The impact of integrated crop-livestock systems:
A review of the components and barriers of the classic farming approach

by

Alison Prather

B.S., Baker University, 2019

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Diagnostic Medicine/Pathobiology

College of Veterinary Medicine

KANSAS STATE UNIVERSITY
Olathe, Kansas

2022

Approved by:

Major Professor
Dr. Paige Adams

Copyright

Abstract

Integrated crop-livestock systems (ICLS) are designed to utilize cover crops, livestock, and cash crops in a sustainable cycle. Existing in agriculture for 8 to 10 millennia, ICLS are beginning to make a comeback in the global effort to make agriculture practices environmentally conscious and sustainable. Research has documented benefits for farm production in weed management, animal performance, crop yield, and diversity through ICLS implementation. The environment benefits from nutrient cycling, methane emission mitigation, and holistic climate resiliency of the farm. Economic strength and prosperity are staples of ICLS through diversified income, risk management, and reduced use of costly additive crop inputs. Barriers do exist for the adoption of ICLS due to gaps in knowledge and research but bolstering by political and social resources to close the gaps can make ICLS a reality for any farmer. This report will examine the benefits, consequences, and barriers of implementing ICLS.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I'd like to acknowledge the mentorship and encouragement of my committee members Dr. Gary Anderson, and Dr. Haley Larson. I'd also like to thank my Major Professor and Advisor, Dr. Paige Adams, for her belief in my potential and assistance in achieving my goals.

Chapter 1: Introduction

In a world of nearly eight billion people that is steadily growing, there is an increasing need for enough food to feed the world. This steady and sometimes rapid growth puts pressure on the agriculture industry to keep up and maintain high production yields. The pressure touches all corners of agriculture including crop production and livestock to provide the products and by-products the world needs to run. A great deal of this pressure comes by way of an increase in the demand for meat in low- and middle-income countries (de Souza Filho et al., 2019). When it comes to food security, one in nine people cannot access sufficient protein, contributing to global food insecurity (Sekaran et al., 2021).

Over time this increasing demand has caused an evolution in the way livestock and crops are produced, resulting in high specialization and condensation of products at the producer level. Producers now specialize in one continuous crop or one continuous species of livestock, which decreases crop diversity and catalyzes the negative effects of condensed cattle production. This monoculture cultivation has resulted in 88% of United States farms specialized in either crops or livestock, and only 8% of farms reporting income from more than four field crops (Hayden et al., 2018). Agriculture accounts for 10% of global greenhouse gas (GHG) emissions, with ruminants (cattle) now accounting for 36-48% of total greenhouse gas (GHG) emissions within the livestock sector (de Souza Filho et al., 2019). These statistics indicate that this specialized form of agriculture is not necessarily a sustainable way to feed the world and promote the health of the environment (Sekaran et al., 2021). Studies conducted to discover sustainable ways of agriculture have led the industry toward regenerative and sustainable practice adoption, which are capable of restoring soil health, increasing biodiversity, and ultimately benefitting the economic stress of producers (Carvalho et al., 2018). One such way of adopting sustainable agriculture is by implementing integrated crop-livestock systems (ICLS).

Integrated crop-livestock systems are characterized as agroecological systems in which the agricultural activities align with the natural processes of the ecosystem (Sinclair et al., 2019). Composed of inputs and outputs in a cycle that continuously benefits all components of the farm operation, ICLS is considered a sustainable agricultural system (Gliessman and Ferguson, 2019). While there are variations in components of ICLS, this report will primarily focus on cash crops like corn and soybeans, livestock like beef cattle, and cover crops like legumes, grasses, and cereals, wherein the cover crops feed the livestock who in turn fertilize the soil in preparation for the cash crop resulting in higher yield and lower production costs (Gliessman and Ferguson, 2019). Thus, each output of one land unit becomes an input for another part of the system like the cover crop residue for cattle feed and cattle manure for field fertilizer.

Figure 1 illustrates these relationships between farm operations, the environment, and farmer economy, highlighting the benefits to be had within the system. Synergy is created within the cycle, allowing for each pillar to reach optimization (Sinclair et al., 2019). While Figure 1 does not provide an exhaustive list of benefits within ICLS, it does shed light on the main drivers for farmers to consider in converting to ICLS. These drivers will be examined and discussed throughout the remaining chapters of this report. It is important to note the cyclical and reciprocal characteristics of the divers in which a benefit of one pillar to another induces the benefit in response (Sinclair et al., 2019). This is a common characteristic of any agroecological system but is especially robust in the design of ICLS (Gliessman, 2020).

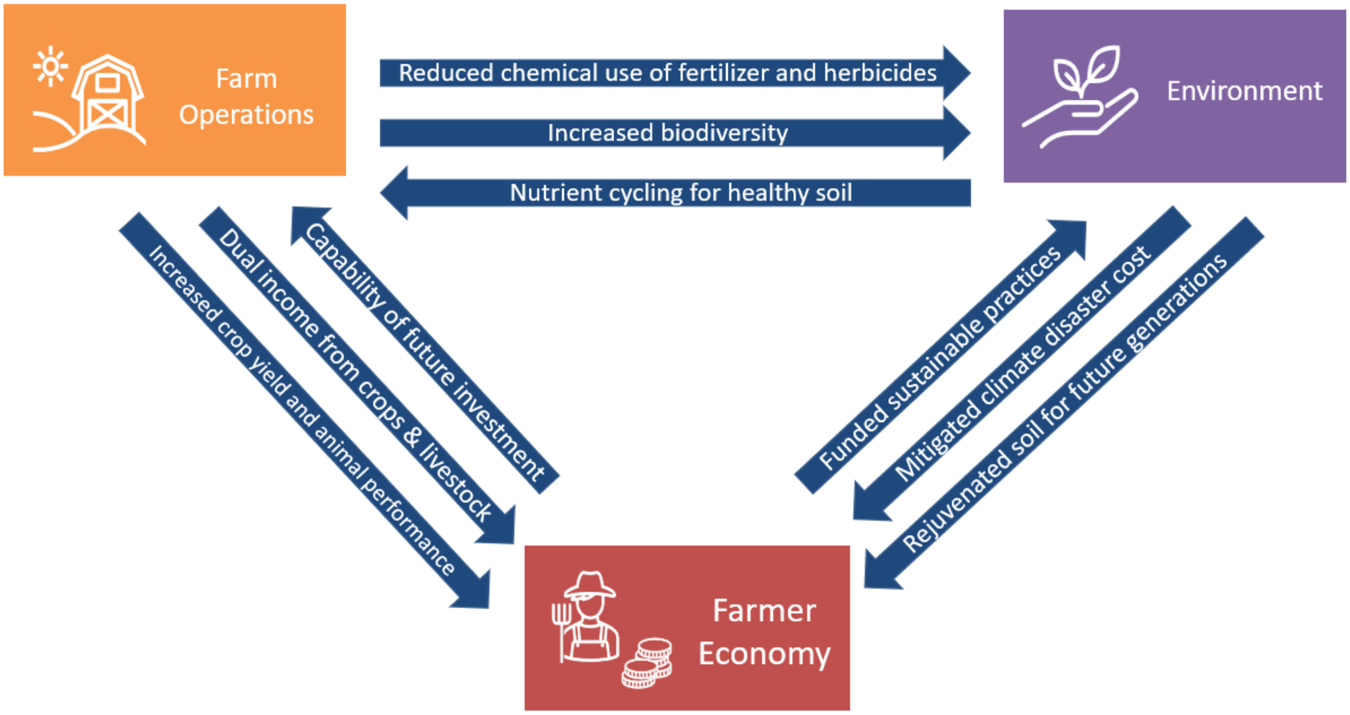

Figure 1 Graphic illustration of the cyclical relationship between farm operations, the environment, and farmer economy seen within integrated crop-livestock systems.

When this system is properly utilized, the overall efficiency of the farm and productivity of both crops and livestock see benefits (Gliessman and Ferguson, 2019). The main solutions ICLS can provide are food security through optimized farm operations, environmental rejuvenation, and economic diversification for the farmer (Sekaran et al., 2021). While these systems are effective in many areas of agricultural need, there are drawbacks and consequences to consider when evaluating the efficacy of the system. Barriers of adoption pose a threat via practical, social, and political challenges farmers must overcome in the process of adoption. Knowledge gaps in the long-term effects of ICLS further drive a wedge between farmers and the benefits the ICLS can provide to a rural community and agricultural industry. The following chapters in this report will examine the aspects of the ICLS with respect to farm operations, the environment, the farmer economy, and system adoption.

