12-2021

Distillers' Grains: Past, Present, and Future Economic Analyses

Daniel E. Gertner
University of Nebraska-Lincoln, gertner.dan@gmail.com

DISTILLERS’ GRAINS: PAST, PRESENT, AND FUTURE ECONOMIC ANALYSES

by

Daniel E. Gertner

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agricultural Economics

Under the Supervision of Professor Elliott J. Dennis

Lincoln, Nebraska

December, 2021

DISTILLERS' GRAINS: PAST, PRESENT, AND FUTURE ECONOMIC ANALYSES

Daniel E. Gertner, M.S.

University of Nebraska, 2021

Advisor: Elliott J. Dennis

This thesis is comprised of four chapters, each of which discusses or conducts economic research related to the distillers' grains market. The first three chapters are meant to be standalone papers. Chapter four provides potential paths forward in distillers' grains research based on the findings of the first three chapters and concludes the thesis.

The first chapter conducts a comprehensive literature review that categorizes and summarizes economic research on distillers' grains products. This section shows how the physical market has moved beyond the current academic understanding of market products and structure. Existing research finds that traditional distillers' grains products positively contribute to the livestock feeding industry, but much of the research covered in the literature review appeared in the early 2000s or shortly thereafter, leaving many current questions in the distillers' grains industry unexplored.

Chapter 2 estimates the magnitudes of and relationships between distillers' grains price changes in response to the COVID-19 market shock using panel fixed effect models. The price fluctuations indicate that livestock producers favored the flexibility provided by dried distillers' grains (DDGS) and, therefore, drove those prices upward more significantly than modified wet distillers' grains (MDGS) and wet distillers' grains (WDGS) prices. The disparate price responses by grain type and location offer some insight into how markets may respond in the event of future market shocks.

Consequently, the results from this analysis can assist both ethanol plants and livestock producers in better preparing for future market shocks.

The third chapter proposes an equilibrium displacement model (EDM) of the U.S. ethanol industry to estimate the short-run impacts of market shocks on prices and quantities in the distillers' grains complex. The results of the EDM analysis indicate that the responses of ethanol and each type of distillers' grain to market shocks rely heavily on the relationships between the products. Applying the EDM framework to real-world events can help both plants and producers in adjusting their operations to minimize the impacts of market shocks.

DEDICATION AND AUTHOR'S ACKNOWLEDGEMENTS

This thesis would not be possible without the support and guidance of my advisor, Dr. Elliott Dennis. Since beginning my employment with him as a college senior, he has been a steady source of advice and encouragement for all things academic and professional.

I would also like to express my gratitude to my advisory committee members, Dr. Richard Perrin and Dr. Galen Erickson. A special thank you to Dr. Erickson for reviewing and refining the literature review in Chapter 1, to Dr. Taro Mieno for providing econometric assistance in Chapter 2, and to Dr. Perrin for his patience and insight in developing the equilibrium displacement model in Chapter 3.

Finally, I would like to thank the people who helped me along my graduate school journey. Special thanks to my wife, Ellie, my parents, Ruth and Dwight, and countless other family and friends who have supported me over the past year and a half.

TABLE OF CONTENTS

CHAPTER 1 - A REVIEW OF THE ECONOMIC LITERATURE ON DISTILLERS' GRAINS

Abstract

During the domestic ethanol boom of the mid-2000s to early 2010s, ethanol co-products grew to play a crucial role in both ethanol plant revenue streams and livestock feeding rations. Distillers' grains co-products of ethanol production do more than provide an additional revenue stream for plants; they also allow for diversified, value-added product offerings. The purpose of this paper is to provide a comprehensive literature review that categorizes and summarizes economic research on distillers' grains products. It is specifically shown how the physical market has moved well beyond the current academic understanding of market products and structure. Existing research finds that traditional distillers' grains products positively contribute to the livestock feeding industry, especially in their ability to offset the impacts to the grain markets introduced by increased ethanol production. But much of the research covered in this literature review appeared during the ethanol boom of the first decade of the 2000s and shortly thereafter, which leaves many current questions in the distillers' grains industry unexplored.

Introduction

During the domestic ethanol boom of the mid-2000s to early 2010s, ethanol co-products grew to play a crucial role in both ethanol plant revenue streams and livestock feeding rations. As ethanol production grew both domestically and internationally, so, too, did distillers' grains – a co-product of ethanol production – production and use. Increased distillers' grains market penetration led to the expanded importance of distillers' grains to ethanol plant revenue. When the ethanol industry experiences supply or demand volatility, distillers' grains profits can often help regain revenue lost from altered ethanol production, highlighting the significance of distillers' grains to the current and long-term viability of the ethanol industry.

The growing revenue share of distillers' grains has led ethanol plants to search for methods to extract additional value out of each product in the distillers' grains space. In differentiating distillers' grains beyond the traditional three-product offering, ethanol plants hoped to (1) create new revenue streams and (2) diversify their profit sources to hedge against adverse market shocks in each subsection of the industry. Consequently, plants have developed new technologies to modify or refine distillers' grains to extract additional value. Innovations have included pelletized distillers' grains, de-oiled distillers' grains, high protein distillers' grains, corn oil, and a variety of other products that allow plants to maximize the monetization of the natural co-products of ethanol production. These new products have further differentiated distillers' grains and have helped to establish distiller-type feeds as goods with increasingly separate demand structures from the ethanol market. Given the fundamental changes to the distillers' grains products commonly studied in the economic literature, these value-added feeds have potentially modified previous conclusions.

The purpose of this paper is to provide a comprehensive literature review that categorizes and summarizes economic research on distillers' grains products. The paper demonstrates how the physical market has moved well beyond the current academic understanding of market products and structure. Peer-reviewed journal articles, extension publications, and conference presentations between 1990 to 2021 were gathered from economic, business, and animal science databases. Papers were filtered for relevance and then organized into eight general research categories, as determined by the stated objectives of each article. Studies are synthesized and summarized by themes, topics, types of distillers' grains, market locations, and other impacted markets within each general research category.

Most economic research related to distillers' grains has primarily focused on the growth, impact, and future of the ethanol industry itself rather than conducting distillers'-grains-centered analyses. As a result, ethanol's impact on regional and national economies inhabits a well-explored segment of the academic literature (see An et al. (2011) for review of relevant studies). Distillers' grains – long considered a secondary by-product of biofuel production – occupy a far less defined portion of the literature. The economic research that does exist has primarily focused on dried distillers' grains. When other co-products are analyzed – such as wet and modified wet distillers' grains – the focus is often on how they vary or compare to dried distillers' grains.

Existing research finds that traditional distillers' grains products positively contribute to the livestock feeding industry, especially in their ability to offset the impacts to the grain markets introduced by increased ethanol production. Very few studies mention innovations in ethanol co-product production such as pelletized, de-oiled, and high protein distillers' grains. The few that conduct more in-depth analyses of value-added co-products primarily examine the feeding value of value-added co-products for a livestock operation and do not explore market impacts. The results of the literature review revealed that value-added products, such as high protein distillers' grains or pelletized distillers' grains, may benefit livestock producers by increasing the feeding value or storability/transportability of distillers' grains. Whether those benefits are experienced by livestock producers depends on prevailing market prices for the products (Perkis et al. 2008; Rosentrater and Kongar 2009).

The rest of this paper is organized as follows. First, additional context to the development and use of distillers' grains production is provided. Second, the methods behind the collection, selection, and organization of the research included in this review are discussed. Third, the ethanol co-product economic research is synthesized into one of eight general categories. Fourth, given the findings from the synthesis section, some future paths forward and their potential implications to the distillers' grains industry are provided. The fifth section summarizes and concludes the paper.

Distillers' Grains Market Development

Ethanol plant co-product production

Distillers' grains are most commonly produced via the dry-grind ethanol production process as opposed to the wet milling process, the latter of which primarily results in corn gluten feed by-products. The dry-grind process aims to ferment the highest possible percentage of the corn kernel. In this process, the entire corn kernel is processed, and little is left to waste. The starch in the kernel is converted to ethanol and carbon dioxide, while the remaining protein, lipids, fiber, minerals, and vitamins are converted into co-products such as thin stillage and wet distillers' grains. The thin stillage that is not recycled as processing water is concentrated into condensed distiller solubles (CDS) through evaporation, which can be mixed with wet distillers' grains to become WDGS and then dried into modified wet distillers' grains (MDGS) or dried distillers' grains (DDGS) (Liu 2011). Although CDS are typically added back to distillers' grains, they can also be sold as a separate by-product to beef cattle fed low-quality forage diets (USDA NIFA 2019).

