye-S reduced soil losses by 39% and 33% of the control, respectively, and averaged across all locations. Between the cover crops considered, the M/Rye-S sequence was the least effective in curbing erosion, likely because it covered the soil for a shorter period than camelina and pennycress. (Cecchin et al., 2021) 4 mg/ha/yr vs. 6 mg/ha/yr.
			High	75%	Daryanto et al., (2018) note reductions up to 75% from cover crops generally.
	GhG reduction	Carbon sequestration (tons per acre per year)	Low	0.15	Assumed to be half of the otherwise upper bound reviewed in the literature.
			High	0.3	The Nature Conservancy, (2016) reporting on cover crops generally.
		Global Warming Potential (kg CO2e / ha)	Low	579	Global warming potential estimated by three different methods indicated that winter camelina had a GWP of 579 to 922 kg CO2e ha−1 as compared with maize, which ranged from 1043 to 2999 kg CO2e ha−1. Adding a second crop after winter camelina, increased GWP by 235 to 540 kg CO2e ha−1 according to the GREET model, by 584 to 610 kg CO2e ha−1 according to SimaPro and by 403 to 508 kg CO2e ha−1. Maize in monoculture (MNSD) had the highest GWP except when the CLM method was used, which estimated similar GWP to the dual crop systems. (Berti et al., 2017).
			High	922	Use of fertilizer with cover crops appears to impact GWP: when the cover crops were fertilized with N, the control (i.e. no cover crop) had lower GWP than the other treatments, due to a higher contribution of N-fertilizer production to the GWP of the sequences with cover crops. (Cecchin et al., 2021).

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Winter Annual Oilseeds	On-farm economics	Revenue per acre per year - Winter Camelina only ($/acre)	Low	$133	"At reasonable WC yields (1000 lbs/ac) and price ($0.25/lb), as well as soybean yield drag (15%) and gross revenue ($499/ac), WC could add an additional $40 net revenue per acre for growers."
			High	$494	
		Revenue per acre per year - Soy relayed with WC	Low	$465	From FG Returns_Costs_Net Returns spreadsheet. Also referenced were Covercress' publicized figures. https://www.covercress.com/farmers.cfm FINBIN Average 2013-2022.
			High	$579	
		Net Return per acre per year - Winter Camelina only ($/acre)	Low	$0	
			High	$360	
		Net Return per acre per year - Soy relayed with WC	Low	$143	
			High	$257	
Woody Perennials	Nutrient loss	Woody Perennials - % reduced nitrogen loss - corn	Low	90%	Conservative lower bound, based on potential lower levels of N loss avoided at earlier stages in the crop's life.
			High	99%	Syswerda et al., 2014 studying a poplar system anc compared to corn.
	Soil erosion	% reduced soil erosion - corn	Low	30%	Assumed lower bound based on measured 51% for short rotation willow (Gamble, 2012).
			High	51%	Short-rotation Willow System (Gamble, 2012). In the second experiment, a native grass mixture reduced the average sediment concentration in surface runoff by 87% and 90% relative to a corn-soybean rotation and no-till corn, respectively. Sediment concentrations in surface runoff from short-rotation willow did not differ from the corn-soybean rotation, but were reduced in fall surface runoff by 51% relative to no-till corn. These results suggest that soil conservation can be improved in short-rotation willow systems, but confirm previous findings that native grasses can provide excellent sediment retention relative to annual systems. (Gamble, 2012).
	GhG reduction	Global Warming Potential (tons CO2e / acre)	Low	1.57	Short-rotation woody crops. Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
			High	2.98	Windbreaks/Shelter breaks. Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Woody Perennials	On-farm economics	Hazelnut - Revenue per acre	Average	$4,300	Based on the documented performance of our advanced selections and a price of $1.50/lb. for in-shell nuts, our hedgerow hazelnut system at maturity will generate average annual revenue of $4,300/acre, and net return to capital of $3,300/acre (Fischbach, 2020), with break-even in nine years. This profit potential is comparable to production in the Willamette Valley of Oregon.
		Hazelnut - Net return per acre (excluding land rent)	Average	$3,300	Based on the documented performance of our advanced selections and a price of $1.50/lb. for in-shell nuts, our hedgerow hazelnut system at maturity will generate average annual revenue of $4,300/acre, and net return to capital of $3,300/acre (Fischbach, 2020), with break-even in nine years. This profit potential is comparable to production in the Willamette Valley of Oregon.
		Aronia - Revenue per acre	Average	$12,000	At maturity - Savanna Institute, (2022).
Perennial Oilseeds	Nutrient loss	% reduced nitrogen loss - corn	Low	33%	Perennial Flax is likely to have similar root structure to annual flax, thereby having similar N avoided potential, when growing and less runoff when dormant compared to a fallow field. As a result, we will use cover crop values as a conservative proxy for the additional avoided N loss of perennial flax vs. annual flax. (Syswerda et al., 2011).
			High	88%	Cup plant proxy for silphium. Reduced N loss by up to 88% in wet conditions against corn in Germany (Grunwald et al., 2021).
	Soil erosion	% reduced soil erosion - corn	Low	25%	Perennial Flax is likely to have similar root structure to annual flax, but because its root system will exist continuously there is additional avoided soil erosion in the winter and spring. As a result, the lower bound here is expected to be similar to what a cover crop would achieve. (SARE Technical Bulletin, 2019).
			High	95%	Cup plant proxy for silphium. Reduced soil loss by nearly 99% against corn in Germany. (Grunwald et al., 2021).
	GhG reduction	Global Warming Potential (t CO2e / acre)	Low	0.27	Perennial Flax is likely to have similar root structure to annual flax, but because its root system will exist continuously there is additional sequestration possible. As a result, the lower bound here is expected to be similar to what a cover crop would achieve. Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
			High	1	Cup plant (Silphium perfoliatum) increased SOC compared to Maize (Grunwald et al., 2021). For Perennials as a category, they have potential to sequester up to 1 Mg of Co2e per acre per year, while annuals are likely to emit 0.41 to 1.14 Mg/ha/yr (Robertson et al., 2000).

Table 11. CLC Crop Model inputs

	Wedge	Effect compared to BAU	Scenario	Figure in Year 1	Sources
Perennial Oilseeds	On-farm economics	Perennial flax revenue per acre - referencing annuals as proxy	Average	$259	Assuming perennial flax accessing a similar market to annual flax so facing similar prices or a premium for sustainability, although perennial flax yields may be less than annual and so have less revenue per acre, potentially evening out revenues per acre. Average 2013-2022 FINBIN.
		Perennial flax net return per acre (excluding land rent) - referencing annuals as proxy	Average	$27	Assuming perennial flax has similar costs and revenue ratio to annual flax, although may be less costs required due to fewer passes on field needed in years 2 and 3 following crop establishment, Average 2013-2022 FINBIN.
		Perennial sunflower revenue per acre - referencing annuals as proxy	Average	$441	Assuming perennial sunflower is accessing a similar market to annual sunflower so facing similar prices or a premium for sustainability, although perennial sunflower yields may be less than annual and so have less revenue per acre, potentially evening out revenues per acre Average 2013-2022 FINBIN.
		Perennial sunflower net return per acre (excluding land rent) - referencing annuals as proxy	Average	$10	Assuming perennial sunflower has similar costs to annual sunflower, although may be less cost due to fewer passes on field needed? In which case, net returns could potentially be higher assuming revenues are similar between perennial and annual variants. Average 2013-2022 FINBIN.