Chapter 2: Background

To understand the role integrated crop livestock systems (ICLS) can play in helping agriculture adapt to the needs and characteristics of today's world, it is imperative to know what modern agriculture in the United States is like. Researchers characterize modern agriculture as large areas of single, genetically-similar crops requiring heavy use of chemicals, animals raised in crowded confinement, loss of small- and medium-scale farms, policies that support large-scale farms, and more (Gliessman, 2020). Attention on sustainable, agroecological systems like ICLS have emerged as modern agriculture has been challenged by the climate and consumer demand for more product (Devlet, 2021). Outside of environmental and social challenges, modern agriculture has become interwoven into the economy as globalization and international trade of agricultural inputs has taken off (Devlet, 2021). These conditions catalyzed the genetically modified crops movement in an attempt to manufacture resilient agriculture to meet demand in the face of drought, flooding, irregular temperatures, and other effects of climate change (Devlet, 2021). In the wake of these challenges and movements, calls for sustainable agriculture have stimulated a rebirth of agroecology and organic practices (Chabert and Sarthou, 2019).

Integrated crop-livestock systems are one such system that has experienced growth amid calls for sustainable agriculture (Chabert and Sarthou, 2019). In many ways ICLS exemplifies the definition of an agroecological system, given that it contains the agroecological principles. The principles consist of recycling, input reduction, soil health, animal health, biodiversity, synergy, economic diversification, co-creation of knowledge, social values and diets, fairness, connectivity, land and natural resource governance, and participation (Wezel et al., 2020). Designed with these principles in mind, ICLS is capable of mitigating compounding obstacles of increased pressure and competition over renewable resources, rural poverty, specialization within agricultural and food industries, loss of biodiversity and climate change consequences (Wezel et al., 2020). This drives its compatibility with international agricultural systems especially.

In many ways, integrated crop-livestock systems are the historical origin of the modern farm. Integrated crop-livestock systems (ICLS) go as far back as 8 to 10 millennia ago, in the Middle East and Southern Asia (Sekaran et al., 2021). Records of integrated operations of crops, trees, livestock, and fish farming have been found in China from 1600-800 BCE and in Europe from the 16th century (Sekaran et al., 2021). For several millennia, people would survive off the land with multiple food sources through planted food and livestock. As agricultural technology has advanced forward from horse-drawn plows and the invention of the tractor to mass production, globalization has become the new normal.

While large and efficient food production has been necessary to provide for the ever-growing population, there have been effects associated with globalization. Specifically, United States agriculture has experienced prominent levels of specialization through the increasing demand and globalization of agriculture (Kumar et al., 2019). With the emergence of tractors and electric farm equipment, producers began to build a fleet that was tailored to high-yielding monoculture and fairly closed farming systems (Abson, 2019). These systems are well suited to globalization and increasingly depend on global commodity markets for input and outputs to be profitable (Abson, 2019). This is how polarized production regions became cemented into the core agriculture system of America, seeing direct consequences in productivity of operations, stability against fluctuating variables, persistence of success over time, and justified costs and benefits of productivity (Abson, 2019). In recent years, climate challenges such as water deficits and soil erosion in marginal land has prompted such regions to implement diversified crop rotations (DCR) consisting of three or more crops being rotated (Wang et al., 2021). DCR mirrors the rotating design of ICLS and is often included when farmers are integrating cattle and organic practices (Wang et al., 2021). DCR adoption experiences barriers in politics, social spheres, and practicality, similar to those of ICLS discussed in Chapter 6 (Wang et al., 2021). Such challenges must be overcome in order to take steps toward diversification in the modern American agriculture industry.

Most countries with high adoption are middle- to low-income countries, often with large quantities of impoverish communities (Garrett et al., 2017). These countries typically have smaller operations of crop and livestock production, making conversion easier. Most dryland farming systems of Sub Saharan Africa utilize ICLS (Sekaran et al., 2021). Cattle production in Southeast Asia has largely adopted ICLS with 75-90% of ruminants raised on ICLS (Sekaran et al. 2021). The resulting synergy and diversification from ICLS show direct economic benefits over time for smallholder operations through the ability to expand outputs without extra inputs and sophisticated technology, making regions like these an optimal place for adoption (Asante et al., 2019). Perhaps the biggest move toward ICLS has been seen in Brazil, where the area of ICLS used has doubled in the last 10 years (Sekaran et al., 2021). As a major player in the beef industry, Brazil’s drastic move toward ICLS has played a significant role in scientific and economic exploration around the benefits of increased animal performance and crop yield. Conversely, Chapter 6 evaluates barriers of adoption from these angles to understand ICLS from a holistic perspective.

Chapter 3: Effects on farm operations

As mentioned in the introduction (Chapter 1), one key area of significance that is affected by integrated crop-livestock systems (ICLS) is the farm itself. There are key components of ICLS that are responsible for a direct effect on other outputs in order for the system to be successful. In an ICLS, there are three components to study with regard to farm operations: weed management, crop yield, and animal performance (Carvalho et al., 2018). Many of these components overlap and have dual purposes in the ICLS, further contributing to the efficient and sustainable nature of the system. The components all work together and, in many ways, incorporate with the other key areas of significance that will be covered in the following chapters of this report.

Weed management via cover crops

Weed management is a key practice in farming with many options for the prevention of damage to crops by weeds (Carvalho et al., 2018). Research shows weed-crop competition contributes to a 45-95% decrease in crop yield if weed growth is not controlled (Mennan et al., 2020). In modern farming, herbicides have been implemented for controlling weed growth before, during, and after crop production (Schuster et al., 2019). In recent years, consumers and policymakers have become aware of potential danger to workers, consumers, beneficial insects, and the environment as a whole when synthetic herbicides and other fumigants are used in crop production (Carvalho et al., 2018). Integrated crop-livestock systems have been proposed as an alternative to herbicides (Mennan et al., 2020). This is achieved through the use of cover crops during periods when no cash crop is being grown in the fields. Cash crops are primarily produced for commercial value to be sold each year as a source of income for the farmer (Garrett et al., 2017). Cash crops are more commonly seen on larger operations as opposed to operations that practice subsistence farming. In this design, cover crop biomass along with allelopathic potential for some species creates physical barriers on the soil surface and chemical barriers within the soil to inhibit weed growth, especially in vegetable cash crops (Mennan et al., 2020). While research exists on the inhibitory characteristics of cover crops for weed management, the resulting effect on crop yield must be better understood for farmers to optimize their strategy.

Cover crops grown in ICLS serve the purpose of soil surface coverage, weed management, and increased soil fertility for the benefit of cash crops (Schuster et al., 2019). Compatibility between cover crops and cash crop protection varies, making cover crop selection a key component for success in weed management (Mennan et al., 2020). The cover crop types consist of cereals, legumes, Brassicaceae plant, and non-legumes (Mennan et al., 2020). It is important to understand what cover crops-cash crops pair well together, as well as what weeds are best inhibited. Depending on what allelochemicals are produced by the cover crop, specific weed species are chemically suppressed, making connections between cover crop, cash crop, and target weed species (Mennan et al., 2020). After selecting of the optimal cover crop for crop yield, the mechanism of weed management via cover crops is fairly simple. Cover crop residues provide a physical barrier to weed emergence resulting in reduced weed infestations and herbicide use (Schuster et al., 2019). With the proper use of cover crops, farmers can expect enhanced soil health, nutrient cycling, suppression of soil-borne pathogens and weeds, and optimized water use when the time comes for the cash crop to be produced (Planisich et al., 2021).

A recurring theme for ICLS lies within an increased need for proper management of farm operations (Hayden et al., 2018). The amount of cover crop residue left on the soil surface at the time of cash crop planting can alter the effectiveness of the ICLS system. Insufficient cover crop biomass can negatively influence weed management (Schuster et al., 2019), while over-abundance of cover crop biomass can damage seeding and crop establishment (Mennan et al., 2020). Balancing the remaining cover crop biomass largely lies in managing cattle grazing, bringing the cover crop's other purpose in ICLS into play. Within this system, cover crops are used for forage and grazing to feed cattle. Only 30% of the world's grazing lands are being used for cattle production, leaving room for incorporation of grazing in production systems like ICLS (de Souza Filho et al., 2019). Through optimization of herbage intake and sward height, a balance can be maintained between nutrition for cattle, and optimal residue coverage for cash crop production. In a study comparing annual ryegrass-soybean rotation production with and without dairy heifers grazing, herbage production was 60% higher for grazing treatments that yielded a maximum average daily gain of 1.10 kg/day and live weight of 427 kg/ha at sward heights of 16.1-20.6cm (Planisich et al., 2021). These results supported the hypothesis that beneficial synergy was achieved when the annual ryegrass acted as a dual forage and service cover crop (Planisich et al., 2021). In order for the benefits to come to fruition, grazing must be managed closely to avoid over-grazing, which can reduce biomass to the point that there is not enough weed protection for the next cash crop.