In recent years, the distillers' grains market has expanded beyond the traditional offerings of dried, modified wet, and wet distillers' grains to include dried distillers' grains with solubles, pelletized distillers' grains, de-oiled distillers' grains, high-protein distillers' grains, and a variety of additional products. These products help to further differentiate distillers' products from each other and provide additional revenue opportunities for ethanol plants.

Ethanol plants continually seek to market distillers' grains as they are an inevitable by-product of the ethanol production process. This comes in the form of finding new ways to market current distillers' grains or by creating new value-added products. In absence of a market for distillers' grains, the co-products must be produced and disposed of by the plants, often at a sizeable cost, and at times can reduce ethanol production. By marketing distillers' grains to livestock producers, ethanol plants monetize a necessary waste product, while livestock producers gain an often more affordable feed source for livestock rations with increased performance. This relationship between ethanol plants and livestock producers underscores the distillers' grains market.

Co-Products Use

Distillers' co-products have been produced for as long as the alcoholic distilling process itself, or since about 800 BCE (Shipman, 1998). Although the history of feeding those co-products to animals is less robust, the practice still has a long history; the first study about feeding distillers' grains to cattle was published in 1907 (Aguilar, 2013). For much of the 20th century, the only distillers' by-products that existed on a large scale came from alcoholic beverage production. But the proliferation of fuel ethanol production in the early 2000s created a new supply of distillers' by-products that were centered around areas of high agricultural production.

Initially, ethanol plants began selling distillers' grains feeds to local livestock operations in the form of WDGS with 60-65% moisture to avoid disposing of the by-products as waste. Given distillers' grains' high crude protein contents (25-35%), early market participants primarily considered distillers' grains to be a protein feed. Therefore, they were generally priced as an imperfect alternative to soybean meal, which has a crude protein content of 45-50%. As the supply of ethanol and distillers' grains grew, the "sister" market shifted to the corn, rather than soybean, market. This was because distillers' grains offered similar nutritional properties to corn while excluding much of the unnecessary starch, which was expended in the ethanol production process. The fact that distillers' grains were produced from corn also meant that their pricing could be tied to the corn market. At the same time, ethanol plants began investing more heavily in distillers' grains technology to complement their co-product revenue stream. This technology most often included drying capabilities that allowed plants to convert wet distillers' grains to more transportable MDGS and DDGS.

While both MDGS and WDGS offer slightly higher feeding values than DDGS (Nuttelman, et al. 2011), their moisture contents and weights make them difficult to ship beyond a limited radius, making DDGS the most common form of distillers' grains nationally. Regardless of the form of distillers' grains, each type offers – in most cases – superior nutritional properties to corn through lower starch content, higher total digestible nutrients, and higher crude protein content (Jenkins 2016). The favorable properties and relative abundance of distillers' grains in areas with high ethanol production rates – paired with a concerted effort by ethanol plants to market distillers' grains as co-products rather than by-products – helped form a market for distillers' grains with a largely separate demand structure from the ethanol sector (Morgan 2020).

Co-product importance to plant profitability

Dried Distillers' Grains with Solubles, Modified Distillers' Wet Grains, and Distillers' Wet Grains are the products that constitute the largest share of the co-product revenue stream for most ethanol plants. According to estimates from the Iowa State ethanol plant profitability model, over the last 15 years, total distillers' grains' percent of plant revenue has increased from approximately 10% to 27% (Hofstrand 2021; Figure 2). Specific breakdowns of the revenue contributions of each type of distillers' grains were not available.

Distillers' grains and other co-products of ethanol production do more than provide an additional revenue stream for plants; they also play a crucial role in maintaining profit margins and allow for diversified, value-added product offerings

(Irwin 2020). Weak crude oil prices paired with steady corn prices over the past half-decade made the margin for error in the ethanol industry thin. To hedge against adverse price trends in the ethanol industry, ethanol plants have focused on diversifying their operations to produce higher-value co-products (Voegele 2020).

The economics behind traditional distillers' grains products and newer products are explored in the academic literature to differing extents. The purpose of this literature review is to identify, compile, synthesize, and analyze the existing economic research about distillers' grains. Doing so will provide insight into the distillers' grains markets while identifying gaps in the literature and charting paths forward for future research.

Selection and Categorization of Economic Distillers' Grains Research

An open literature search was conducted using online databases, including AgEconSearch, Agricola, Cambridge, CAB Abstracts and Global Health, EconLit, JSTOR, PubMed, Scopus, and Wiley Online Library databases. Articles in all databases were retrieved using the search string, "distiller* AND (econ* OR pric*)". All results were limited to publication years between 1990 and 2021. To refine retrieved results, the following database-specific adjustments were made: (1) AgEconSearch results were filtered by English-language articles, (2) CAB Abstracts and Global Health and JSTOR results were filtered by terms found in the abstract, (3) Cambridge results were filtered by "access", (4) and Scopus results were filtered by the keyword "Economics". No modifications were made to the Agricola, EconLit, or Wiley database searches.

In total, 972 articles were retrieved across the nine databases. After removing duplicate articles, 847 results remained. Article titles were then examined for English language and relevance to topics related to biofuels, grains, feed, livestock, and economic analysis. Only titles clearly unrelated to distillers' grains (i.e. "Medication Use Safety During Care Transitions for Children with Medical Complexity") were filtered out. Following the title analysis, 473 articles remained. Next, abstracts and introductions were read to determine their pertinence to the synthesis. This required the articles to discuss and analyze at least one distillers' grain or ethanol feed coproduct. After screening abstracts and introductions, 134 articles remained. Articles that conducted at least one economic analysis related to ethanol feed co-product markets, production, or demand were included in the final review. Economic analysis was broadly defined and meant to include basic cost-benefit analyses in addition to more complex econometric analyses. In total, 110 articles were included in this literature review and synthesis. Figure 1 provides a summary of the total article retrieval and screening process.

Selected articles were classified by peer-reviewed publication status, the type of distiller grains examined, livestock type, other grain markets impacted by distillers' grain use, and location of study. Common research topics between articles were identified and selected as the primary categories. Studies were then classified by which broad topic best fit the paper's content. In situations where a paper could reasonably fit in multiple categories, papers were categorized by the primary analysis of the article. Table 1 summarizes and categorizes all examined papers.

Topics Covered

Although the number of articles included under each topic varied, most topics featured consistent publications from the onset of widespread co-product analyses (2007-2008) to the present. Two categories, cost analysis, and economic impact analysis made noticeable deviations from this trend. The first cost analysis paper featured in this literature review was published in 2006, while the final cost analysis paper was published in 2016. Similarly, the first economic impact analysis paper was published in 2005 and the last was published in 2013. This suggests that these analyses became less popular over time – likely because many basic research questions in these categories were already explored by the mid-2010s.

Peer-Reviewed vs. Non-Peer Reviewed

Peer-reviewed articles are classified as journal papers, books, government studies, conference papers and presentations, and rigorous extension publications. Non-peer-reviewed articles were classified as short extension releases, working papers, and industry articles. In total, 87 peer-reviewed and 23 non-peer-reviewed articles were included in the analysis.

A distinction between peer-reviewed and non-peer-reviewed articles is made because of the differences in structure, content, and purpose of the articles. Peer-reviewed articles typically conduct rigorous economic or cost-benefit analyses that seek to answer a central research question. Non-peer-reviewed papers more often include broad overviews of current events in distillers' grains markets, a basic explanation of a distillers'-related topic, or a relevant yet preliminary economic analysis. Peer-reviewed articles often analyzed the questions initially posed by non-peer-reviewed papers with greater detail which, in the case of distillers' grains, often led to varying results and conclusions between studies. As a result, it was useful to identify which papers were peer-reviewed and non-peer-reviewed (see Table 1). The distinction was not pronounced enough to affect the synthesis of papers by topic, though, so little reference is made to peer review status in the body of this analysis.

Types of Distillers' Grains

Most papers focused on analyzing DDGS (N=106). Far fewer examined other types of distillers' grains such as MDGS (N=12), WDGS (N=18), and value-added products (N=6). The imbalance was likely because DDGS comprise a much larger share of the distillers' grain market than do MDGS, WDGS, and value-added products. From 2016-2020, the average shares of distillers' grains production in the United States were 53%, 12%, and 35% for DDGS, MDGS, and WDGS, respectively (USDA-NASS 2021). The transportability of DDGS versus MDGS and WDGS make DDGS more relevant to a national or global audience. As for value-added co-products, their relatively recent entry to the market – which currently serves to limit their data availability and market share – was likely a primary cause for their limited visibility in the research.