Table 12. Conservation Practice Model Inputs

	Practice	Impact	Scenario	Value	Source(s)
Conservation practice impacts per acre	No-till	% reduced nutrient loss	Low	0%	Assumed base value.
			High	40%	Kaspar et al., (2012).
		% reduced soil erosion	Low	25%	Berti et al., (2017).
			High	40%	Berti et al., (2017).
		reduced GhG emissions per acre	Low	0.07	The Nature Conservancy, (2016).
			High	0.14	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
	Cover crops	% reduced nutrient loss	Low	33%	Syswerda et al., (2011).
			High	75%	SARE Technical Bulletin, (2019).
		% reduced soil erosion	Low	25%	SARE Technical Bulletin, (2019).
			High	50%	Daryanto et al., (2018).
		reduced GhG emissions per acre	Low	0.14	The Nature Conservancy, (2016).
			High	0.27	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.

Table 12. Conservation Practice Model Inputs

	Practice	Impact	Scenario	Value	Source(s)
Conservation practice impacts per acre	Crop rotations	% reduced nutrient loss	Low	30%	Hunt et al., (2017).
			High	75%	Anderson et al., (2007).
		% reduced soil erosion	Low	11%	Mulik et al., (2017).
			High	25%	Anderson et al., (2007).
		reduced GhG emissions per acre	Low	0	The Nature Conservancy, (2016).
			High	0.05	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
	Nutrient management	% reduced nutrient loss	Low	0%	
			High	25%	Minnesota Pollution Control Agency, (2014).
		reduced GhG emissions per acre	Low	0.03	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
			High	0.06	
	Nitrification inhibitors	reduced GhG emissions per acre	Low	0.15	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
			High	0.3	
	CRP land	% reduced nutrient loss	Low	85%	Randall et al., (1997); Schulte et al., (2017).
			High	95%	
		reduced GhG emissions per acre (t/acre)	Low	0.6	Methodology and Assumptions for Greenhouse Gas (GhG) Reduction Estimates for Natural and Working LandsPrepared by GhG Tracking Workgroup of the Climate Subcabinet, Natural and Working Lands Team, January 2022.
			High	1.2	

Section 11: Living Cover Estimation Details

In order to generate the sunburst charts that show the change in living cover over time due to the increased adoption of CLC crops (i.e. the CLC Score), we had to estimate:

1. The proportion of the year that crops would provide cover on the landscape based on historical planting and harvest dates, time to germination, and time to establish some cover.

2. The proportion of the year in which the ground is frozen and no matter what the crop is, there is no productive activity occurring.

3. The acres of each crop that would be on the Minnesota landscape under three select years, 2023, 2035, and 2050.

The combination of these three variables allowed for the ability to estimate the proportion of the year that the average acre of cropland in Minnesota would have a living crop on it. The result, as previously described, is a scenario in which, under medium acreage adoption scenarios, the amount of time the average acre of cropland has no living cover is reduced from 52% of the time to 25% of the time. This then has the corresponding environmental and economic implications previously described.

It is not assumed that the crops will have an impact on soil hydrology until at least two weeks after planting. As a result, the proportion of the year that the crops are given credit for their services of creating ground cover and having roots in the ground is not stretching from plant date to harvest date, but from plant date to harvest date minus two weeks. This approach is applied to both summer and winter annuals to conservatively frame the amount of time they are providing ecosystem services and so as to not assume that a crop planted two days ago will provide the same ecological services as the same one planted 2 months ago, for example.

Table 13 provides the full table of inputs used to generate the ground cover scenario figures.

Table 13. Scenario: Medium acreage

				2023			2035			2050		
	Crop	**Scenario**	**% of 'un-frozen' year with ground cover**	**2023**	**unweighted**	**weighted by % of year with ground cover**	**2035**	**unweighted**	**weighted by % of year with ground cover**	**2050**	**unweighted**	**weighted by % of year with ground cover**
Conventional Annuals	**Corn**	Medium	44%	8,000,000	39%	17%	8,137,265	37%	17%	7,029,328	32%	14%
	Soybeans	Medium	39%	7,500,000	36%	14%	7,628,685	35%	14%	6,589,995	30%	12%
	Spring Wheat	Medium	28%	1,250,000	6%	2%	1,250,000	6%	2%	1,250,000	6%	2%
	Sugar Beets	Medium	39%	455,000	2%	1%	455,000	2%	1%	455,000	2%	1%
	Corn Silage	Medium	29%	400,000	2%	1%	400,000	2%	1%	400,000	2%	1%
	Dry Beans	Medium	28%	200,000	1%	0%	200,000	1%	0%	200,000	1%	0%
	Spring Peas	Medium	28%	90,000	0%	0%	90,000	0%	0%	90,000	0%	0%
	Sunflower	Medium	50%	75,000	0%	0%	75,000	0%	0%	75,000	0%	0%
	Oats	Medium	28%	165,000	1%	0%	165,000	1%	0%	165,000	1%	
	Conventional Cover Crops	Medium	39%	362,700	2%	1%	368,019	2%	1%	325,086	1%	1%
CLC Crops	**Winter Annual Oilseeds**	Medium	39%	5,000	0%	0%	1,233,611	6%	2%	5,468,953	25%	10%
	Kernza®	Medium	100%	2,000	0%	0%	108,325	0%	0%	434,660	2%	2%
	Other Perennial Grains	Medium	100%	0	0%	0%	3,715	0%	0%	409,629	2%	2%
	Winter Annual Cereals	Medium	39%	50,000	0%	0%	545,487	2%	1%	1,447,762	7%	3%
	Winter Pea	Medium	39%	0	0%	0%	500	0%	0%	20,000	0%	0%
	Perennial Forage and Pasture	Medium	100%	2,500,000	12%	12%	3,262,295	15%	15%	4,213,259	19%	19%
	Perennial Grasses	Medium	100%		0%	0%		0%	0%		0%	0%
	Perennial Oilseeds	Medium	100%	0	0%	0%	3,715	0%	0%	409,629	2%	2%
	Woody Perennials	Medium	100%	22,750	0%	0.10%	56,000	0%	0%	113,500	1%	1%
	No Living Cover					52%			47%			32%

Section 12: Examples of Additional Scenarios

Every crop has multiple acreage scenarios. The following two figures (16 and 17) give an example of the low, middle and high range scenarios of acreages for Kernza® and Winter Annual Oilseeds in Minnesota. These being two crops receiving significant research and public attention at the moment. Each crop or crop category has a chart just like these.

Figure 16.