Enhanced crop yield via cover crops

Cover crops have a role to play in cash crop production aside from just weed management. Crop yield is largely increased when cover crops are optimized via rotation and proper combination with soil type (de Souza Filho et al., 2019). Research shows that optimized cover crop residue left on the soil surface at the end of grazing season results in higher crop yield

(Schuster et al., 2019). The nitrogen-fixing nature of legume cover crops enable them to rejuvenate the soil, enriching it with replenished nitrogen, potassium, phosphorous, and sulfur (Carpinelli et al., 2020). These are key components of crop nutrition that contribute to important biochemical processes like photosynthesis and cellular respiration, especially in nutrient-draining species like corn (Carpinelli et al., 2020). The soil microbiome has a critical role in soil health and the natural cycling of these nutrients. When crops are deprived of the optimal amount of these nutrients in the soil or on the soil surface, crop yield suffers. Integrated crop-livestock systems are shown to increase soil biological activity of native microbials and maintain soil fertility in the long-term (Sekaran et al., 2021).

Research shows soil type can also determine success of crop yield and ICLS in general. Meta analysis reveals that annual cash crop yield is more successful with ICLS, especially in loamy soil types (Peterson et al., 2020). Loamy soil is known as an intermediate soil texture and primarily consists of silt, sand, and clay soil. This soil is known for resistance to compaction (a side-effect of cattle grazing), and is resilient against organic carbon loss, erosion, and drought (Peterson et al., 2020). Geographical areas with naturally loamy soil should highly consider implementing ICLS with a better capacity for high grazing intensity without causing damage to weed management and cattle performance (Wezel et al., 2020). Conversely, sandy soils do not pair as well with ICLS, largely due to sandy soil's higher sensitivity in sub-optimal conditions (Peterson et al., 2020). Grazing activity can worsen the sensitivity to climate challenges in sandy soil, causing crop yield to degrade (Peterson et al., 2020).

When managing grazing activity, farmers must work to avoid harmful effects of soil compaction, caused by cattle grazing. Soil compaction occurs when soil bulk density increases and impedes the crop's ability to establish robust root systems to optimize nutrition (Tobin et al., 2020). Increased bulk density and decreased soil water retention are two direct effects of grazing in both the short-term and long-term (Tobin et al., 2020). This not only effects the cover crops, but the cash crops as well, forcing the growing plants to spend more resources for growth than if they were in non-compacted soil (Hudek et al., 2020). When selecting cover crops, it is important to evaluate the root traits such as length, surface area, density, and diameter which all can have an effect on soil preparation for cash crop planting (Hudek et al., 2021). In some situations, cover crops like Brassicaceae radishes are seen to adapt their root systems from a single tap-root to multiple perpendicular roots in order to penetrate compacted soil (Burr-Hersey et al., 2018). Mustard is another Brassicaceae family cover crop species that adapts and multiplies its finer root system to increase soil microporosity in a compaction layer (Hudek et al., 2021). Other species like black oats do not react differently to compaction and fail to decrease bulk density of soil, showing importance of field monitoring while cattle are grazing (Burr-Hersey et al., 2018). This is an example of benefits of rotating cover crops and cash crops to mitigate compaction and increase microporosity of soil for better cash crop growing conditions.

Enhanced livestock production via cover crops

In an ICLS, livestock production serves as a cornerstone of the system. Similar to cover crops, livestock offer two key resources to the farmer: food/revenue and a source of fertilizer via manure. In order for the animal to grow to a profitable size, produce optimal and nutritious fertilizer, and avoid over-grazing the cover crop, producers must be able to manage the herbage intake of their cattle. The main measurement for grazing activity is to measure the sward height of the forage (Planisich et al., 2021). Sward height can be an indicator of herd management characteristics like stocking rate (of cattle), grazing rotations, potential dip in animal productivity, and more (Planisich et al., 2021). With proper supervision of these indicators, farmers can successfully optimize their animal production.

In managing cover crops, sward height is a key indicator of effective grazing management. The ideal sward height for simultaneous weed management and optimized animal production is an important component of successful ICLS (Carvalho et al., 2018). Like many other components of ICLS, sward height has a direct effect on both of variables. Grazing intensity, if left unchecked, can greatly harm the success of a cover crop in sustaining the cow as well of providing protection for the cash crop. High grazing intensity can cause compaction of soil through increased bulk density, which diminishes the quality and health of the soil if cattle are not rotated through grazing areas (Peterson et al., 2020). High grazing intensity can also result in too low sward height of cover crops like Italian ryegrass and mixed black oat, causing cattle to have lower herbage intake (de Souza Filho et al., 2019). The insufficient nutrition results in suboptimal animal production and the producer must supplement the diet, negating the economic benefits of ICLS (Schuster et al., 2019). In most grass cover crops, moderate sward height of 17-23cm allows for the optimal herbage intake and bite mass to promote weight gain in cattle (Planisich et al., 2021).

While cover crops can provide feed for cattle to optimize weight gain, they also contribute to the nutrition of the cattle (Planisich et al., 2021). There are other ways outside of monitoring sward height to be sure cattle are receiving proper nutrition. Farmers are encouraged to implement rotational cover cropping to increase yield and yield stability, break weed and disease cycles through rotating legumes and forages, adding to foraging and reproductive habitat for beneficial insects, and increasing colonization of annual summer crop roots by arbuscular mycorrhizal fungi which enhance access to water and oxygen (Carvalho et al., 2018). Cattle experience diet enhancement when farmers implement rotations of cover crops and nitrogen-fixing crops with higher protein content such as rotating annual ryegrass and soybeans (Planisich et al., 2021), or corn and oats (Sekaran et al., 2021). Use of cover crops like annual ryegrass optimize forage production, favor greater average daily gain (1.1 kg/day), and live weight gain (427 kg/ha), all while promoting crop diversity and managing weed infestation (Planisich et al., 2021). In winter-grazed mixed black oat and Italian ryegrass, an optimal sward height of 17.8cm correlates to the calorie content and nourishment needed to feed 21.1% more people than soy and beef produced outside of ICLS practices (Schuster et al., 2019). Given this, if winter cover crop grazing were fully utilized in Brazil during the off-season for soybeans (75% of Brazil's cultivated hectares), ICLS could theoretically provide enough beef to satisfy the annual beef demand of 119.2 million people (Schuster et al., 2019). Practical barriers discussed in Chapter 6 present the challenges to this becoming reality.

Chapter 4: Effects on the environment

Integrated crop-livestock systems (ICLS) provide key benefits within the agricultural community, but it doesn’t stop there. Integrated crop-livestock systems have profound effects on the health of soil and climate resiliency. As mentioned in Chapter 3, cover crops serve as feed for livestock who in turn provide natural fertilizer and nutrient recycling for soil through manure (Sekaran et al., 2021). This natural fertilizer is highly effective in providing nutrition to plants and soil, as well as being cost-efficient for the farmer. However, there is a balance required to manage grazing intensity and still receive enough manure to prepare the land for the cash crop season.

Nutrient cycling via manure

Nutrient cycling is a direct effect of ICLS in which nutrients ingested by cattle are processed and released back into the environment, creating a never-ending, sustainable cycle (Garrett et al., 2017). There are four main elements released into the ground as manure disintegrates: nitrogen, potassium, phosphorous, and sulfur (Carpinelli et al., 2020). These are critical for biochemical processes for plants and the main inputs used in synthetic fertilizers (Werth et al., 2021). Research has focused in on these elements to determine how the process of uptake works once the manure has been deposited on the soil. Chemically, they all possess slightly differing decomposition rates which creates a form of controlled release into the soil (Carpinelli et al., 2020). Table 1 summarizes the role of the nutrient in plant and soil health, as well as the percentage of the nutrient that is released into the soil after 84 days. This is key information for farmers to understand how long it takes before nutrients begin releasing as well as the longevity of the process. This timing must be managed and understood well in order to optimize the performance of the ICLS.

Nitrogen is the nutrient most present initially in cattle manure and is one of the most crucial nutrients for plant health (Luo et al., 2020). Nitrogen is a key component of fertilizer, typically in the nitrate and ammonium form, promoting growth through biochemical processes that regulate shoot height and tillering (Luo et al., 2020). Potassium is necessary to activate enzyme activity in plants to carry out processes like protein synthesis and metabolism, both of which contribute to plant growth (Carpinelli et al., 2020). We know that 60-70% of the potassium ingested by animals returns to soil, contributing to important potassium balance and maintenance of the soil system (Carpinelli et al., 2020). With so much potassium being returned to the soil, ICLS provides an efficient and sustainable way to keep potassium bioavailable to crops once they are planted. Phosphorous is a staple element in the photosynthesis process, particularly in the conversion of energy into growth and reproduction (Carpinelli et al., 2020). Similar to potassium, phosphorous from manure is highly plant-available and inorganic, resulting in more than 70% of it available for uptake into the soil (Carpinelli et al., 2020). Nitrogen and sulfur play a critical role in the management and growth of native microbial populations in the soil (Carpinelli et al., 2020). These microbes are responsible for decomposing organic matter and nutrient cycling themselves. Plants absorb these nutrients that microbes break down in order to grow robust root systems (Carvalho et al., 2018). Farmers can utilize the nutrient cycling via manure in ICLS to avoid purchasing synthetic fertilizers and bottled microbes that often are not as compatible with the soil as the native population already present.