Commodity Impacted by Distiller Grains

Articles often focused on the impacts that a particular distiller grain had on a specific industry. Three primary sectors were identified – grains (e.g. corn, soybeans, soybean meal, maize, and other feed substitutes), livestock (e.g. beef cattle, dairy cattle, hogs, poultry, and other livestock), and other (e.g. ethanol, industrial gasses, and oil). Many studies examined distillers' grains in relation to more than one sector. Of the 110 articles included in the review, 59 papers studied distillers' grains concerning "grains," 69 related to "livestock," and 31 broadly classified as "other."

Organizing the papers into these larger groups limits does limit some of the insights that are more obvious on a more granular level. For example, only six (8.5%) "livestock" papers include an analysis related to dairy. This is a relatively small amount, given that distillers' grains are common and effective components of dairy cattle feed rations. In general, studies show that DDGS can account for roughly 30% of dry matter in a lactating cow diet without reducing milk yield (Grings et al. 1992). This absence from the research may be because dairy cattle primarily use distillers' grains as a protein source and more easily substitute distillers' grains with other high-protein products when costs increase. The heavy skew toward beef cattle and hogs in this research can also be attributed to the regions of the United States where distillers' grains were studied in the publications. The Great Plains and Midwest. States in these regions skew heavily toward beef cattle and hog production and, therefore, tend to focus on those industries in their analyses.

Location of Study

Many of the domestic papers were published from universities based in the Great Plains and Midwestern regions. Most papers focused on impacts within the U.S – 80 of the 110 articles focused exclusively on domestic markets and 30 incorporated international and export markets in some manner. The 30 articles that incorporated international and export markets centered around DDGS rather than MDGS or WDGS. This is because DDGS are transportable, storable goods in comparison to MDGS and WDGS, which can only travel a limited radius. None of the export market-focused papers explored value-added goods, likely because value-added distillers' grains were introduced fairly recently, and many of the papers explored in this literature review predate their arrival to the market.

Economic Research on Distillers' Grains

The distinctions discussed above – such as types of distillers' grains, commodities impacted by distillers' grains, and location of study – help to better frame the existing state of the economic research related to ethanol co-products. Broader similarities and differences between the papers are discussed in the body of the synthesis. Eighty-seven studies conduct economic or cost-benefit analyses, while 23 (mostly non-peer-reviewed) articles contain broader discussions of distillers' grains markets underpinned by economic theory. The aim of this synthesis is to summarize the economic findings of the existing research while identifying potential areas for future exploration.

Cost Analysis

Articles in the cost analysis section primarily covered three broad categories: (1) ethanol plant cost structures (Rausch et al. 2007; Sesmero et al. 2016), (2) co-product generation (Rosentrater 2006; Rosentrater and Kongar 2009), and (3) environmental costs of ethanol/distillers' grains production (Fabiosa 2009). Publication dates ranged from 2006 to 2016, with all but one paper published before 2010 (Sesmero et al. 2016). All studies focused on distillers' grain production in the United States.

The ethanol plant cost structure studies centered around how ethanol plants use co-products to offset production costs and how variations in co-product production alter the costs faced by ethanol plants (Rausch et al. 2007; Sesmero et al. 2016). Results suggest that ethanol plants market co-products to increase plant revenues, but technological barriers to improving product quality and universality – resulting in distillers' grains high phosphorus content and corn germ and fiber that is indigestible to nonruminants – limited the efficacy of co-products in reliably diversifying revenue streams (Rausch et al. 2007). Further, ethanol plants were found to change their co-product mix in response to price signals (Sesmero et al. 2016). For example, if export demand is weak and local market demand is strong, ethanol plants shift a greater percentage of their distillers' grains production to wet distillers' grains to reduce costs and increase co-product profit margins.

The co-product generation studies focused on future co-product generation rates (Rosentrater 2006) and pelletized distillers' grains production (Rosentrater and Krongar 2009). They found the co-product production process to be heavily dependent on external market forces for future production levels. Therefore, ethanol plants needed to pursue research focused on value-added products to diversify bioethanol revenue streams and hedge against potential adverse market conditions (Rosentrater 2006). Pelletized distillers' grains were one value-added product examined, the production of which was deemed a cost-effective process only in plants benefiting from the economies of scale (Rosentrater and Kongar, 2009).

Finally, distillers' grains were found to reduce the environmental costs of ethanol production by partially offsetting the land use impact of corn for ethanol (Fabiosa 2009). The extent to which distillers' grains offset ethanol production's environmental impact depended on whether feed compounders discounted the distillers' grains nutrient profile to ensure they were at or above a realized nutrient profile 90% of the time. When feed compounders did so, distillers' grains were found to be less effective at offsetting ethanol production's environmental costs versus when no such measures were taken. Regardless of whether feed compounders discounted distillers' grains nutrient profiles, DDGS were more effective at offsetting ethanol's environmental impact than ethanol production scenarios that did not market any co-products.

Cost-Benefit Analysis

Cost-benefit analysis studies constituted the largest portion of the distillers' grains economic literature in this review and featured a greater variety of locations and livestock types than other sections. This variety is likely attributable to the fact that the cost-benefit analysis papers mostly included economic/cost-benefit analyses as complementary components to more central research questions, typically the efficacy of feeding distillers' grains to various livestock types. In other words, these economic analyses were largely budgeting exercises with different feeds within rations. These were included in the synthesis since some measure of the costs and benefits of distillers' grains was included in each study.

Thirty-four papers featuring eight different countries – Brazil (Corassa et al. 2021), Bulgaria (Yildiz et al. 2015), Cuba (Rodriguez et al. 2016), Egypt (Abou-Zied et al. 2012; Allam et al. 2020; El-Deek et al. 2020; El-Rahman et al. 2014; Youssef et al. 2012;), Hungary (Sandor et al. 2021), India (Changan et al. 2019; Sajjan et al. 2017), Philippines (Alvaran et al. 2018), and the United States (Bailey and Kallenbach 2010; Buckner et al. 2008; Coble et al. 2014; Diogenes et al. 2019; El-Hack et al. 2015; Gadberry et al. 2010; Harris et al. 2012; Klopfenstein et al. 2008; Kubas and Firman 2014; Kubas and Firman 2015; Lowe II et al. 2016; Masa'deh et al. 2012; Nunez et al. 2015; Oliveira et al. 2020; Paine et al. 2018; Ranathunga et al. 2010; Roberts 2009; Sandor et al. 2021; Schmit et al. 2008; Schmit et al. 2009; Tidwell et al. 2007; Troyer et al. 2020) – comprised the cost-benefit section of the review.

The studies explored the value of feeding distillers' grains ranging from DDGS to WDGS to high-fat and low-fat DDGS in beef cattle (Bailey and Kallenbach 2010; Buckner et al. 2008; El-Rahman et al. 2014; Gadberry et al. 2010; Klopfenstein et al.

2008; Troyer et al. 2020; Nunez et al. 2015), dairy cattle (Changan et al. 2019; Lowe II et al. 2016; Schmit et al. 2008; Schmit et al. 2009; Ranathunga et al. 2010; Yildiz et al. 2015), dairy buffaloes (Alvaran et al. 2018), fish (Abou-Zied et al. 2012; Allam et al. 2020; Diogenes et al. 2019; Oliveira et al. 2020; Sandor et al. 2021; Tidwell et al. 2007), goats (Paine et al. 2018; Sajjan et al. 2017), poultry (El-Deek et al. 2020; El-Hack et al. 2015; Kubas and Firman 2014; Kubas and Firman, 2015; Masa'deh et al. 2012; Roberts 2009; Rodriguez et al. 2016), hogs (Coble et al. 2014; Harris et al. 2012; Corassa et al. 2021), and rabbits (Youssef et al. 2012). The papers examined distillers' grains' feeding value through the lens of animal performance analyses and models of representative operations and compared the cost of including distillers' grains in animal diets versus the value of the changes in animal performance when fed distillers' grains. Overall, the studies found distillers' grains to be cost-effective, performance-enhancing, profit-improving feed supplements and/or substitutes. These results held across most livestock types, but a few studies found distillers' grains to hurt livestock operation profitability relative to alternative feeds (El-Rahman et al. 2014; Harris et al. 2012; Klopfenstein et al. 2008).

A significant shortcoming with these articles is that most use budgeting to justify economic usefulness. These studies can provide use in the development of larger market models that examine how the efficacy of feeding new and different distillers' co-products to unique livestock types can change market demand and supply. In this way, they can provide a valuable contribution to the existing literature by revealing what combinations of distillers' grains type, location, and livestock type are most viable in the marketplace and, therefore, hold the most potential for more complex economic analyses.