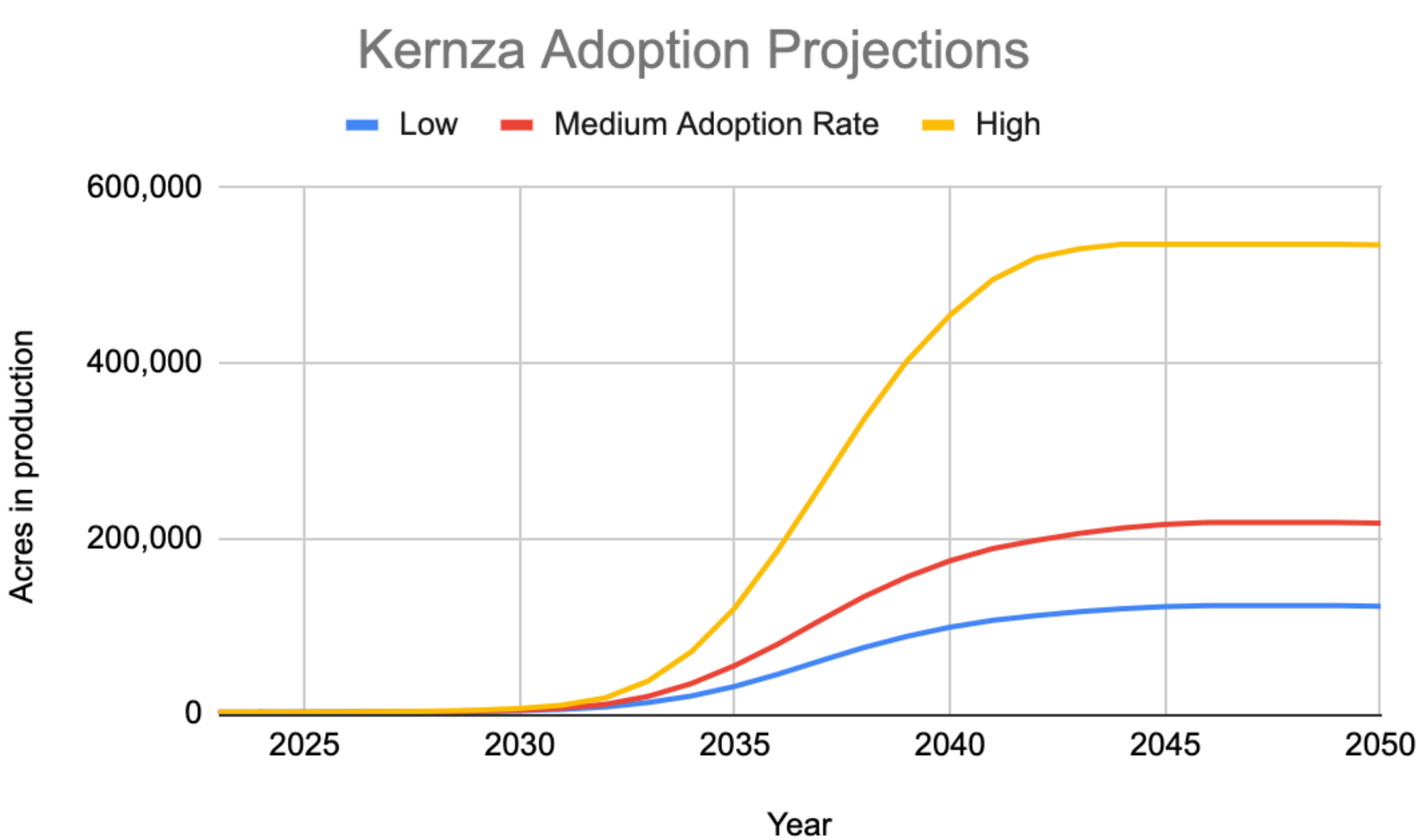
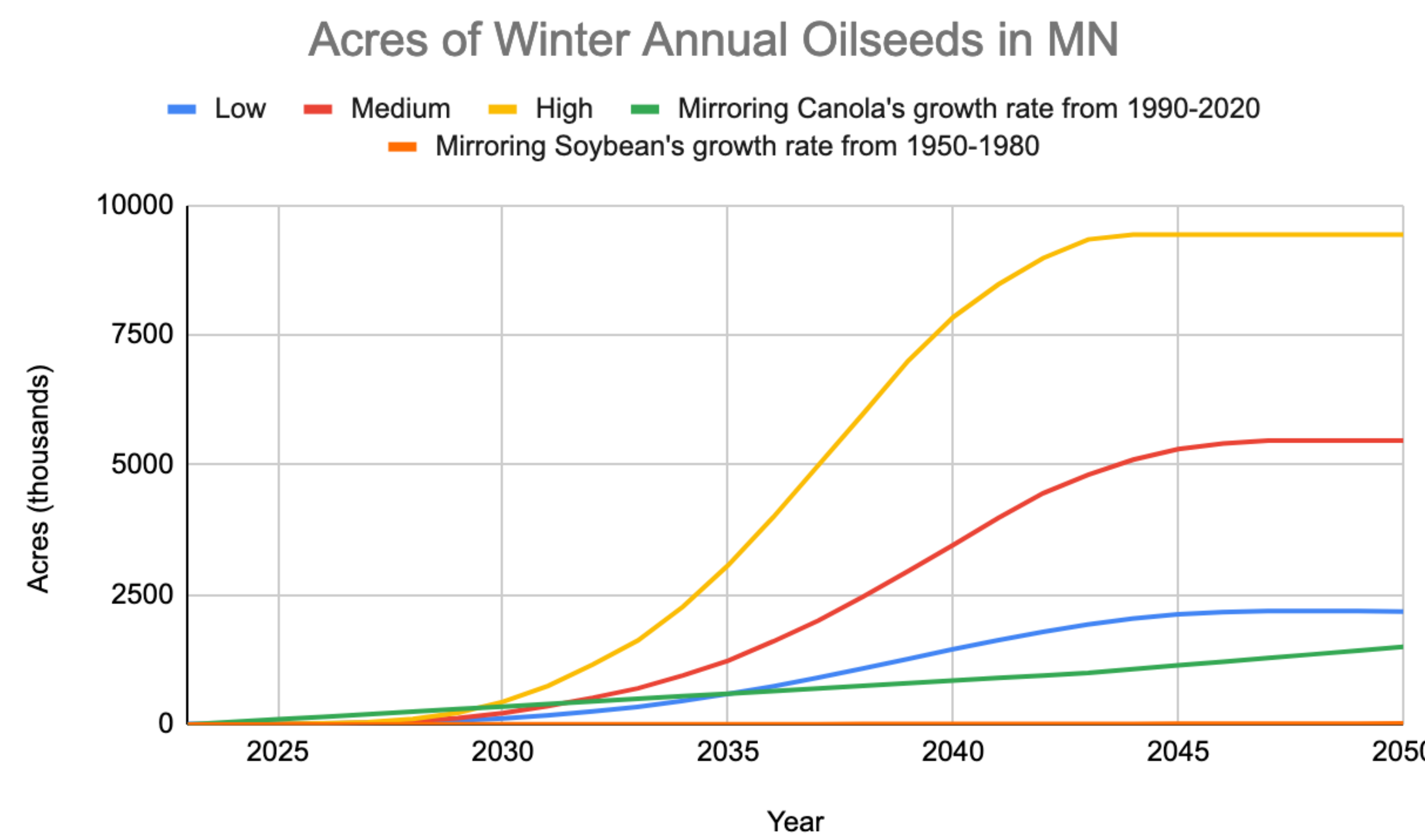