In a study by Carpinelli et al. (2020) the release rates were examined of nitrogen (N), potassium (K), phosphorous (P), and sulfur (S) to determine how long dung could continuously release the nutrients. The study showed that nutrients would be released approximately 84 days after entering the animal. Nitrogen is released first and is followed by potassium. Potassium releases quite rapidly because it is released in a water soluble form, taking only 5-6 days to disintegrate (Carpinelli et al., 2020). Sulfur takes 8-9 days to release into the environment and can remain constant for up to 84 days once the initial release has begun (Carpinelli et al., 2020). Phosphorous remained similar to sulfur, taking longer to begin releasing than nitrogen and potassium. By the end of the 84 days, 60% of N, 42% of P, 68% of K, and 38% of S in the manure was completely released (Carpinelli et al., 2020). While this release rate is fairly constant, there are factors that will disrupt these levels. Many studies have centered in on the presence or absence of trees in the field, noting that it does make a difference (Carpinelli et al., 2020). Systems with trees experience less even distribution of manure, seeing concentrations around water points, gates, and fences (Carpinelli et al., 2020). Cattle tend to gravitate toward stationary points when not actively grazing (Carpinelli et al., 2020). This creates lower levels of nutrient release in these areas and a need for additional fertilizing measures.

Table 1. Summary of the role of each nutrient in plant and soil health, and the corresponding percentage that releases into the soil within 84 days after ingestion per research by Carpinelli et al., 2020.

Nutrient	Nitrogen	Potassium	Phosphorous	Sulfur
Benefit to plants	Promotes growth of shoots in root system	Key aspect of biochemical processes for plants and soil system maintenance	Necessary for photosynthesis; particularly conversion of energy into growth and reproduction	Imperative to the successful management and growth of native microbes in the soil
Percentage released into soil after 84 days	60% released	68% released	42% released	38% released

Farmers must also overcome challenges to nutrient cycling and fertilization from the climate as well. Wetness for too long a period of time can have detrimental consequences to cycling, regardless of time of year (Carpinelli et al., 2020). Farmers must incorporate weather patterns in their area into their planning and management of the grazing/manure fertilizer portion of the ICLS. Heat can speed up microbial activity with nitrogen, but wetness can slow the nutrient release process (Carpinelli et al., 2020). A balance must be found in these aspects of nutrient cycling.

Methane emission mitigation via cover crops

It is risky to attempt to offset the uneven natural distribution of manure with increasing the stocking rate of the cattle. Increasing livestock production per area is not a valid solution because it leads to expanded nutrient losses through methane emission in decoupled carbon cycles (de Souza Filho et al., 2019). Such effects can be seen in feedlot operations in which the combined effects of cattle manure, synthetic inputs for crops, and fumes from feed raise emissions rates (Werth et al., 2021). Much of the conversation about enteric methane emissions from cattle revolves around the nutrition of the animals and the resulting effects of different feed (Dillon et al., 2021). Many researchers are investigating essential oils, inhibiting feed additives, and the incorporation of phytochemicals into feed in an attempt to alter the cow's nutrition and production of methane (Dillon et al., 2021). ICLS presents another possibility of methane emission mitigation through the use of cover crops as feed.

A study by Berhanu et al. (2019) explored the alternative of determining optimal forage species for the control of methane (CH_4) emissions in Ethiopia. Ethiopia is a significant leader in livestock production with estimated 60 million head of cattle and 61 million sheep and goats known for utilizing ICLS (Berhanu et al., 2019). While the forage species in this study were all tropical plants, the study identified a connection between chemical composition and methane production by cattle. The species with higher acid detergent lignin (ADL) were connected with lower methane production (Berhanu et al., 2019). ADL uses a concentrated sulfuric acid solution to determine digestibility of forages by the amount of lignin in the residue (Fukushima et al., 2015). High ADL indicates reduced digestibility and energy uptake for ruminant species, making this strategy of determining methane-mitigating forages convoluted by sacrifices to animal nutrition (Fukushima et al., 2015). This route could require further nutritional supplement inputs for cattle, potentially negating the sustainable design of inputs and outputs in ICLS.

Another area of potential for mitigating methane emissions through forage species are tannin-rich forage species such as *Desmodium paniculatum* (panicled tick trefoil) and *Lespedeza procumbens* (trailing bush-clover) in temperate locations (Fagundes et al., 2020). In a study by Fagundes et al. (2020) condensed tannin (CT)-rich legumes like panicled tick trefoil and trailing bush-clover were found to have benefits on *in vitro* methane emissions and rumen microbiota. These tannin-rich species created bioreactivity in rumen microbial species resulting in simultaneous enhancement of ruminal bacteria and reduction of methanogenic archaea and protozoa responsible for methanogenesis (Fagundes et al., 2020). Similar to the ADL study, these CT-rich legumes are limited in nutritional value due to degradability, suggesting that they may serve better as a component to nutritional strategies used in ICLS. These potential limitations also require more research into the practicality of these cover crops for animal feed and nutrition.

Climate resiliency

Integrated crop-livestock systems act as a natural protector against climate change by increasing farm resilience and ability to adapt to challenges (Garrett et al., 2017). The systems have natural buffering mechanisms like improved crop productivity, nutrient cycling, economic risk mitigation, and livelihood diversification (Sekaran et al., 2021). With a combination of livestock and crop production, climate challenges are less likely to cost the farmer all of the season's profit through a diversified operation (Ortiz-Bobea et al., 2018). This is a prime example of how specialization in American agriculture has made farmers susceptible to unforeseen challenges like drought, fire, flood, hail, etc. (Ortiz-Bobea et al., 2018). Diversification is a key aspect of ICLS to create resiliency in farm operations as we see regions of high specialization like the Midwest, leaving farmers are more susceptible to damage from the climate (Ortiz-Bobea et al., 2018). Integrated crop-livestock systems provide the infrastructure needed to mimic the natural nutrient cycling of ecosystems when diversification is incorporated (Carvalho et al., 2018). This diversification through ICLS helps mitigate the climate sensitivity that continuous crops cannot overcome (Sinclair et al., 2019).

Out of all the ways land and people can be affected by climate change, agriculture is the most vulnerable due to its dependency on social and ecological factors (Srinivasa Rao et al., 2019). Researchers cite adaptive capacity as the measure of a farm's ability to mitigate climate risks effectively enough to create resilience (Srinivasa Rao et al., 2019). Through this research, 30 sustainability indicators for climate resilient agriculture were identified and sorted into the most appropriate based on the agroecological system and region (Srinivasa Rao et al., 2019). To corroborate the Ortiz-Bobea et al. (2018) study discussed in the previous paragraph, the indicators revolve around levels of diversity shown to indicate higher resilience with higher diversity within multiple dimensions including social, economic, ecological, reliability, productivity, and many more (Srinivasa Rao et al., 2019). Indicators for climate resiliency included staple ICLS factors like crop and livestock biodiversity, cropping intensity, fertilizer usage, GHG emissions, economic income from crops and livestock, human population density, and adoption of improved practices (Srinivasa Rao et al., 2019). This is further evidence that ICLS design is optimized to protect the land against acute and chronic climate challenges.

Chapter 5: Effects on the economy

When evaluating and proposing an uncommon agriculture system, it's important to consider all aspects that would affect the lives of the producers and communities adopting it. The economic potential of the system has warranted plentiful research to explore the benefits and consequences alike. There are countless benefits to be had when integrated crop-livestock systems (ICLS) are implemented, especially in the mid- to low-income communities that suffer in the modern large-scale agriculture industry (Kumar et al., 2019).

Socioeconomic consequences of integrated crop-livestock systems

The agricultural industry took a hard hit economically in recent years due to increasing demand for food, higher production costs, and more competitive markets that push for higher yields, quality, and profitability (Sekaran et al., 2021). On top of a general demand increase, consumers now push for environmentally friendly practices that, in many cases, require farmers to alter their operations (Hayden et al, 2018). Without the buy-in of consumers, a high price tag to adopt sustainable practice is enough to discourage farmers from adopting ICLS (Sekaran et al., 2021). It can cost farmers more in the initial transition to ICLS, largely due to the need for more expansive management and skill set (Kumar et al., 2018). Incorporating livestock into a farming operation or vice versa requires the farmer to either learn the skills himself or hire additional support. While this can be daunting at first, it can have a profound effect on the surrounding communities. Through providing multiple income sources and more diverse operations, ICLS can also promote employment opportunities in rural areas (Sekaran et al., 2021). The jobs that are created by growth of operations enable rejuvenation in the community which, in turn, draws in others to be part of the growing operation. This community revival is a key benefit of ICLS in the long-term, which can potentially help farmers overcome the initial fear of taking on more. This community building also leads to farmer partnerships and more interpersonal relationship building that results in symbiotic relationships (Hayden et al., 2018).