Demand Analysis

The demand analysis research in this literature review and were divided into four broad categories: (1) Contextual Demand (Gertner and Dennis 2020; Gertner and Dennis 2020; Olson and Capehart 2019), (2) Livestock Demand (Clemens and Babcock 2008; Fabiosa 2008; Jones et al. 2007; Stockton 2006; Stockton and Stalker 2012; Suh and Moss 2014; Suh and Moss 2016; Wright et al. 2012), (3) Location Demand (Dooley 2008; Wang et al. 2011), and (4) Potential Demand (Beckman et al. 2011; Conley 2013; Dooley 2008; Ferris 2011; Hoffman and Dohlman 2011). The categories were determined by the primary research question from which ethanol co-product demand was analyzed.

The contextual demand papers focused on distillers' grains demand in response to external market forces, such as the COVID-19 pandemic, increased export demand, and ethanol production incentives (Gertner and Dennis 2020; Gertner and Dennis 2020; Olson and Capehart 2019). All three articles were published after 2019 and emphasized the extent to which distillers' grains markets rely on exogenous variables. More specifically, distillers' grains prices and demand were found to be supported by increases in ethanol production, export opportunities, and storability, all of which helped the co-product markets to rapidly recover from the initial impacts of COVID-19 (Gertner and Dennis 2020; Gertner and Dennis 2020).

Articles centering around the demand for distillers' grains from livestock focused primarily on cattle, hogs, and general livestock markets (Clemens and Babcock 2008; Fabiosa 2008; Jones et al. 2007; Stockton 2006; Stockton and Stalker 2012; Suh and Moss 2014; Suh and Moss 2016; Wright et al. 2012). The eight articles broadly concluded feeding distillers' grains were viable methods for increasing returns to livestock operations. The articles pointed to nutritional variability, cost of transportation, corn prices, and feeding methods as factors that have significant impacts on the demand for and efficacy of feeding distillers' grains. Demand for distillers' grains from livestock operations was found to be sluggish to adjust to changes in these influencing factors (Suh and Moss 2014). In other words, only about a fifth of the long-run response to a change in the prices of feed grains was found to occur in the same marketing year as the price change (Suh and Moss 2014). Six of the articles were published before 2012, while two were published after 2014. Additionally, six of the eight studies only explored the demand for DDGS, while two expanded the analyses to include MDGS and WDGS. Given the (1) increased visibility of distillers' grains in the marketplace and (2) increased heterogeneity in product types and characteristics, there is little understanding of how the factors affecting the demand for distillers' grains from livestock operations have evolved over time.

The two location demand papers examined factors influencing distillers' grains production in Indiana and the United States as a whole (Dooley 2008; Wang et al. 2011). Results included the prediction that livestock producers in Indiana and the United States would, overall, have ready access to distillers' grains in the coming years (Dooley 2008). The importance of including co-products in ethanol plants' life cycle analyses was also stressed (Wang et al. 2011). Both location-based demand papers were published before 2012 and focused only on DDGS, indicating the need for updated and expanded additions to the economic research in this area to further explain the impact of location on co-product demand. Without location-specific studies, the demand structures of ethanol plants outside the major production zone of the Midwest remain unclear. An unclear understanding of location's impact distillers' grains demand, therefore, leaves researchers unable to analyze the impact of location-specific market shocks.

The future demand for ethanol co-products primarily focused on DDGS characteristics and market forces shaping their potential demand (Beckman et al. 2011; Conley 2013; Dooley 2008; Ferris 2011; Hoffman and Dohlman 2011). Feed quality heterogeneity and levels of per-animal consumption were topics of concern in the earlier articles in the section, while the prospect of demand outpacing supply was the focus of the more recently published articles. Three of the four studies focused exclusively on the future of DDGS demand (Beckman et al. 2011; Conley 2013; Dooley 2008; Hoffman and Dohlman 2011), while one study explored the viability of the market potential of extracting corn oil from DDGS for biodiesel production (Ferris 2011). Overall, the outlook for ethanol co-products demand was deemed positive.

Economic Impact Analysis

Studies exploring the economic impacts of ethanol co-products primarily did so through three lenses: (1) impacts on grains markets (Elobeid et al. 2006; Fabiosa 2009; Ferris 2013; Markham 2005; Yu and Hart 2009), (2) impacts on livestock markets (Munkvold et al. 2008; Schmit et al. 2008; Skinner et al. 2012; Taheripour et al. 2010), and (3) environmental impacts (Bremer et al. 2011; Taheripour et al. 2008).

In the studies examining the impact of distillers' grains on grain markets, the primary focus was the effect of distillers' grains production on grain market structures and prices – specifically corn (Yu and Hart 2009) and wider feed grain markets (Elobeid et al. 2006; Fabiosa 2009; Ferris 2013; Markham 2005). Papers analyzing the relationship between distillers' grains and corn markets found that the onset of widespread ethanol production changed the directional flows of corn in the United States. In other words, corn flowed in-state to ethanol plants and then primarily out-of-state in the form of ethanol and distillers' grains (Yu and Hart 2009). This changed the domestic supply dynamics of feed by altering what products were available and where. Studies exploring the broader relationships between distillers' grains prices and feed grains prices found that correlations of general feed ingredient prices and crude oil prices increased dramatically since wide-scale ethanol production began (Fabiosa 2009). This was because feed and fuel markets became more intertwined as corn was directed toward both animal feed and fuel ethanol markets. Because of corn's unique status as both a livestock and fuel feedstock, the fact that the co-product of corn ethanol production, distillers' grains, could be fed to livestock in place of corn helped temper the inflationary effect of increased ethanol production on grain prices (Elobeid et al. 2006; Ferris 2013; Markham 2005). The earliest of these five studies was published in 2005, and the latest was published in 2013, with three 2009 publications. DDGS were the primary co-products of focus in the grain impact analysis research. Given the changes in ethanol and co-product production over the past decade, and the increased quantity of grains allocated toward that production, updated analyses of the impacts of ethanol co-products on grain markets would fill a currently unaddressed gap in the literature.

Studies centering around the impacts of ethanol co-products on livestock markets all focused on DDGS in their analyses. Additionally, the studies found that – while increased ethanol production increased general feed costs for livestock producers – DDGS helped to alleviate those impacts and provided economic and nutritional benefits not present in previously-used feedstuffs (Munkvold et al. 2008; Schmit et al. 2008;

Skinner et al. 2012; Taheripour et al. 2010). Biofuel mandates were found to encourage additional crop production and discourage livestock production in most global regions, especially for non-ruminant livestock that benefit less from ethanol co-products (Taheripour et al. 2010). All three studies were published in 2012 or before, meaning the analyses were unable to account for the many developments in the types and quality of ethanol co-products over the past decade. These changes in ethanol co-products undoubtedly impact the livestock industry, but the nature of those impacts is unknown.

The studies exploring the economic and environmental impacts of ethanol co-products found that excluding co-product production from economic analyses of ethanol plants alters the results of biofuel mandates in systematic ways (Taheripour et al. 2008). Models including co-products show smaller changes in the production of cereal grains and larger changes to produce oilseeds in the US and EU than models excluding co-products (Taheripour et al. 2008). Additionally, feeding co-products to livestock were found to reduce the environmental footprint of ethanol plants relative to gasoline (Bremer et al. 2011). As with many of the previously discussed studies, the environmental and economic impact study only accounts for DDGS and WDGS in their analyses and were published in 2008 and 2011. The economic impacts of recent more specialized ethanol co-products have not been examined.

Price Analysis

Price analysis research in this literature review fell primarily into three broad categories: (1) price discovery (Etienne and Hoffman 2015: Fabiosa 2008; Hubbs et al. 2009; Irwin and Good 2013; Springer and Schmitt 2018; Van Winkle et al. 2008), (2) co-product price effects (Irwin and Good 2015; Suh and Moss 2017), and (3) co-product price relationships (Etienne et al. 2017; Johnson et al. 2015). The price analysis section of the literature contained one of the largest proportions of recent publications of any section in this analysis, with most of the papers published since 2015.

The papers on price discovery in ethanol co-product markets all focused exclusively on DDGS in the United States. In general, the articles found nutritional composition (Fabiosa 2008), location (Van Winkle and Schroeder 2008), and corn and soybean meal prices to be the most important determinants of DDGS prices (Etienne and Hoffman 2015). The valuation of nutritional components varied by the type of livestock demanding DDGS. For example, higher protein levels did not necessarily garner higher DDGS prices for hog operations, although they did for cattle operations (Hubbs et al. 2009). Given the relative recency of most of these studies, future contributions to the literature would have the greatest impact by diversifying the product types and locations examined. Price discovery analyses beyond DDGS and the United States would help to better frame the pricing structures of ethanol co-products around the world.