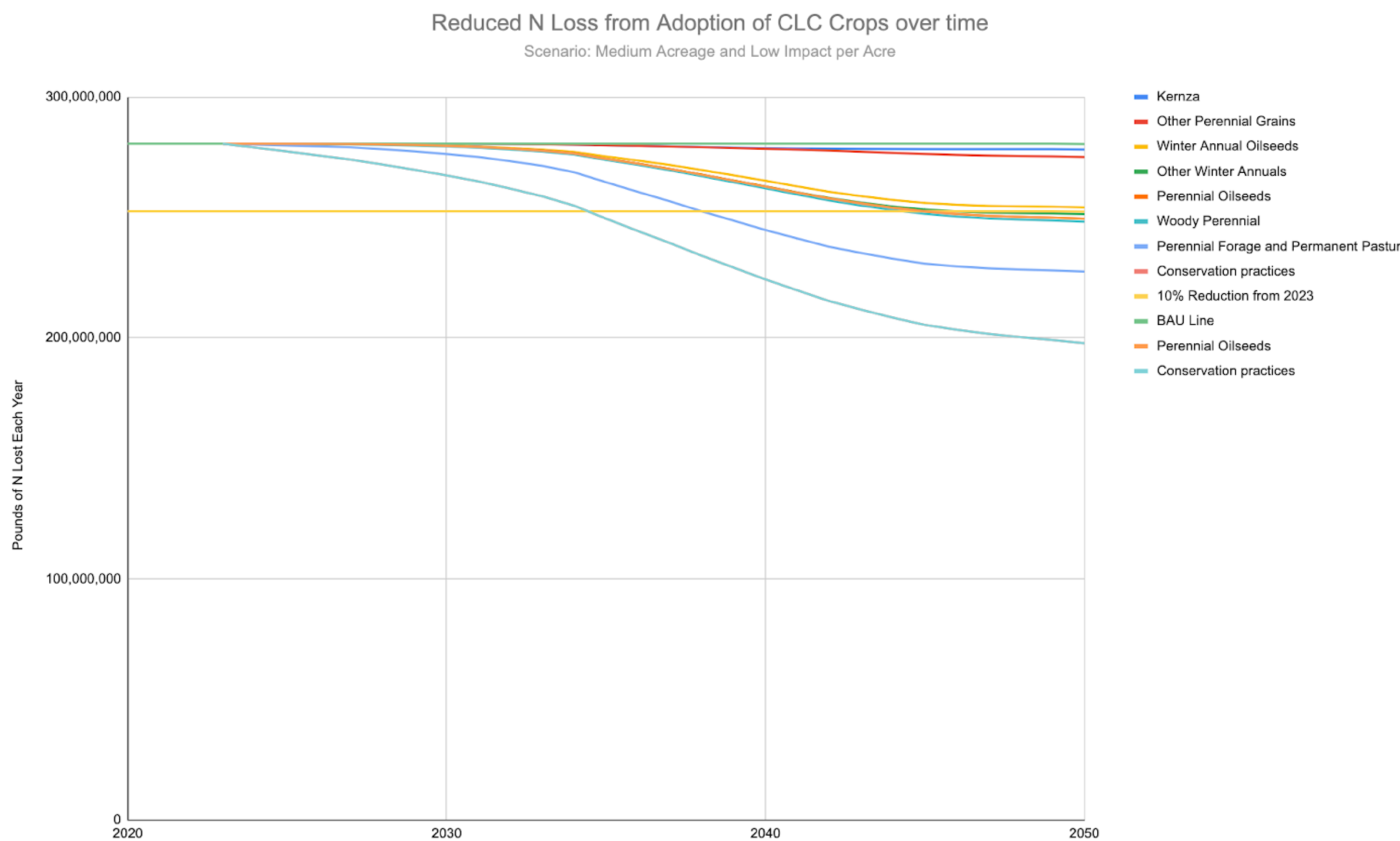
Figure 17.



Given the combination of variable acreages and variable impacts per acre, there are several potential forms each wedge chart could take. The following provides examples of how the impacts differ.

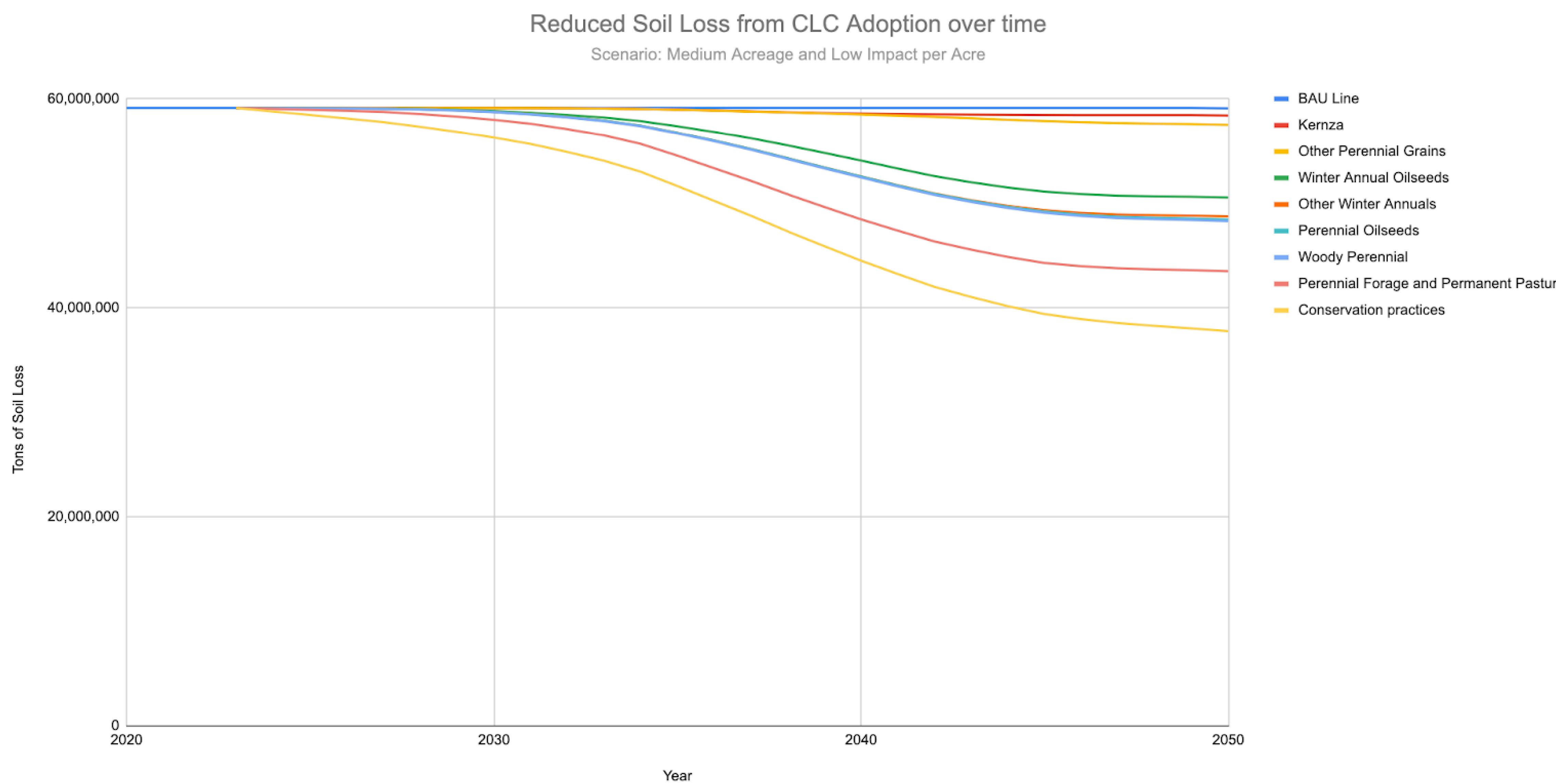
In Figure 18 we see the scenario of medium acreage and low impact per acre. This provides an example of how CLC crops perform when using their lowest measured impact from the literature. The difference in cumulative impact is relatively small given the range between medium impact and low impact per acre is fairly small.