Product diversification via integrated crop-livestock systems

Integrated crop-livestock systems offer farmers a way to move toward sustainability with built-in backups through higher production diversity. In many cases, rural communities face lower income and sometimes have to work the land they have to survive through subsistence farming (Hayden et al., 2018). Integrated crop-livestock systems increase the income of poor subsistence farming communities that account for approximately 70% of people living in poverty (Sekaran et al., 2021). As mentioned in the discussion about climate resiliency, people who rely on their land to provide for them can have more than one product to depend on for income and nourishment when livestock are added to crop farming. The income from incorporated livestock allows for purchase of other high-quality foods, inputs, animals for restocking, or other requirements for future ICLS production (Sekaran et al., 2021). In fact, smallholder households who use ICLS typically consumed a variety of cereals and vegetables, fish, fruit, milk, meat, and eggs enabling them to achieve dietary requirements (Sekaran et al., 2021). If grazing intensity is properly managed, the cattle produced have the calorie content and nourishment needed to feed 21.1% more people when compared to soy and beef produced outside of ICLS practices (Schuster et al., 2019). This means that you get more quality *and* quantity for the time and effort to produce beef in addition to the crops they already produce. The dietary diversification that comes along with ICLS can improve the lives of those in struggling rural communities.

Economic analysis of smallholder systems

Farming operations can greatly differ depending on the size of the operation, location, and resources available (Carvalho et al., 2018). Smallholder farms are typically those consisting of five acres or less and are widely common worldwide. In a smallholder ICLS, the benefits of diversification directly impact the farmer with more opportunities for income resources as well as more food security for the family (Asante et al., 2019). Smallholders that most benefit from these positives typically live in low-income communities where people commonly live off their own land. Smallholder systems are not immune from specialization which often takes control much quicker in smaller operations (Ortiz-Bobea et al., 2018). Larger farms tend to have more financial resources to support multiple crop/product production in American agriculture (Asante et al., 2019). A smallholder farmer suddenly taking on livestock or crops is a daunting feat. It is initially more expensive for small operations to diversify, but the economic benefits of dual income and lower production costs show a clear return on investment over time (Asante et al., 2019). Utilizing ICLS can also bring the return of pollinator populations and natural pest management due to the return of diversity within the system (Hayden et al., 2018). This agroecological effect results in reduced input cost on the farmer for chemical and synthetic solutions to crop management (Hayden et al., 2018). When management has achieved properly monitored grazing intensity, evenly distributed fertilization, sufficient cover crop residue levels, and sustainable nutrient cycling, the economic benefits of ICLS will begin. This could take 2-3 seasons before the soil is rejuvenated and the operation is staffed enough to be successful, but ICLS show greater viability among years in returns to land and management (Poffenbarger et al., 2017). While it will be difficult for many to reach this milestone, the economic benefits from subsistence farming, diversification, the reduction of crop input costs, and dual income will allow the farmer to recover from the initial investment costs.

Economic analysis of integrating cattle to farming

Raising cattle and farming crops are two very different professions and lifestyles, each requiring skill sets that ensure safety and sustainable profit. For many, it is a more difficult transition incorporating cattle into operations considering there are laws and regulations that come into play (Kumar et al., 2019). Such a change would require a farmer to become familiar with the necessary care for the animals, identifying the optimal stocking rate, ensure compliance with production regulations, and cover the initial investment costs (Kumar et al., 2019). Raising cattle is the most commonly integrated livestock production of ICLS; However, there are other options for farmers that might even benefit their particular crop operation more so than cattle would.

Farmers can invest in raising smaller livestock and experience similar benefits to those that accompany cattle. The incorporation of small livestock is a key diversification strategy in which animals like smaller ruminants, specifically sheep and goats, not only serve as fertilizer and nutrient cycling resources, but as a type of crop insurance to fall back on in the event of crop failure (Sekaran et al., 2021). For example, sheep were integrated in vineyard production, which resulted in 1.3 fewer herbicide applications annually and 2.2 fewer mows annually (Niles et al., 2017). This resulted in cost savings of $56.00 and $64.00 respectively per hectare before including saved costs on fertilizer and feed for the sheep (Niles et al., 2017). The mean farm size in this study was 104 hectares, resulting in a mean annual savings of $12,480 for the average farm (Niles et al., 2017). Not only did the addition of sheep save the farmer money, but time as well. Farmers concerned about having the staffing capabilities to successfully operate ICLS can consider all sorts of livestock alternatives. Small livestock can be an excellent compromise for the smallholder who operates a smaller acreage, as shown by the vineyard study (Niles et al., 2017). The farmer can still get the most out of the land with the ICLS benefits, regardless of size. The addition of livestock to farming operations serves as a risk management tool for farmers to have relatively guaranteed income, no matter what damage the climate or market variability does to their crop revenue (Sekaran et al., 2021).

Chapter 6: Barriers to adoption

Like with any type of change, there are barriers that must be overcome before benefits can unfold. In the case of integrated crop-livestock systems (ICLS), there are limitations in place that restrict the conversion of agricultural systems into ICLS (Sekaran et al., 2021). Naturally, ICLS has its own set of pros and cons to consider before it can be adopted into practice, causing for hesitation in the agricultural community. Outside of the flaws in the system design, there are practical, social, and political barriers to overcome on the road to adoption. Table 2 summarizes the barriers that will be expanded upon in the following subsections of Chapter 6. Gaps in knowledge call for further research in order to provide the proof points farmers desire in their consideration of ICLS.

Table 2. An organized summary of the main barriers within the categories of practical, social, and political challenges to overcome in order for ICLS to succeed.

Political Barriers	Social Barriers	Practical Barriers
Little governmental advocacy	Geographical specialization	Insufficient management resources
Existing counteractive policies	Financial costs; lack of backing	Insufficient investment capital
Lack of rural credit or governmental programs to fund conversion	Lack of education to handle management complexity	Consequences of unbalanced pillars (cover crops, animals, cash crops)
Continuous government action to increase specialization	Pride and comfort with current practice	Crop residue usage dilemma

Practical barriers to adoption

There are barriers within the design of ICLS that must be explored to ensure the risk is worth the reward before a farmer commits to ICLS. Soil compaction is a potential disadvantage to ICLS that can cause crop growth reduction and less ability to grow new crops (Sekaran et al., 2021). Soil compaction can be caused by cattle grazing when fields are too wet, and the soil is physically compacted. That being said, this consequence can be avoided via proper management strategies (Sekaran et al., 2021) and strategically selected cover crops with compatible root systems (Burr-Hersey et al., 2018). Allowing cattle to overgraze can also result in decreased health of forage species in the rangelands (Sekaran et al., 2021). Diminished health in the native forage populations results in less optimized nutrition for the livestock and reduced animal performance (Sekaran et al., 2021). A proper balance of natural nutrients within the animals, forage species, and food crops is key in order for the ICLS to perform optimally. The relationship between grazing land and animal production is illustrated well in the paper by de Souza Filho et al. (2019) in which the authors determined the optimal levels of sward height, biomass consumption, animal production, and nutrient recycling to the soybean crop. With accurate management of these variables, farmers can optimize production and avoid negative effects of compaction for the cash crop.

Farmers who adopt and implement ICLS still have other design challenges to overcome. For example, a potential disadvantage comes from the use of crop residue for animal feed as opposed to uses like mulch, fuel, construction material, etc. (Sekaran et al., 2021). This can cause a dilemma for the farmer if a use other than feed could potentially provide financial relief at the time while utilizing the ICLS is less instantly gratifying. As previously mentioned, there is a period of time in the initial adoption of ICLS where costs outweigh revenue. The long-term success of the system depends on the farmer's capability of getting past the initial costs and not giving in to quicker pay-offs like crop residue for use outside of weed management.

Before entering into ICLS, farmers need a formidable team and management plan ready to go in order to minimize the initial cost period. ICLS adoption in an established, specialized large farm showed the following labor requirements increases: 59% with crop rotation diversification, and 217-232% with the integration of cattle (Poffenbarger et al., 2017). These are financial changes that require planning and commitment to see through to the benefits. For the transition to be smoother and more efficient, some researchers call for scientists and farmers to work together in order to create a concrete, demand-led solution that fits their needs based on the local ecological and economic environment (Sinclair et al., 2019). The possibility of a personalized ICLS that reflects the unique characteristics of the farmer's various environments could make the difference needed for more farmers to be on board (Sinclair et al., 2019).