The two price effect papers examined ethanol co-product prices through disparate lenses: one explored the effects of a decline in DDGS prices, while the other analyzed the effects of changes in corn prices on DDGS. The first highlighted the risk of declining DDGS prices without declines in corn or soybean meal prices, which, ceteris paribus, would shrink ethanol plants' profit margins (Irwin and Good 2015). Increases in corn prices, on the other hand, were found to lead to increases in DDGS prices – the production of which did not constitute a large enough share of the livestock feed market to offset corn price increases (Suh and Moss 2017). Both studies explored only DDGS prices in the United States, so suggestions for potential contributions to the literature mirror those provided above.

In the two price relationship papers, the authors examined spatial and time-varying price relationships between DDGS, corn, and soybean meal prices. Corn and soybean meal were found to contribute to each other's prices, and corn was found to act as the largest contributor of uncertainty in DDGS prices (Johnson et al. 2015). DDGS prices were not found to influence corn and soybean meal prices (Etienne et al. 2017). Both studies examined the U.S. market and only examined DDGS prices. It is assumed that broad conclusions are likely to be similar between any individual ethanol co-product and corn and soybean prices. However, the effects of specialization and differentiation of ethanol co-products on price relationships are unknown, as is whether product differentiation strengthens or weakens the relationship to corn and soybean meal prices.

Risk Management

Seven studies comprised the risk analysis section of the literature review and explored topics primarily relating to cross-hedging, futures contracts, and transaction costs (Bekkerman and Tejada 2017; Brinker et al. 2009; Dahlgran and Gupta 2019; Murguia and Lawrence 2010; Tejada 2012; Tonsor 2008; Weseen and Kerr 2014). The studies were published from 2008 to 2019.

The overall scope of risk management studies in the ethanol co-product domain is limited. Only North American studies were found and analyzed in this literature review, and each study focused on DDGS for risk management. Studies investigating risk management of ethanol co-products in international settings and a diversified range of co-products would add to the breadth and depth of this corner of the literature.

The studies came to differing conclusions of the potential effectiveness of cross hedging DDGS with corn and soybean meal prices and, similarly, the potential efficacy of a DDGS futures contract in mitigating price risk. Given the fact that the attempt to create and maintain a DDGS futures contract failed, the studies following the failed contract more readily admitted the difficulty of cross hedging DDGS with corn and soybean meal, while those published before the introduction of the contract were more optimistic about its potential.

Techno-Economic Analysis

The techno-economic analysis papers in this literature review could be primarily categorized into two groups: (1) papers exploring the economics of converting distillers' grains to biofuel (DeRose et al. 2019; Kumar et al. 2010; O'Brien et al. 2020; Wang et al. 2009) and (2) using novel processes to enhance distillers' grains' production or value (Barnharst et al. 2021; Kurambhatti et al. 2021; Perkis et al. 2008; Rodriguez et al. 2010; Srinivasan et al. 2006; Srinivasan 2013; Wood et al. 2011; Wood et al. 2012; Zhang et al. 2014). Their publication dates ranged from 2006 to 2021, and all studies were based in the United States.

Studies exploring the economic feasibility of using distillers' grains for additional fuel production generally explored the costs and benefits of modular engineering processes for converting distillers' grains into biofuels or biogases. For the most part, converting distillers' grains to fuel was found to be energy efficient and technically feasible, but the economic practicality of the processes was highly dependent on economies of scale and prevailing market prices. As a result, no definitive economic conclusion was reached across all four papers. The other techno-economic analyses papers – those exploring enhancements in distillers' grains production and/or value – primarily analyzed how to produce distillers' grains more efficiently or how to extract additional value out of distillers' grains (Barnharst et al. 2021; Rodriguez et al. 2010; Wood et al. 2011; Wood et al. 2012). These research studies also came to differing conclusions about the efficacy of these processes.

In general, the studies exploring enhancements to the distillers' grains production process itself found those enhancements to be feasible (Barnharst et al. 2021; Rodriguez et al. 2010; Srinivasan et al. 2006; Srinivasan 2013; Wood et al. 2011; Wood et al. 2012), while the research analyzing processes producing new products were less definitive (Kurambhatti et al. 2021; Perkis et al. 2008; Rodriguez et al. 2010; Zhang et al. 2014). All papers conducted their analysis in the United States market. There is little research on whether international market players on either the ethanol or livestock production side would value these processes differently.

Trade

Papers focused on international trade and production of ethanol co-products primarily fell under two primary categories: (1) United States co-product exports (Babcock et al. 2008; De Matteis et al. 2019; DeOliveira et al. 2017; Fabiosa et al. 2009; Good 2015; Good 2016; Good 2016; Hubbs 2018; Jewison and Gale 2012) and (2) international co-product production (De Matteis et al. 2018; Strydom et al. 2010; Strydom et al. 2010; Tokgoz 2008). The publication years ranged from 2008 to 2019 and all focused on the export of DDGS. Given the low transportability of MDGS and WDGS, the focus on dried distillers' products was less exclusionary in nature than some of the previous studies in other sections. Differentiation exists within dried distillers' productions in the form of de-oiled, high protein, and pelletized products, though, and none of these products were explored in the studies.

Papers that focused on U.S. exports of ethanol co-products centered around potential export demand and export progress, and export demand from China was a primary focus (DeOliveira et al. 2017; Fabiosa et al. 2009; Good 2015; Good 2016; Jewison and Gale 2012). The primary determinants of export demand were found to be the importing country's meat production, technical barriers to trade, tariffs, and US ethanol production (De Matteis et al. 2019). Overall, export outlooks were deemed positive, with quality heterogeneity concerns identified as one of the most significant barriers to increased export activity (Babcock et al. 2008; DeOliveira et al. 2017; Fabiosa et al. 2009; Good 2015; Good 2016; Good 2016; Hubbs 2018; Jewison and Gale 2012). Finally, China was found to be a major player in the market, with the ability to almost singlehandedly drive DDGS demand when fully participating in the marketplace (DeOliveira et al. 2017; Fabiosa et al. 2009; Good 2015; Good 2016; Jewison and Gale 2012).

Trade and international use of co-products papers with a specific focus on co-product production in international markets explored the implications of ethanol and co-product production in Argentina (De Matteis et al. 2018), the European Union (Tokgoz 2008), and South Africa (Strydom et al. 2010; Strydom et al. 2010). Studies found that ethanol production increased the competitiveness of feed industries in the countries and regions explored. The benefit of feed competitiveness was a result of DDGS reducing phosphorus contents of feed rations and reducing ration costs – both not available without

DDGS (De Matteis et al. 2018). No studies examined other ethanol co-products nor how internationally produced DDGS differ from those produced domestically.

Revealed Needs for Additional Research

In total, the 110 papers analyzed in this literature review covered a broad swath of economic topics in the distillers' grains domain. Still, many research questions remain unanswered by the existing distillers' grains economic literature.

One potential research path involves revisiting many of the topics already discussed in this paper. Most of the studies included in this review were published more than five years ago. Given the significant advancements in the domestic and international distillers' grains industries, more up-to-date research is needed to verify prior results and examine new developments in the distillers' grains domain. These studies could answer questions relevant to producers, academics, and industry professionals by exploring how distillers' grains markets have evolved in recent years, whom those changes have benefited, and what – if any – distillers' grains are most cost-effective for ethanol plants and livestock producers. These studies could fall under any of the categories included in this paper and would be valuable contributions to the literature.

Another path for research is to analyze highly specialized and value-added distillers' products, for which there are currently few published academic studies. Due to the increasing amount of these products in the distillers' grains and livestock feed industries, quantifying their economic costs, benefits, and impacts are much-needed additions to the literature. Research could help to uncover whether there are potential unrealized profits for ethanol plants in the value-added space and whether these products are cost-effective for producers. Cost, demand, and/or economic impact analysis studies would be the most likely studies for these questions and would provide relevant information to the present-day distillers' grains industry.

From a livestock feeding perspective, proper valuation of nutritional characteristics of distillers' grains from conventional and new value-added processes is essential for livestock nutritionists and producers to make economic substitutions. Beef cattle perform differently (better) in most scenarios where distillers' grains are used (Bremer et al. 2011). For other livestock, such as dairy cattle, swine, and poultry, most companion grains, like soybean meal, are simple substitutes as performance is not influenced. As a result, an economic valuation of the nutritional components of DDGS by livestock type would be a valuable contribution to the literature.