Figure 18.



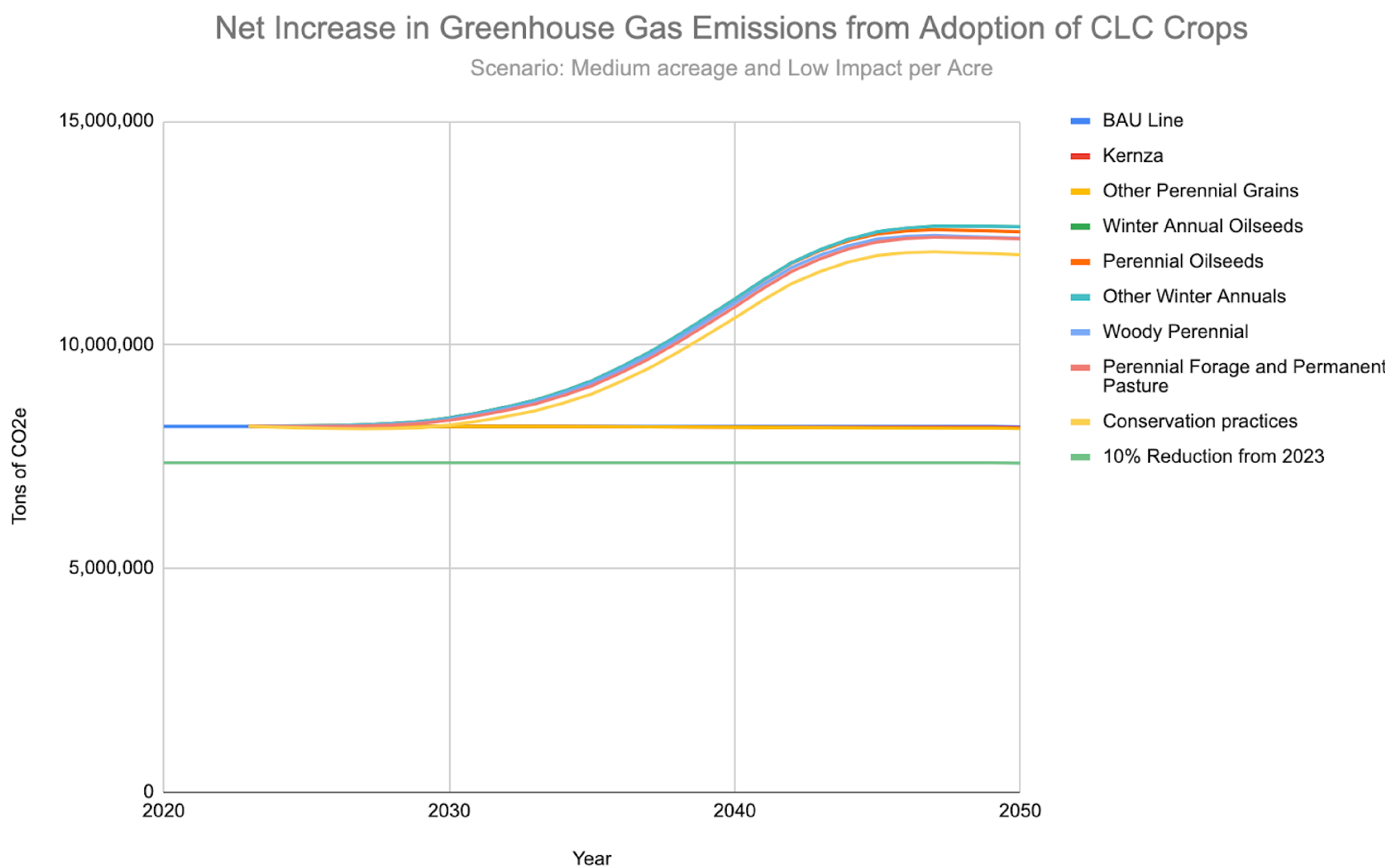
Similarly, when applying a low impact per acre value to CLC crops' ability to reduce soil erosion, the total benefits are reduced but an aggregate impact of nearly 20% (as opposed to 35% under the medium impact scenario), is still realized (See Figure 19).

Figure 19.



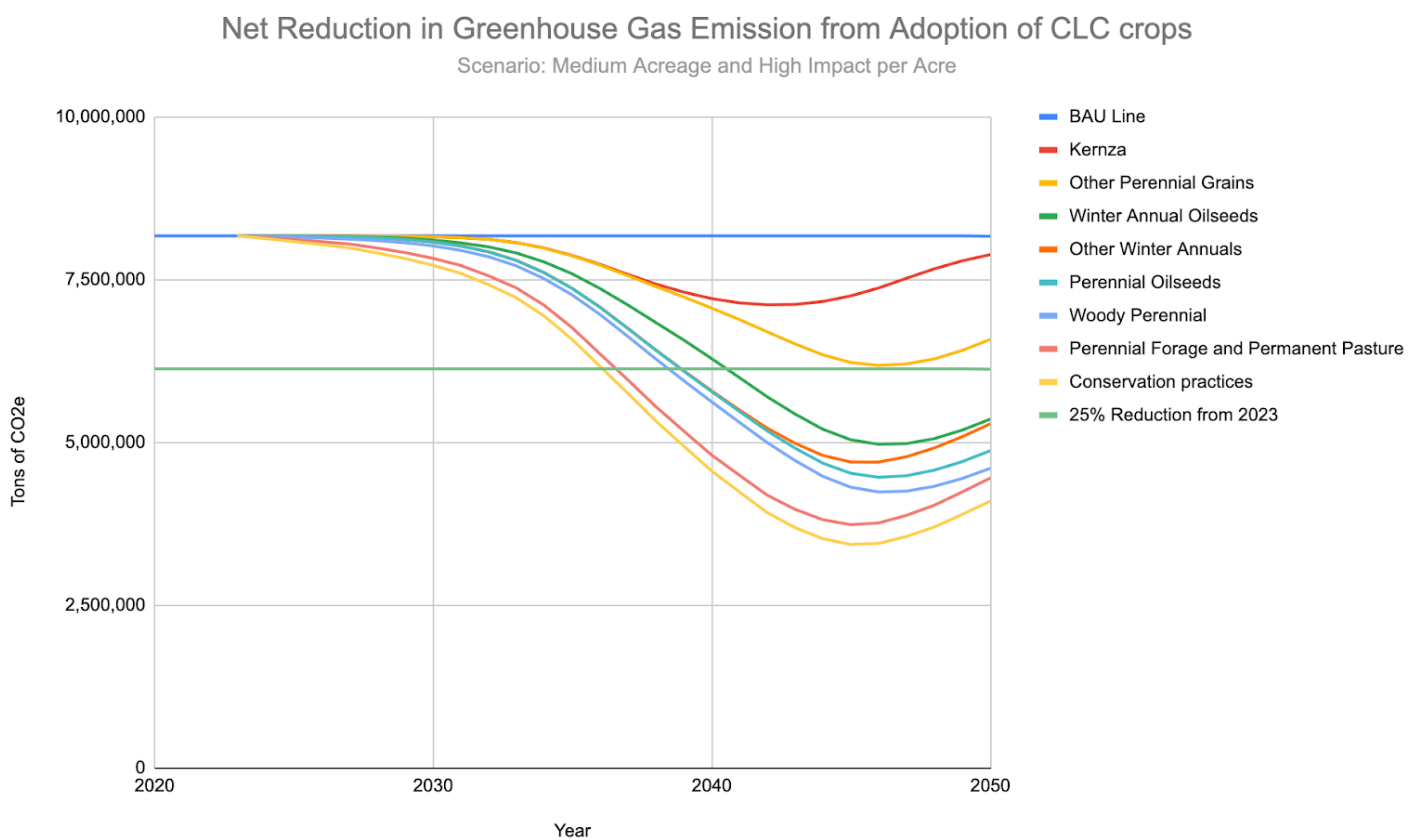
As described in the main report, the change in GhG emissions can either be positive or negative depending on the assumptions used. Figure 20 shows the net increase in emissions when including the potentially large increase that comes from agricultural intensification via the integration of winter annual oilseeds into millions of summer annuals' acres.