Social barriers to adoption

Stigma surrounds innovative ideas in any industry and ICLS in the agricultural industry is no different. Integrated crop-livestock systems are often more popular with smallholders in low income communities with key benefits of food security, lower input costs, higher nutrition, risk mitigation, etc. There are more challenges to adoption in high-income communities where agriculture has become highly specialized (Sekaran et al., 2021). The Corn Belt (12 north central states) of the United States is a prime example of specialized farming systems. These systems have been long established since before the turn of the century with help from the advancement of technology and the capitalist push for higher yields and profits than ever before (Ortiz-Bobea et al., 2018). Farmers claim the discouragement for adoption stems from these norms, the complexity of management, biophysical conditions, and financial costs (Hayden et al., 2018). Social farming norms include the dominant specialized agriculture systems and markets, lack of financing and insurance compatible with ICLS, and the regulatory environment that comes with managing both crops and animals (Hayden et al., 2018). Making the change requires greater capital and labor inputs than the undiversified cash grain system so many farms operate with today (Poffenbarger et al., 2017). It is crucial that farmers receive assistance in overcoming these norms, both financially and socially, ideally from the government and policies in place (Garrett et al., 2017).

Political barriers to adoption

In the United States, the high degree of specialization in agriculture poses a great challenge to the ability of ICLS to be adopted. Farmers are bombarded with a lack of resources, financial and managerial, making ICLS adoption highly daunting. Adoption challenges like lack of investment, sustainable awareness, lack of skills by producers, and market competition prevent ICLS of being widely adopted, regardless of the benefits they provide (Sekaran et al., 2021). It is important that political and regulatory powers are prompted for action to aid farmers in adopting sustainable practices in general (Hayden et al., 2018). Key efforts must be made via organizational and institutional support to push fresh marketing opportunities for awareness alongside government policy providing capital, markets, and educational services (Sekaran et al., 2021). Without political support and funding, ICLS faces massive hurdles of adoption in the United States (Asante et al., 2019).

Until policymakers turn their attention to ICLS, it is likely to remain lowly adopted (Asante et al., 2019). Half of the challenge comes from an inability to foster support for a system that, at the moment, primarily thrives in smallholder arenas (Kumar et al., 2019). In the United States, there are policies in place that discourage diversification through incentivizing crop planting in marginal areas and soils that are not agroecologically suitable (Kumar et al., 2019). This means farmers are motivated to grow crops where they cannot sustainably be produced, negating the core principle of ICLS itself (Hayden et al., 2018). The resulting long-term rejuvenation of farmland through the agroecological design of ICLS is largely attractive to the farming community (Sekaran et al., 2021). Efforts to preserve land for future generations to work are a prime goal and sense of pride for farmers, especially the American farmer (Hayden et al., 2018). There must be higher participation and support from government agencies to help ICLS adoption flourish under the current economic and political climate in the United States (Hayden et al., 2018).

Some areas of sustainable agriculture are beginning to incentivize conservation practices, like in the rural credit policy in Brazil. This policy was created initially as an attempt for Brazil to reduce greenhouse gases nearly 40% by 2020, reachable by restoring 15 million hectares of degraded pasture, increasing 5.5 million hectares of cultivation area with biological nitrogen fixation, and adding four million hectares of ICLS (Carrer et al., 2020). The funds for the rural credit policy were distributed through a network of commercial banks and credit cooperatives with special lines created for ICLS diffusion specifically (Carrer et al., 2020). While there were flaws in the credit program through quantity constraints, transaction cost constraints, and risk aversion constraints, the incentives effectively created diffusion of ICLS in Brazilian agriculture (Carrer et al., 2020). Integrated crop-livestock system adoption was 37.5% higher in farmers with access to the rural credit than in those without (Carrer et al., 2020). Rural credit proved to be a major asset to farmers adopting ICLS, primarily in the areas of input costs and equipment investment, to enable farmers to invest in ICLS with lower interest rates (Carrer et al., 2020). Utilizing rural credit in Brazil certainly sped up the adoption rate of ICLS and helped farmers through the initial investing, proving that programs like subsidized credit can make it possible for farmers to adopt sustainable practices like ICLS where it otherwise might be impossible (Carrer et al., 2020).

The customizable nature of ICLS allows farmers to design their operations to meet their needs and limitations. For areas where the expense of implementing cattle are too great, small ruminants provide similar benefits typically less investment costs than large livestock like cattle (Niles et al., 2017). Beginning with small ruminants like sheep and goats is potentially more realistic in the mid- to low-income smallholder communities benefitted by ICLS where they are also more popular types of livestock compared to the United States (Asante et al., 2019). Recommendations for policymakers in smallholder communities include strategies that enhance overall farm productivity through the combination of specific crops and livestock such as legumes and nitrogen-depleting crops like maize (Asante et al., 2019). Actions by governments, policymakers, and development agencies that encourage diversification can further support adoption of ICLS in these communities (Asante et al., 2019).

Knowledge gaps as barriers to adoption

With high levels of risk involved in a systematic change to farm operations, the potential for unknown negative consequences of ICLS are highly deterring to the farming community (Hayden et al., 2018). There are large gaps of knowledge creating barriers that future research needs to address. Farmers require proof of concept and profit before they are inclined to take a risk and change tactics (Hayden et al., 2018). If the research and awareness does not cover the main concerns of farmers, there will be no movement toward adoption. The agronomic quality of land after introducing cattle is one such barrier for adoption (Peterson et al., 2020). Historical research has centered in on nutrient cycling, soil quality, crop yield, and animal performance as the perceived key concerns of farmers, when that is not necessarily the case. These variables address profitability of ICLS and longevity of the land. There is little literature regarding animal behavior and welfare in ICLS, a primary concern for a cattle rancher considering incorporating crops and forage to the operation (Garrett et al., 2017). The relationships between biodiversity, pest and disease control, greenhouse gas mitigation, and drought tolerance of ICLS are largely under-researched, leading to hesitation of adoption (Garrett et al., 2017). Pest and disease control are primary costs for farmers and a lack of information on ICLS with respect to these concerns discourage adoption (Hayden et al., 2018).

Knowledge gaps exist outside of the farm as well, in the economic and political viability of ICLS. Most economic literature investigates the commercial values of ICLS including supply chain and policy barriers preventing farmers from adopting the system (Garrett et al., 2017). However, there is little to be found regarding the more complex social outcomes and cultural factors discouraging farmers from adoption (Garrett et al., 2017). In the effort to overcome social stigma and cultural drive to specialize, it is crucial to understand the relational factors preventing farmers from converting. The relationship between the knowledge gaps and three pillars of ICLS (farm operations, environment, and farmer economy) is one future research must work to bolster. Figure 2 exhibits the overlap of key areas for future research that must be addressed within the pillars.

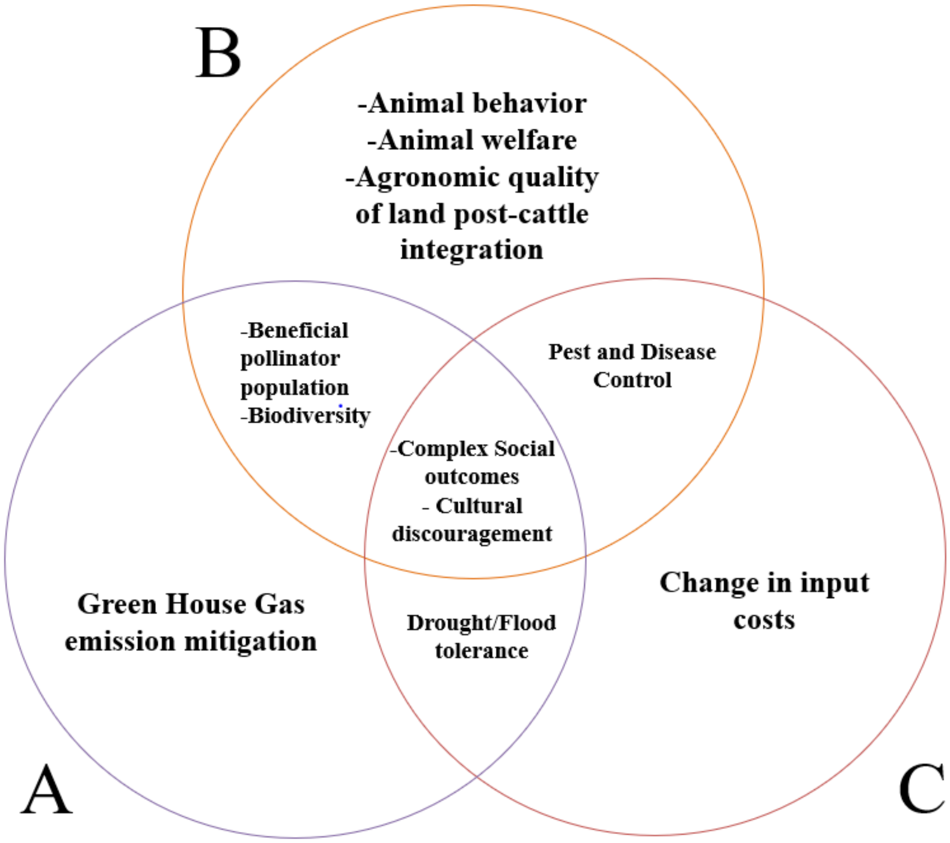

Figure 2. A Venn diagram illustrating the overlap of knowledge gaps within the three pillars of ICLS: A) the environment, B) farm operations, and C) farmer economy.