Additionally, further research into the disparate demand structures for DDGS, MDGS, and WDGS is needed. While DDGS is logical for national and global economics for both plants and end-users, wet and modified distillers' are critical for many local cattle (dairy and beef) producers. In these markets, the price may, or may not, reflect national price trends. Data suggest price fluctuation for different months throughout the year, likely reflecting supply and demand principles. A more in-depth understanding of the level of connectedness, or lack thereof, of these markets would help in analyzing each type of distillers' grain.

Expanding the scope of international research is another need. Given the scale of both the ethanol and livestock feeding industries in the United States, many studies have already explored the basic economics of distillers' grains from both the ethanol plant and livestock producer perspectives. Whether these economics are the same internationally – given unique market structures, differing end users, and varying feed inputs – is largely unexplored beyond basic cost-benefit analyses in lower-visibility industries such as aquaculture and alternative poultry operations. Further international research on distillers' grains may help to uncover areas in which domestic ethanol plants could expand their reach. Conversely, adverse outcomes to international distillers' grains markets may portend an unfriendly future domestically. Either way, research in this area would help to better frame the state of the global distillers' grains industry. Any of the research categories found in this literature review would be useful angles from which to explore international distillers' grains topics.

Future research studies would also do well to branch out beyond analyses that primarily explore beef cattle and hogs. Given beef cattle and hogs' importance to the distillers' grains industry, the heavy focus on those species in ethanol co-product research is understandable, but it has resulted in several gaps in the literature. Is there a viable path forward for ethanol co-products in the dairy, poultry, and aquaculture industries? Are there species currently underutilizing distillers' grains from a profit maximization perspective, or will the market fail to expand beyond beef cattle and hogs? These studies would likely consist primarily of cost and demand analyses and would help to determine the long-term path of distillers' grains demand.

Finally, given the significant changes in the ethanol and distillers' grains industries over the past decade, additional research charting possible paths forward for both industries is required to better understand what lies ahead for distillers' grains, biofuels, and their adjacent industries. These studies would likely be a combination of the various research paths proposed above. In these studies, potential products, end-users, and locations would be compared and analyzed to determine the trajectory of the distillers' grains industry and how that trajectory can be altered in ways favorable to both ethanol plants and end-users. Given the fact that these studies would need to examine ethanol co-products from multiple perspectives, they would likely consist of a mix of cost, demand, and price analysis. These studies are crucial to allow ethanol plants, producers, and industry participants to better plan for the future of their respective industries.

Conclusion

Much of the research covered in this literature review appeared during the ethanol boom of the first decade of the 2000s and shortly thereafter. Overall, research has found distillers' grains to be cost-effective, profitable, and potentially impactful products with the potential for significant market growth.

While the research pieces covered in this literature review provide a general template for a few possible future studies, the literature to date has been far from comprehensive in its examination of the distillers' grains market. This is evidenced by the suggested paths forward for research, along with the section-by-section discussions of potential shortfalls of the papers. The literature review was limited by the depth and breadth of the databases used in the study. Any journal articles not stored in the databases listed in the Methods section were not included in the literature review. Similarly, any articles not retrieved by the search terms detailed in the Methods section were not captured in this study.

The makeup of the ethanol and distillers' grains industries is very different from a decade ago, roughly when many of the papers in this review were published. More economic research is required to better understand the path forward for both ethanol plants and livestock producers. Recent developments of new, differentiated products in the distillers' grains markets have the potential to change the industry, but little research has addressed these new topics. Such research would better inform policy, planning, and decision-making from both ethanol plant and producer perspectives and would more accurately reflect today's distillers' grains industry.

References

Abd El-Hack, M.E., M. Alagawany, M.R. Farag, and K. Dhama. "Use of Maize Distiller's Dried Grains with Solubles (DDGS) in Laying Hen Diets: Trends and Advances." Asian Journal of Animal and Veterinary Advances 10, no. 11 (2015): 690–707. https://doi.org/10.3923/ajava.2015.690.707.

Abou-Zied, R. M., and M. M. E. Hassouna. "Evaluation of Farmmade Diets Containing Distillers' Dried Grains with Solubles on Nile Tilapia Production in Commercial Earthen Ponds." Egyptian Journal of Nutrition and Feeds 15, no. 2 (2012): 419–24.

Allam, B. W., H. S. Khalil, A. T. Mansour, T. M. Srour, E. A. Omar, and A. A. M. Nour. "Impact of Substitution of Fish Meal by High Protein Distillers' Dried Grains on Growth Performance, Plasma Protein and Economic Benefit of Striped Catfish (Pangasianodon Hypophthalmus)." Aquaculture 517 (2020): 734792.

Alvaran, C. A. P., I. J. Domingo, and D. L. Aquino. "Influence of Distillers' Dried Grain Solubles (DDGS) on Intake, Nutrients Digestibility and Milk Production of Dairy Buffaloes." Journal of Biological Engineering Research and Review 5, no. 1 (2018): 24–29.

An, Heungjo, Wilbert Wilhelm, and Stephen Searcy. "Biofuel and Petroleum-Based Fuel Supply Chain Research: A Literature Review." *Biomass and Bioenergy* 35, no. 9 (October 2011): 3763–74. https://doi.org/https://doi.org/10.1016/j.biombioe.2011.06.021.

Babcock, Bruce, Dermot J. Hayes, and John D. Lawrence. "Using Distillers' Grains in the U.S. and International Livestock and Poultry Industries," 2008, 259 pages.

Bailey, N. J., and R. L. Kallenbach. "Economic Favorability of Feeding Distillers' Dried Grains with Solubles and Round-Bale Silage to Stocker Cattle." Professional Animal Scientist 26, no. 4 (2010): 375–79.

Barnharst, Tanner, Xiao Sun, Aravindan Rajendran, Pedro Urriola, Gerald Shurson, and Bo Hu. "Enhanced Protein and Amino Acids of Corn-Ethanol Co-product by Mucor Indicus and Rhizopus Oryzae." Bioprocess and Biosystems Engineering 44, no. 9 (September 2021): 1989–2000. https://doi.org/10.1007/s00449-021-02580-0.

Beckman, Jayson, R. Keeney, and W. Tyner. "Feed Demands and Co-product Substitution in the Biofuel Era." Agribusiness 27, no. 1 (2011): 1–18.

Bekkerman, Anton, and Hernan A. Tejeda. "Revisiting the Determinants of Futures Contracts Success: The Role of Market Participants." Agricultural Economics 48, no. 2 (March 2017): 175–85.

Bremer, V. R., A. K. Watson, A. J. Liska, G. E. Erickson, K. G. Cassman, K. J. Hanford, and T. J. Klopfenstein. "Effect of Distillers' Grains Moisture and Inclusion Level in Livestock Diets on Greenhouse Gas Emissions in the Corn-Ethanol-Livestock Life Cycle1." The Professional Animal Scientist 27, no. 5 (October 1, 2011): 449–55. https://doi.org/10.15232/S1080-7446(15)30517-9.

Bremer, V.R., A.K. Watson, A.J. Liska, G.E. Erickson, K.G. Cassman, K.J. Hanford, and T.J. Klopfenstein. "Effect of Distillers' Grains Moisture and Inclusion Level in Livestock Diets on Greenhouse Gas Emissions in the Corn-Ethanol-Livestock Life cycle1." The Professional Animal Scientist 27, no. 5 (2011): 449–55. https://doi.org/10.15232/s1080-7446(15)30517-9.

Brinker, Adam J., Joseph L. Parcell, Kevin C. Dhuyvetter, and Jason R. V. Franken. “Cross-Hedging Distillers’ Dried Grains Using Corn and Soybean Meal Futures Contracts.” Journal of Agribusiness 27 (2009): 1–15.

Buckner, C.D., T.L. Mader, G.E. Erickson, S.L. Colgan, D.R. Mark, K.K. Karges, M.L. Gibson, and V.R. Bremer. “Evaluation of Dry Distillers’ Grains Plus Solubles Inclusion on Performance and Economics of Finishing Beef Steers1.” Professional Animal Scientist 24, no. 5 (2008): 404–10. https://doi.org/10.15232/S1080-7446(15)30884-6.

Changan, S.D., S.M. Bhalerao, A.V. Khanvilkar, and V.U. Dhande. “Wet Distillers’ Grain Solubles (WDGS) Production Performance in Cows.” Indian Veterinary Journal 96, no. 8 (2019): 38–40.

Clemens, Roxanne, and Bruce A. Babcock. “Steady Supplies or Stockpiles? Demand for Corn-Based Distillers’ Grains by the U.S. Beef Industry.” AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.6051.