Figure 20.



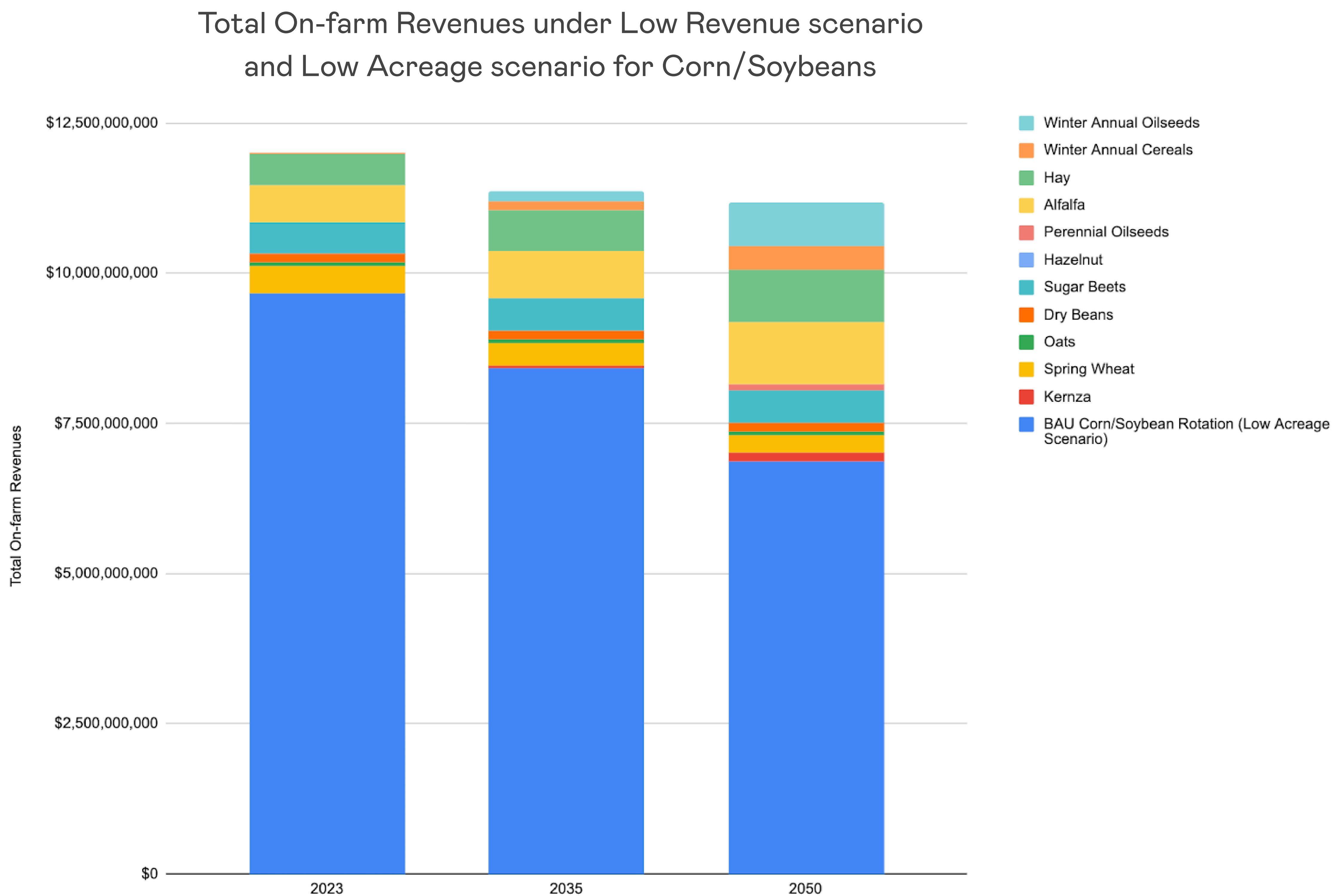
However, when best management practices are applied, and we assume comparable yields and net returns being achieved, the net reduction in emissions can be sizable. The best case view shows nearly 50% reduction in emissions.

Figure 21.



When turning to different scenarios of on-farm revenues, Figure 22 shows how total revenues per year for select crops (those crops with existing data), can actually decrease as CLC crop adoption increases when the lower bound of revenue for crops is utilized. This is not the desired scenario, and as a result, efforts must be made to help ensure this scenario is not realized, in particular by ensuring that maximum revenues can be realized from new CLC crops and that acreage for conventional summer annuals does not drop off too quickly.

Figure 22.



Section 13: Evidence Gap Analysis

A recurring theme in the subject matter expert interviews conducted was the interest in this analysis and the simultaneous lack of information to feed the analysis. In multiple cases, experts noted the 'lack of crystal ball' that would be needed to provide the answers Ecotone was after. As a result, many of the scenarios communicated in this report are the first 'stakes in the ground' for these topics. As research around CLC crops and their environmental and economic impacts develops it is expected that these scenarios will change. Similarly, as markets develop for those crops that are in early stages of commercialization or pre-commercialization, there will be lots of learnings around market size, pricing, profitability, etc. available for updating these scenarios.