Future Research

In order for ICLS to overcome skepticism within the farming community, research must be expanded past the main topics of profitability and immediate environmental benefits. Future research must aim to close the gaps in practical, social, and political barrier categories. The gaps highlighted in Figure 2 represent the direction of future research. With knowledge gaps identified within the three pillars, the next step is to design future research in a fashion that addresses farmer concerns and works in favor of ICLS awareness and information. Table 3 suggests future research topics that can utilize the identified knowledge gaps to break down the practical, political, and social barriers of adoption of ICLS.

Table 3. Potential topics for future research related to the knowledge gaps identified within the three pillars that can break down the practical, political, and social barriers of adoption.

Practical Future Research	Political Future Research	Social Future Research
Effect of increased biodiversity on pollinator and pest populations	Comparison of methane mitigation of ICLS vs. cattle feed additives	Cultural discouragement in the agriculture industry
Effect of increased biodiversity input costs for pest management	Environmental benefits of ICLS for future policy incentivization	Cultural discouragement in the immediate rural community
Animal performance amid pest infestation of grazing cover crop feed	Current policy and incentives to specialize agriculture in the United States	Presence of alienation for ICLS converters in their specialized communities
Health and behavior fluctuations in livestock during transition to ICLS	Potential success of rural credit program in United States	Comparison of positive and negative social outcomes of a farmer adopting ICLS

Practical barriers primarily require answers to gaps within the farm operations pillar. This is the largest gap to fill with most need split between the condition of animals and wildlife around ICLS (Garrett et al., 2017). Effects on the welfare and behavior of cattle in these systems need to be evaluated to discover benefits and consequences for the farmer who is concerned for their livestock's quality of life and health. There is little research around the potential nutritional supplements needed in ICLS for cattle if the cover crops considered most nutritious are not compatible with the geography. For the health of the cattle in the system, it is important to understand the health and behavior fluctuations that accompany a transition from specialized beef operations to ICLS with grazing the primary feed strategy.

Animal conditions also extend into beneficial pollinator populations and pest and disease control efforts, who are known to accumulate with the enhanced biodiversity that accompanies

ICLS (Hayden et al., 2018). While some data exists on the return of pollinators with ICLS, there are gaps in understanding the ratio of beneficial to harmful insects and the additional costs that may accompany them (Hayden et al., 2018). While biodiversity and beneficial pollinator population growth is a positive for the environment, it is important to understand the effect not only on crops, but on livestock as well. Research should be performed to determine if there is competition between pests and livestock for the cover crop feed. It is crucial that livestock ingest healthy cover crop in order to maximize nutrient intake, animal performance, and nutrient cycling within the whole system (Planisich et al., 2021). The return of pollinators and pests alike could also have direct effect on the input needs for the crop season, another area of research needed to further provide practical and economic information for farmers. Integrated crop-livestock systems are designed to reduce the need for pesticide and herbicide use, so there must be more research on the effect of increasing biodiversity on pest and disease prevalence. These knowledge gaps must be addressed to better inform farmers of the practical implications of ICLS.

Political barriers tend to be wrapped around funding and support of diversification efforts. In order to increase funding from the government, future research should investigate the environmental impact of ICLS on GHG emission mitigation, returning pollinator populations, agronomic quality of land post-cattle introduction, and drought and flood tolerance (Peterson et al., 2020). Similar to the Brazilian rural credit and carbon credit programs within the United States, linking environmental benefits to ICLS and funding adoption efforts from the government could greatly improve adoption rate (Carrer et al., 2020). Many government initiatives include environmental commitments like these, making this an important goal for future research to investigate and spread awareness about. Research exists on methane emissions associated with cover crops for livestock feed; however, comparisons between ICLS as a mitigation strategy and new feed additive technology are necessary to bolster the existing research on mitigation ability. To break down political barriers, research must be driven in a direction that grabs the attention of policymakers and the agricultural community. Data is a primary strategy to gain the buy-in of these groups (Ortiz-Bobea et al., 2018).

Social barriers exist in the center of the three pillars where each effects the other. Change is often met with human hesitation, especially when a farmer's career, family obligation, and community are all depending on them to produce the best quality. With the practical and political barriers, farmers better understand the physical, financial, and governmental aspects of adopting ICLS; however, if adoption is to be successful, they need to understand the social implications of conversion. It is unknown what cultural discouragement farmers may meet within their immediate and industry-wide communities. Research on the strength and severity of peer pressure to not deviate from the farmer norms need to be investigated to better understand how to equip a farmer with the knowledge and credibility to justify the change to their community (Ortiz-Bobea et al., 2018). To further put farmers at peace with the consequences of change, future studies need to incorporate the relationship changes and social outcome post-conversion to ICLS, especially in highly specialized areas like the corn belt. If the community is found to punish the farmer for deviating, there needs to be further investigation into the psychology behind the aversion to conversion. Research should also investigate the opposite outcome and determine if there is potential for a ripple effect of increasing adoption within small rural communities. These complex social outcomes could provide comfort and justification for farmers ready to adopt ICLS and move away from the specialization within their community.

Chapter 7: Conclusion

Through consulting modern research on a timeless agricultural system, the benefits to be had from integrated crop-livestock systems (ICLS) are clear. Incorporating cover crops for weed management and feed for livestock creates natural fertilizer to catalyze nutrient cycling in farmland primed for crop yield. Farmers experience increased crop diversity via rotated crops contributing to diet diversity, food security, dual income of products, and employment opportunities where ICLS are utilized. Economic output is increased with higher animal performance and crop yield, less cost from crop inputs for management purposes, and sustainable practices. While there is more research to be done to cover gaps in knowledge that create barriers to adoption, added education and policy support can make scalable conversion a reality for farmers. This report examined the aspects of ICLS with respect to farm operations, the environment, farmer economy, and system adoption. With proper education, management, and support, ICLS could effectively improve the lives of millions of people via sustainable food sources and production, rejuvenated and resilient environments, and a formidable economy.

References

Abson, J. D. (2019). Chapter 19 – The economic drivers and consequences of agricultural specialization. *Agroecosystem Diversity*. 301-315, ISBN 9780128110508. https://doi.org/10.1016/B978-0-12-811050-8.00019-4.

Asante, B. O., Villano, R. A., & Battese, G. E. (2019). Evaluating complementary synergies in integrated crop-livestock systems in Ghana. *International Journal of Social Economics*, *47*(1), 72–85. https://doi.org/10.1108/ijse-04-2019-0274

Berhanu, Y., Olav, L., Nurfeta, A., Angassa, A., & Aune, J. B. (2019). Methane emissions from ruminant livestock in Ethiopia: Promising forage species to reduce CH4 emissions. *Agriculture*, *9*(6), 130. https://doi.org/10.3390/agriculture9060130

Burr-Hersey, J. E., Mooney, S. J., Bengough, A. G., Mairhofer, S., & Ritz, K. (2018). Correction: Developmental morphology of cover crop species exhibit contrasting behaviour to changes in soil bulk density, revealed by X-ray computed tomography. *PLOS ONE*, *13*(1). https://doi.org/10.1371/journal.pone.0190759

Carpinelli, S., da Fonseca, A. F., Weirich Neto, P. H., Dias, S. H., & Pontes, L. da. (2020). Spatial and temporal distribution of cattle dung and nutrient cycling in integrated crop–livestock systems. *Agronomy*, *10*(5), 672. https://doi.org/10.3390/agronomy10050672

Carrer, M. J., Maia, A. G., de Mello Brandão Vinholis, M., & de Souza Filho, H. M. (2020). Assessing the effectiveness of rural credit policy on the adoption of integrated crop-livestock systems in Brazil. *Land Use Policy*, *92*, 104468. https://doi.org/10.1016/j.landusepol.2020.104468