Coble, K. F., J. M. DeRouchey, M. D. Tokach, R. D. Goodband, J. C. Woodworth, and S. S. Dritz. “Effects of 30% Dried Distillers’ Grains with Solubles and 5% Added Fat Prior to Slaughter on Growth Performance, Carcass Characteristics, and Economics of Finishing Pigs.” Edited by B. Goodband, M. Tokach, S. Dritz, J. Derouchey, and J. Woodworth. Kansas State University Swine Day 2014. Report of Progress 1110, Manhattan, Kansas, USA, 20 November, 2014, 2014, 187–95.

Conley, Dennis M. “Analysis for Strategic Planning Applied to Ethanol and Distillers’’ Grain.” International Food and Agribusiness Management Review 16, no. 3 (September 1, 2013): 37–54.

Corassa, A., I. P. A. S. Lautert, A. P. S. Ton, C. Kiefer, C. O. Brito, M. Sbardella, and H. C. Souza. “Viability of Brazilian Distillers’ Dried Grains with Solubles for Pigs.” Semina: Ciencias Agrarias (Londrina) 42, no. 3 (2021): 1159–74. https://doi.org/10.5433/1679-0359.2021v42n3p1159.

Dahlgran, Roger A., and Rajat Gupta. “Corn-Crush Hedging – Does Location Matter?” AgEcon Search, 2019. https://doi.org/10.22004/ag.econ.309624.

De Matteis, Maria C., T. Edward Yu, Christopher N. Boyer, and Karen L. DeLong. “Analyzing Determinants of US Distillers’ Dried Grains with Solubles Exports.” Agribusiness 35, no. 2 (April 1, 2019): 168–81. https://doi.org/10.1002/agr.21575.

De Matteis, Maria C., T. Edward Yu, Christopher N. Boyer, Karen L. DeLong, and Jason Smith. “Economic and Environmental Implications of Incorporating Distillers’’ Dried Grains with Solubles in Feed Rations of Growing and Finishing Swine in Argentina.” International Food and Agribusiness Management Review 21, no. 6 (2018): 803–16. https://doi.org/10.22004/ag.econ.274995.

DeOliveira, Vanessa, Kate Brooks, and Lia Nogueira. “A Short Introduction to the Distillers’’ Dried Grains Export Market.” AgEcon Search, February 8, 2017. https://doi.org/10.22004/ag.econ.306997.

DeRose, Katherine, Fang Liu, Ryan W. Davis, Blake A. Simmons, and Jason C. Quinn. “Conversion of Distiller’s Grains to Renewable Fuels and High Value Protein: Integrated Techno-Economic and Life Cycle Assessment.” Environmental Science & Technology 53, no. 17 (September 3, 2019): 10525–33. https://doi.org/10.1021/acs.est.9b03273.

Diogenes, A. F., A. Basto, T. T. Estevao-Rodrigues, S. Moutinho, T. Aires, A. Oliva-Teles, and H. Peres. "Soybean Meal Replacement by Corn Distillers' Dried Grains with Solubles (DDGS) and Exogenous Non-Starch Polysaccharidases Supplementation in Diets for Gilthead Seabream (Sparus Aurata) Juveniles." Aquaculture 500 (2019): 435–42. https://doi.org/10.1016/j.aquaculture.2018.10.035.

Dooley, Frank J. "Market Analysis for Dried Distillers' Grain in Indiana." AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.46340.

Dooley, Frank J. "U.S. Market Potential For Dried Distillers' Grain With Solubles." AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.46342.

El-Deek, Ahmed A., Ahmed A. A. Abdel-Wareth, Mona Osman, Mohammed El-Shafey, Ayman M. Khalifah, Alaa E. Elkomy, and Jayant Lohakare. "Alternative Feed Ingredients in the Finisher Diets for Sustainable Broiler Production." Scientific Reports 10, no. 1 (October 20, 2020): 17743. https://doi.org/10.1038/s41598-020-74950-9.

Elobeid, Amani E., Simla Tokgoz, Dermot J. Hayes, Bruce A. Babcock, and Chad E. Hart. "The Long-Run Impact of Corn-Based Ethanol on the Grain, Oilseed, and Livestock Sectors: A Preliminary Assessment." AgEcon Search, 2006. https://doi.org/10.22004/ag.econ.18290.

El-Rahman, H. H. A., Y. A. A. El-Nomeary, M. M. Shoukry, and M. I. Mohamed. "Effect of Substitution of Cotton Seed Meal by Two Various Protein Sources on Productive Performance of Fattening Crossbred Calves." American-Eurasian Journal of Agricultural & Environmental Sciences 14, no. 9 (2014): 811–16.

Etienne, Xiaoli L., and Linwood A. Hoffman. "Price Discovery and Risk Management in the U.S. Distiller's Grain Markets." AgEcon Search, 2015. https://doi.org/10.22004/ag.econ.205125.

Etienne, Xiaoli L., Andres Trujillo-Barrera, and Linwood A. Hoffman. "Volatility Spillover and Time-Varying Conditional Correlation between DDGS, Corn, and Soybean Meal Markets." Agricultural and Resource Economics Review 46, no. 3 (December 2017): 529–54.

Fabiosa, Jacinto F. "Distillers' Dried Grain Product Innovation and Its Impact on Adoption, Inclusion, Substitution, and Displacement Rates in a Finishing Hog Ration." AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.43556.

Fabiosa, Jacinto F. "Land-Use Credits to Corn Ethanol: Accounting for Distillers' Dried Grains with Solubles as a Feed Substitute in Swine Rations." AgEcon Search, 2009. https://doi.org/10.22004/ag.econ.48854.

Fabiosa, Jacinto F. "Not All DDGS Are Created Equal: Nutrient-Profile-Based Pricing to Incentivize Quality." AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.44755.

Fabiosa, Jacinto F. "The Impact of the Crude Oil Price on the Livestock Sector under a Regime of Integrated Energy and Grain Markets." AgEcon Search, 2009. https://doi.org/10.22004/ag.econ.49240.

Fabiosa, Jacinto F., James M. Hansen, Holger Matthey, Suwen Pan, and Francis C. Tuan. "Assessing China's Potential Import Demand for Distillers' Dried Grain: Implications for Grain Trade." AgEcon Search, 2009. https://doi.org/10.22004/ag.econ.55553.

Ferris, John N. "Impacts of the Federal Energy Acts and Other Influences on Prices of Agricultural Commodities and Food." AgEcon Search, 2013. https://doi.org/10.22004/ag.econ.150245.

Ferris, John N. "Potential for Corn Oil Extracted from Distillers'' Dried Grain and Solubles as a Feedstock for Biodiesel." AgEcon Search, 2011. https://doi.org/10.22004/ag.econ.115632.

Gadberry, M. S., P. A. Beck, M. Morgan, D. Hubbell, J. Butterbaugh, and B. Rudolph. "Effect of Dried Distillers' Grains Supplementation on Calves Grazing Bermudagrass Pasture or Fed Low-Quality Hay." Professional Animal Scientist 26, no. 4 (2010): 347–55.

Gertner, Daniel, and Elliott Dennis. "Distillers' Grains Pre, During, and Post COVID-19: Ongoing Recovery and Structural Demand Implications." AgEcon Search, October 7, 2020. https://doi.org/10.22004/ag.econ.309757.

Gertner, Daniel, and Elliott Dennis. "Impact of COVID-19 on Demand for Distillers' Grains from Impact of COVID-19 on Demand for Distillers' Grains from Livestock Operations Livestock Operations." AgEcon Search, May 27, 2020. https://doi.org/10.22004/ag.econ.309740.

Good, Darrel. "Export Progress for Corn, Ethanol, and Distillers'' Grains." Farmdoc Daily 6 (May 9, 2016). https://doi.org/10.22004/ag.econ.283270.

Good, Darrel. "Review of Export Progress for Corn, Ethanol, and Distillers' Grains." Farmdoc Daily 5 (May 11, 2015). https://doi.org/10.22004/ag.econ.283119.

Good, Darrel. "Understanding the Pricing of Distillers'' Grain Solubles." Farmdoc Daily 3 (July 12, 2013). https://doi.org/10.22004/ag.econ.282372.

Good, Darrel. "Weekly Outlook: Exports of Ethanol and Distillers'' Grains Remain Strong." Farmdoc Daily 6 (February 8, 2016). https://doi.org/10.22004/ag.econ.232884.

Grings, E.E., R.E. Roffler, and D.P. Deitelhoff. "Responses of Dairy Cows to Additions of Distillers' Dried Grains with Solubles in Alfalfa-Based Diets." Journal of Dairy Science 75, no. 7 (1992): 1946–53. https://doi.org/10.3168/jds.s0022-0302(92)77954-5.