Still, it is important to recognize the value proposition today to be able to inform investments today. This analysis, while facing limited evidence, has developed scenarios with sufficient information to guide future decisions given most decisions to be made do not require exact values. For most decisions that stakeholders face, perfect information is not required. And this analysis has shown that the signals for the environmental and economic impacts are strong enough in most cases to show the extent CLC crops and cropping systems will be better or worse and at an approximated scale to show the potential value on the table.

More specific to the evidence gaps, projecting future crop prospects in Minnesota entails several uncertainties that make accurate predictions challenging. These uncertainties stem from various factors, including climate change, technological advancements, market dynamics, and policy developments. Here are some key uncertainties in projecting future crop prospects in Minnesota:

1. Climate change: Climate variability and change significantly influence crop yields and growing conditions. Uncertainties exist in predicting the extent and pace of climate change, including changes in temperature, precipitation patterns, and extreme weather events. These uncertainties make it difficult to anticipate the specific impacts on crop productivity, water availability, and pest and disease dynamics.

2. Technological advancements: Rapid advancements in agricultural technologies, such as precision agriculture, genetic engineering, and data analytics, introduce uncertainties into crop projections. The adoption and effectiveness of these technologies, along with potential breakthroughs in crop breeding or farming practices, can significantly influence future crop yields, resource efficiency, and resilience to environmental stresses.

3. Market dynamics: The global and domestic agricultural markets are subject to various economic and trade factors that introduce uncertainties into crop projections. Fluctuations in commodity prices, changes in consumer preferences, trade policies, and market demand for specific crops can all impact the profitability and viability of different crops. Uncertainties in predicting these market dynamics make it challenging to project future crop prospects accurately.

4. Policy and regulation: Government policies and regulations related to agriculture, including environmental regulations, subsidies, and trade agreements, can have substantial impacts on crop production and profitability. Changes in policy frameworks, both at the local and national levels, introduce uncertainties into future crop projections. Shifts in support for specific crops or changes in environmental regulations may alter the economic feasibility of certain agricultural practices or influence crop choices.

5. Socioeconomic factors: Demographic changes, population growth, dietary trends, and consumer preferences also contribute to uncertainties in projecting future crop prospects. Shifting demographics and dietary preferences can drive changes in crop demand and the types of crops grown. Additionally, socioeconomic factors, such as labor availability, farm consolidation, and land use decisions, impact the agricultural landscape and add uncertainties to crop projections.

Based on these macro level uncertainties, the below outline key topics for this analysis that had varying evidence gaps.

Acreage projections - Pre-existing estimates for future potential changes in acreage in Minnesota were very limited. Interviews with the FG research teams and some external subject matter experts acknowledged their own proposed approach to estimating acreage potential of individual CLC crops but also admitted the significant assumptions associated with those estimates.

Environmental effects - The environmental argument for Forever Green crops is strong although data is often not crop specific. Instead it is often the principle of continuous living cover that shows positive water, soil and climate value propositions. In many cases, studies looking at the GhG emissions of a crop were focused on carbon sequestration potential rather than the full global warming potential of the crop production process as a whole. This lack of data made it harder to recognize how much emissions would change with the adoption of CLC cropping systems.

Economic effects - As many CLC crops are either not commercialized or are in the early stages of commercialization the economic effects are often not well understood. For those crops that have been commercialized, pilots and modeling suggest profitability when integrated appropriately to the farm context. Crops will have to show profitability competitive with corn and soy and to an extent that adoption is incentivized. The existing estimates also tend not to account for transition costs that a grower may experience to adopt the new crops. Certain crop categories have worked to address this, such as the work from Grassland 2.0, a collaboration housed at the University of Wisconsin-Madison supporting the adoption of perennial forage and grazing. Further, while there is considerable interest in the regional economic effects of CLC crops and cropping systems, this has generally not led to research on the topic.

Returns on scaling - Most CLC crops are implemented at small scales, if at all. Assessments of how environmental or economic benefits may accrue as adoption increases is reliant on modeling. As a result, we do not know how the environmental or economic impacts may change as adoption increases.

Barriers to scaling - CLC crops exist in a highly uncertain market environment. This means lots of market potential but many steps needed to realize that potential. By definition, each crop has a market opportunity(s) but faces either genetic, agronomic, market demand, behavioral, financial, policy barriers and/or lack of support.

When looking at the specific crop categories, there is variability in the amount of data and evidence available as well. Table 14 shows how certain crop categories have been studied in more detail than others with regard to their environmental and economic values. This is largely in alignment with the extent the crop has already been commercialized - more commercialized crops have been studied more. This is a summary of information available documenting the evidence today. Existing efforts have tended to focus on a selection of CLC crops such as Kernza®, Alfalfa, or Winter Camelina, and have taken a software-supported watershed-specific modeling approach. These efforts provide very specific data points for us to reference and collecting these data points provides us with a range of values. These data points inform the selection of low, medium, and high scenarios.

Table 14. Evidence Availability by Crop Category

Topic	Perennial Grains	Perennial Oilseeds	Winter Annual Oilseeds	Other Winter Annuals (Winter rye, etc.)	Woody Perennials (Fruit, Nut, Biomass)	Perennial Forage and Pasture (biomass, forage, prairie)
Environmental impact	Green	Red	Green	Green	Yellow	Green
Economic impact	Green	Yellow	Green	Yellow	Yellow	Green
Crop prospects	Yellow	Red	Green	Yellow	Yellow	Yellow
Transferable information	Yellow	Yellow	Yellow	Green	Yellow	Green

Key:

- Red = Minimal to no data exists on crops in the category
- Yellow = Some data exists but may have significant uncertainties and be for a single crop in the crop category
- Green = Data for at least one crop in the crop category exists and is from a quality study

Definitions:

Environmental - Studies on soil erosion, nutrient reduction, water quality and/or GhG emission.
Economic - Studies on the costs, net returns and/or economic effects of crops.
Crop Prospects - Studies on the market size, available acreage, marketability, yields, agronomics.
Transferable Information - Studies on crops with characteristics similar to those in the crop category.

Box 12: Future Means to Explore Acreages

Developing acreage scenarios for a single crop could be a project in and of itself as very detailed approaches can be taken that utilize a variety of existing market information, crop development timing, likelihood of regulatory changes, the pace of climate change, etc. While each of these variables were taken into consideration in the development of the acreage scenarios utilized in this analysis, deep dives into the market(s) for each CLC crop could be conducted that provide Serviceable Obtainable Market (SOM), Serviceable Available Market (SAM), Total Addressable Market (TAM) estimates.

For example, Dr. Fischbach has outlined a detailed market research plan for Hazelnuts that could provide very specific market sizing information that could be used for backcasting the amount of acreage needed to serve each market. This would include estimating the size of farmers market sales data, replacing turkish hazelnuts in grocery store bulk bins, finding sales data on hazelnut-derived products, etc.

Similarly, Dr. Wiersma has outlined an acreage estimate for Rye based on a market opportunity - incorporation into swine diets. If hybrid winter rye grown in Minnesota could replace the estimated 20% of Minnesota's corn that is used in swine diets, there would be an estimated need of 1 million acres of hybrid winter rye needed.

This project can be readily updated as these more detailed acreage projections are developed for each CLC crop.