Carvalho, P. C., Peterson, C. A., Nunes, P. A., Martins, A. P., Filho, W. de, Bertolazi, V. T., Kunrath, T. R., de Moraes, A., & Anghinoni, I. (2018). Animal production and soil characteristics from integrated crop-livestock systems: Toward sustainable intensification. *Journal of Animal Science*, *96*(11), 4923–4923. https://doi.org/10.1093/jas/sky357

Chabert, A., & Sarthou, J.-P. (2020). Conservation Agriculture as a promising trade-off between conventional and organic agriculture in Bundling Ecosystem Services. *Agriculture, Ecosystems & Environment*, *292*, 106815. https://doi.org/10.1016/j.agee.2019.106815 de Souza Filho, W., Nunes, P. A., Barro, R. S., Kunrath, T. R., de Almeida, G. M., Genro, T. C., Bayer, C., & de Faccio Carvalho, P. C. (2019). Mitigation of enteric methane emissions through pasture management in integrated crop-livestock systems: Trade-offs between Animal Performance and Environmental impacts. *Journal of Cleaner Production*, *213*, 968–975. https://doi.org/10.1016/j.jclepro.2018.12.245

Devlet, A. (2021). Modern agriculture and Challenges. *Frontiers in Life Sciences and Related Technologies*. https://doi.org/10.51753/flsrt.856349

Dillon, J. A., Stackhouse-Lawson, K. R., Thoma, G. J., Gunter, S. A., Rotz, C. A., Kebreab, E., Riley, D. G., Tedeschi, L. O., Villalba, J., Mitloehner, F., Hristov, A. N., Archibeque, S. L., Ritten, J. P., & Mueller, N. D. (2021). Current state of enteric methane and the carbon footprint of beef and dairy cattle in the United States. *Animal Frontiers*, *11*(4), 57–68. https://doi.org/10.1093/af/vfab043

Fagundes, G. M., Benetel, G., Carriero, M. M., Sousa, R. L., Muir, J. P., Macedo, R. O., & Bueno, I. C. (2021). Tannin-rich forage as a methane mitigation strategy for cattle and the implications for rumen microbiota. *Animal Production Science*, *61*(1), 26. https://doi.org/10.1071/an19448

Fukushima, R. S., Kerley, M. S., Ramos, M. H., Porter, J. H., & Kallenbach, R. L. (2015). Comparison of acetyl bromide lignin with Acid Detergent lignin and Klason lignin and correlation with in vitro forage degradability. *Animal Feed Science and Technology*, *201*, 25–37. https://doi.org/10.1016/j.anifeedsci.2014.12.007

Garrett, R. D., Niles, M. T., Gil, J. D. B., Gaudin, A., Chaplin-Kramer, R., Assmann, A., Assmann, T. S., Brewer, K., de Faccio Carvalho, P. C., Cortner, O., Dynes, R., Garbach, K., Kebreab, E., Mueller, N., Peterson, C., Reis, J. C., Snow, V., & Valentim, J. (2017). Social and ecological analysis of commercial integrated crop livestock systems: Current knowledge and remaining uncertainty. *Agricultural Systems*, *155*, 136–146. https://doi.org/10.1016/j.agsy.2017.05.003

Gliessman, S. R. (2020). Transforming Food and agriculture systems with agroecology. *Agriculture and Human Values*, *37*(3), 547–548. https://doi.org/10.1007/s10460-020-10058-0

Gliessman, S., & Ferguson, B. G. (2019). Keeping up with the Agroecology Movement: Priorities for Agroecology and Sustainable Food Systems. *Agroecology and Sustainable Food Systems*, *44*(1), 1–2. https://doi.org/10.1080/21683565.2019.1675241

Hayden, J., Rocker, S., Phillips, H., Heins, B., Smith, A., & Delate, K. (2018). The importance of social support and communities of practice: Farmer perceptions of the challenges and opportunities of integrated crop–livestock systems on organically managed farms in the northern U.S. *Sustainability*, *10*(12), 4606. https://doi.org/10.3390/su10124606

Hudek, C., Putinica, C., Otten, W., & De Baets, S. (2021). Functional root trait-based classification of cover crops to improve soil physical properties. *European Journal of Soil Science*. https://doi.org/10.1111/ejss.13147

Kumar, S., Sieverding, H., Lai, L., Thandiwe, N., Wienhold, B., Redfearn, D., Archer, D., Ussiri, D., Faust, D., Landblom, D., Grings, E., Stone, J. J., Jacquet, J., Pokharel, K., Liebig, M., Schmer, M., Sexton, P., Mitchell, R., Smalley, S., … Jin, V. (2019). Facilitating crop–livestock reintegration in the Northern Great Plains. *Agronomy Journal*, *111*(5), 2141–2156. https://doi.org/10.2134/agronj2018.07.0441

Luo, L., Zhang, Y., & Xu, G. (2020). How does Nitrogen Shape Plant Architecture? *Journal of Experimental Botany*, *71*(15), 4415–4427. https://doi.org/10.1093/jxb/eraa187

Mennan, H., Jabran, K., Zandstra, B. H., & Pala, F. (2020). Non-chemical weed management in vegetables by using cover crops: A Review. *Agronomy*, *10*(2), 257. https://doi.org/10.3390/agronomy10020257

Ortiz-Bobea, A., Knippenberg, E., & Chambers, R. G. (2018). Growing climatic sensitivity of U.S. agriculture linked to technological change and regional specialization. *Science Advances*, *4*(12). https://doi.org/10.1126/sciadv.aat4343

Niles, M. T., Garrett, R. D., & Walsh, D. (2017). Ecological and economic benefits of integrating sheep into viticulture production. *Agronomy for Sustainable Development*, *38*(1). https://doi.org/10.1007/s13593-017-0478-y

Peterson, C. A., Deiss, L., & Gaudin, A. C. (2020). Commercial integrated crop-livestock systems achieve comparable crop yields to specialized production systems: A meta-analysis. *PLOS ONE*, *15*(5). https://doi.org/10.1371/journal.pone.0231840

Planisich, A., Utsumi, S. A., Larripa, M., & Galli, J. R. (2021). Grazing of cover crops in integrated crop-livestock systems. *Animal*, *15*(1), 100054. https://doi.org/10.1016/j.animal.2020.100054

Poffenbarger, H., Artz, G., Dahlke, G., Edwards, W., Hanna, M., Russell, J., Sellers, H., & Liebman, M. (2017). An economic analysis of integrated crop-livestock systems in Iowa, U.S.A. *Agricultural Systems*, *157*, 51–69. https://doi.org/10.1016/j.agsy.2017.07.001

Schuster, M. Z., Lustosa, S. B., Pelissari, A., Harrison, S. K., Sulc, R. M., Deiss, L., Lang, C. R., de Faccio Carvalho, P. C., Gazziero, D. L., & de Moraes, A. (2019). Optimizing forage allowance for productivity and weed management in integrated crop-livestock systems. *Agronomy for Sustainable Development*, *39*(2). https://doi.org/10.1007/s13593-019-0564-4

Sekaran, U., Lai, L., Ussiri, D. A. N., Kumar, S., & Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security – a review. *Journal of Agriculture and Food Research*, *5*, 100190. https://doi.org/10.1016/j.jafr.2021.100190

Sinclair, F., Wezel, A., Mbow, C., Chomba, S., Robiglio, V., and Harrison, R. 2019. "The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture." Rotterdam and Washington, DC. Available online at www.gca.org.

Srinivasa Rao, C., Kareemulla, K., Krishnan, P., Murthy, G. R. K., Ramesh, P., Ananthan, P. S., & Joshi, P. K. (2019). Agro-ecosystem based sustainability indicators for Climate Resilient Agriculture in India: A conceptual framework. *Ecological Indicators*, *105*, 621–633. https://doi.org/10.1016/j.ecolind.2018.06.038

Tobin, C., Singh, S., Kumar, S., Wang, T., & Sexton, P. (2020). Demonstrating short-term impacts of grazing and cover crops on soil health and economic benefits in an integrated crop-livestock system in South Dakota. *Open Journal of Soil Science*, *10*(03), 109–136. https://doi.org/10.4236/ojss.2020.103006

Wang, T., Jin, H., Fan, Y., Obembe, O., & Li, D. (2021). Farmers' adoption and perceived benefits of diversified crop rotations in the margins of U.S. corn belt. *Journal of Environmental Management*, *293*, 112903. https://doi.org/10.1016/j.jenvman.2021.112903

Werth, S. J., Rocha, A. S., Oltjen, J. W., Kebreab, E., & Mitloehner, F. M. (2021). A life cycle assessment of the environmental impacts of cattle feedlot finishing rations. *The International Journal of Life Cycle Assessment*, *26*(9), 1779–1793. https://doi.org/10.1007/s11367-021-01957-3

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A Review. *Agronomy for Sustainable Development*, *40*(6). https://doi.org/10.1007/s13593-020-00646-z