Section 14: Regional Economic Impact Test Case

Modeling economic ripple effects faces greater obstacles than on-farm economic scenarios due to the use of economic input-output (EIO) tools available. EIO projections are not rigorously conducted with current tools. The IMPLAN Model, which Ecotone uses, estimates impacts assuming that the relationships between industries and households is the same as the current year and/or a given prior year. It does not estimate how market linkages will change in the future. Thus, EIO is a review of what has happened vs. what will happen. To make a projection of what the economy will look like ten years from now, for example, it would be necessary to predict all the demands for consumption ten years from now, and know all the new commodities and technologies that will be available at that time. Local availability of resources to meet that demand would also need to be known. So, any economic impact projection would be based on a sizable assumption that the market structures of today will be similar going forward.

Due to this limited ability to forecast economic impacts, there is still an option to create various 'visions' of economic impact using the current market structure. This is the approach used for communicating on-farm economics - different acreage scenarios are applied to the current market prices of crops to show how on-farm economics would look were the current crop portfolio in Minnesota to change. It does not forecast actual on-farm economics in the future.

To explore the ability to capture the regional economic impact of CLC crops and specifically, the benefit of a more localized value chain, we leveraged FGI's Kernza® Supply Chain Model which estimates total value chain costs per acre and allows us to estimate gross revenues across the value chain per acre of production. This figure is approximately $1,500. To estimate the economic impact per acre we can multiply this by the economic multiplier for the relevant industry. Since this is the value chain revenue as a whole, the grain farming sector would not be appropriate, but the flour milling sector would provide us with a final product (i.e. Kernza® flour) which can be bought in stores today. Reviewing the economic multiplier for the flour milling sector in Minnesota gives us a value of 2.56. For every $1 in revenue, the flour milling industry in Minnesota supports $2.56 of economic activity in Minnesota. This uses the industry average purchasing for flour milling in terms of the proportion of grain purchases from inside or outside of Minnesota. If we change the regional purchase coefficient, ie. the proportion of the grain purchased from within Minnesota, to be 100%. When this adjustment is made, the economic multiplier is increased to 2.62, a small but at scale, potentially significant change.

Using the value chain revenue per acre ($1,500) multiplied by the two economic multipliers shows total economic activity supported in Minnesota to be $3,923 (industry average) and $4,015 (Minnesota-sourced grain purchases only). Thus, for every acre of Kernza® production, there would be approximately $92 of additional local economic activity supported in Minnesota if the flour miller in Minnesota purchased only Kernza® grown in Minnesota.

Similar statements can be made when considering the impact on jobs. For example, by purchasing exclusively Minnesota grown grain, the job multiplier for a flour mill in Minnesota increases from 7.99 to 8.24 - an additional .25 jobs are supported for every 1 job that exists in a flour mill buying only Minnesota grain.

Table 15. Data Points to Estimate the Change in Economic Impact from Kernza®

Value chain economics	Post-production costs per acre		$389	For conventional Kernza® Grain - UMN FGI Kernza® Supply Chain Model v.4 (from Colin Cureton).
	Total value chain costs per acre		$1,179	For conventional Kernza® Grain - UMN FGI Kernza® Supply Chain Model v.4 (from Colin Cureton). Assumes 30% markup in line with Supply Chain Model assumption.
	Gross revenues for value chain per acre (estimated)		$1,532	For conventional Kernza® Grain - UMN FGI Kernza® Supply Chain Model v.4 (from Colin Cureton).
Regional economic contribution (from more localized supply chain between grain production and final product stages)	Economic multiplier	Low	2.56	IMPLAN's Grain Farming sector Type SAM multiplier for all of MN: 2.13.
		High	2.62	Total production and supply chain costs w/ a markup are about equivalent to the on-farm revenue (Colin Cureton's Kernza® supply chain model v.4). As a result, total value chain output per acre (including on-farm revenue) is about $400 - $2000. This effectively assumes all components of the value chain exist within MN. Need to check if this is the case for the grain sector, flour milling sector, soybean, other oilseed processing sector, Wholesale - Grocery and related product wholesalers, etc. so that it is not a 1-1 swap with conventional corn impact. Flour milling result: When purchasing all grain from within MN - the economic multiplier increases from 2.56 to 2.62.
	Economic impact in MN per acre	Non-localized	$3,923	Calculated.
		Localized	$4,015	Calculated.
	Jobs multiplier	Low	7.99	IMPLAN's Grain Farming sector Type SAM multiplier for all of MN: 3.1.
		High	8.24	Flour milling result: When purchasing all grain from within MN - the jobs multiplier increases from 7.99 to 8.24. For every 1 job created, an additional .25 jobs are supported in the Kernza® value chain compared to the grain value chain generally.
	Labor income multiplier	Low	4.82	IMPLAN's Grain Farming Sector Type SAM multiplier for all of MN: 2.93.
		High	4.92	Flour milling result: When purchasing all grain from within MN - the jobs multiplier increases from 4.82 to 4.92.

Section 15:

Comparing On-farm and Lifecycle Greenhouse Gas Emissions of Winter Annual Oilseeds

To help understand the greenhouse gas (GhG) benefits of winter annual oilseeds, we needed to do a comparison between the potential increase in on-farm emissions from winter annual oilseed adoption, relative to no winter annuals, and the potential reduction in emissions from aviation jet fuel and biodiesel derived from winter annual oilseeds when compared to petroleum-based jet fuel and diesel.

To make this comparison involved converting and then comparing on-farm emissions to the size of the emission savings from the transportation fuels. The conversion had to go from 'tons co2e per acre' to 'kg co2e per megajoule (Mj)' of fuel. Using an estimated yield of winter camelina of 1,000 lbs/acre and an estimated 6.38 lbs of winter camelina seed needed per 1 Mj of jet fuel (Li and Mupondwa, 2014) resulted in on-farm emissions of approximately -5.2 - 10.5 lbs co2e per Mj (See Table 16).

Fan et al., (2013) and Shonnard et al., (2010) estimated co2e emission savings from camelina-based jet fuel and biodiesel versus petroleum-based jet fuel and diesel to be 60-90% and 40-60% respectively. Using these values the average emission reduction (middle of the range of savings) equates to approximately 14.9 lbs of co2e per Mj for biodiesel and 25.5 lbs of co2e per Mj for jet fuel (Table 17). As a result, even under the high on-farm emission scenario (10.5 lbs of co2e per Mj) the net savings from replacing petroleum-based fuels outweighs the potential increase in on-farm emissions.

Table 16. On-farm Emissions

Emissions (tons co2e per acre)	Low impact (Net increase)	0.825
	Medium impact	0.209
	High impact (Net reduction)	-0.407
Emissions (lbs co2e per Mj)	Low impact (Net increase)	10.527
	Medium impact	2.667
	High impact (Net reduction)	-5.193

Table 17. Estimating Emission Reductions for Winter Camelina-based Fuels

	Winter camelina fuels: Emission ranges		Petroleum-based fuels: Emission ranges		Net savings for winter camelina-based fuels compared to petroleum-based fuels		Average emission savings relative to petroleum-based fuels
Biodiesel (co2e per Mj)	7.61	24.72	12.68	49.44	5.07	24.72	14.9
Hydroprocessed Renewable Jet Fuel (co2e per Mj)	3.06	31.01	7.65	77.52	4.59	46.51	25.55