Harris, E. K., E. P. Berg, T. C. Gilbery, A. N. Lepper, H. H. Stein, and D. J. Newman. "Effects of Replacing Soybean Meal with Pea Chips and Distillers' Dried Grains with Solubles in Diets Fed to Growing-Finishing Pigs on Growth Performance, Carcass Quality, and Pork Palatability." Professional Animal Scientist 28, no. 1 (2012): 1–10.

Hoffman, Linwood A., and Erik Dohlman. "Market Potential for U.S. Distillers'' Grains Exceeds Likely Supply Growth." Amber Waves, 2011, 3–3. https://doi.org/10.22004/ag.econ.120967.

Hofstrand, Don. "Tracking Ethanol Profitability: Ag Decision Maker." Tracking Ethanol Profitability. Iowa State University, September 14, 2021. https://www.extension.iastate.edu/agdm/energy/html/d1-10.html.

Hubbs, Todd, Bhawna Bista, Paul Preckel, and Brian Richert. "Valuing Dried Distillers' Grains with Solubles for Use in Swine Diets." Journal of the ASFMRA (American Society of Farm Managers and Rural Appraisers) 2009 (2009): 188–200. https://doi.org/10.22004/ag.econ.189865.

Hubbs, Todd. "Export Potential for Corn, Ethanol, and Distillers' Grains." Farmdoc Daily 8 (May 29, 2018). https://doi.org/10.22004/ag.econ.282891.

Irwin, Scott, and Darrel Good. "Ethanol Production Profits: The Risk from Lower Prices of Distillers' Grains." Farmdoc Daily 5 (March 12, 2015). https://doi.org/10.22004/ag.econ.201330.

Irwin, Scott. 2020. *2019 Ethanol Production Profits: Just How Bad Was It?* January 29. https://farmdocdaily.illinois.edu/2020/01/2019-ethanol-production-profits-just-how-bad-was-it.html.

Jenkins, Karla H. 2016. *Understanding the Difference between Corn and Corn Distillers' Grains as Energy Supplements for Pasture Cattle.* August. https://beef.unl.edu/difference-between-corn-and-corn-distillers'-grains-as-energy-supplements-for-pasture-cattle.

Jewison, Michael, and H. Frederick Gale. "A Market for U.S. Distillers' Dried Grains Emerges in China." Amber Waves, no. 4 (2012). https://doi.org/10.22004/ag.econ.142408.

Johnson, Matthew, T. Edward Yu, Andrew P. Griffith, Kimberly L. Jensen, and Seong-Hoon Cho. "Regional Dynamic Price Relationships between Distillers' Dried Grains and Feed Grains." AgEcon Search, 2015. https://doi.org/10.22004/ag.econ.196900.

Jones, Crystal, Glynn T. Tonsor, J. Roy Black, and Steven R. Rust. "Economically Optimal Distiller Grain Inclusion in Beef Feedlot Rations: Recognition of Omitted Factors." AgEcon Search, 2007. https://doi.org/10.22004/ag.econ.37574.

Klopfenstein, T. J., G. E. Erickson, and V. R. Bremer. "BOARD-INVITED REVIEW: Use of Distillers' by-Products in the Beef Cattle Feeding Industry." Journal of Animal Science 86, no. 5 (May 2008): 1223–31. https://doi.org/10.2527/jas.2007-0550.

Kubas, T. A., and J. D. Firman. "Effects of Yellow Grease Addition to Broiler Rations Containing DDGS with Different Fat Contents." International Journal of Poultry Science 13, no. 8 (2014): 437–41.

Kubas, T. A., and J. D. Firman. "Effects of Yellow Grease Addition to Tom Turkey Rations Containing DDGS with Different Fat Contents." International Journal of Poultry Science 14, no. 3 (2015): 127–34.

Kumar, Ajay, Yasar Demirel, David D. Jones, and Milford A. Hanna. "Optimization and Economic Evaluation of Industrial Gas Production and Combined Heat and Power Generation from Gasification of Corn Stover and Distillers' Grains." Bioresource Technology 101, no. 10 (May 2010): 3696–3701. https://doi.org/10.1016/j.biortech.2009.12.103.

Kurambhatti, Chinmay, Jae Won Lee, Yong-Su Jin, Ankita Juneja, Deepak Kumar, Kent D. Rausch, M. E. Tumbleson, Sadia Bekal, and Vijay Singh. "Process Design and Techno-Economic Analysis of 2'-Fucosyllactose Enriched Distiller's Dried Grains with Solubles Production in Dry Grind Ethanol Process Using Genetically Engineered Saccharomyces Cerevisiae." Bioresource Technology 341 (December 2021): 125919. https://doi.org/10.1016/j.biortech.2021.125919.

Liu, KeShun. "Chemical Composition of Distillers' Grains, a Review." Journal of Agricultural and Food Chemistry 59, no. 5 (2011): 1508–26. https://doi.org/10.1021/jf103512z.

Lowe, J. K., C. N. Boyer, A. P. Griffith, J. C. Waller, G. E. Bates, P. D. Keyser, J. A. Larson, and E. Holcomb. “The Cost of Feeding Bred Dairy Heifers on Native Warm-Season Grasses and Harvested Feedstuffs.” Journal of Dairy Science 99, no. 1 (January 2016): 634–43. https://doi.org/10.3168/jds.2015-9475.

Markham, Steve. “Distillers’ Dried Grains and their Impact on Corn, Soymeal, and Livestock Markets.” AgEcon Search, 2005. https://doi.org/10.22004/ag.econ.32831.

Masa’deh, M. K., S. E. Purdum, and K. J. Hanford. “Distillers’ Dried Grains with Solubles in Pullet Diets.” Journal of Applied Poultry Research 21, no. 3 (2012): 531–39. https://doi.org/10.3382/japr.2011-00431.

Morgan, Tyne. 2020. *Ethanol Plants Could Soon Start Producing for DDGs, Not Ethanol.* March 27. https://www.drovers.com/article/ethanol-plants-could-soon-start-producing-ddgs-not-ethanol.

Murguia, Juan M., and John D. Lawrence. “Comparing Different Models to Cross Hedge Distillers’ Grains in Iowa: Is It Necessary to Include Energy Derivatives?” AgEcon Search, 2010. https://doi.org/10.22004/ag.econ.285319.

Nunez, A. J. C., T. L. Felix, S. C. Loerch, and J. P. Schoonmaker. “Effect of Dried Distillers’ Grains with Solubles or Corn in Growing Cattle Diets, Followed by a Corn-Based Finishing Diet, on Performance of Feedlot Cattle.” Animal Feed Science and Technology 207 (2015): 267–73. https://doi.org/10.1016/j.anifeedsci.2015.06.010.

Nuttelman, Brandon L., Will A. Griffin, Josh R. Benton, Galen E. Erickson, and Terry J. Klopfenstein. 2011. *Comparing Dry, Wet, or Modified Distillers’ Grains Plus Solubles on Feedlot Cattle Performance.* Lincoln, Nebraska: The Board of Regents of the University of Nebraska.

O’Brien, S., J. A. Koziel, C. Banik, and A. Bialowiec. “Synergy of Thermochemical Treatment of Dried Distillers’ Grains with Solubles with Bioethanol Production for Increased Sustainability and Profitability.” Energies 13, no. 17 (2020). https://doi.org/10.3390/en13174528.

Oliveira, K. R. B., J. G. Segura, B. A. Oliveira, A. C. L. Medeiros, R. D. Zimba, and E. M. M. Viegas. “Distillers’ Dried Grains with Soluble in Diets for Pacu, Piaractus Mesopotamicus Juveniles: Growth Performance, Feed Utilization, Economic Viability, and Phosphorus Release.” Animal Feed Science and Technology 262 (2020). https://doi.org/10.1016/j.anifeedsci.2020.114393.

Olson, David W., and Thomas Capehart. “Dried Distillers’ Grains (DDGs) Have Emerged as a Key Ethanol Coproduct.” Amber Waves:The Economics of Food, Farming, Natural Resources, and Rural America 2019, no. 9 (October 1, 2019). https://doi.org/10.22004/ag.econ.302876.

Paine, J. M., C. K. Jones, J. Lattimer, and A. R. Crane. “Impact of Including Distillers’ Dried Grains with Solubles at Expense of Soybean Meal on Boer-Influenced Goat Growth Performance.” Translational Animal Science 2, no. Suppl 1 (September 2018): S93. https://doi.org/10.1093/tas/txy074.

Perkis, David, Wallace Tyner, and Rhys Dale. “Economic Analysis of a Modified Dry Grind Ethanol Process with Recycle of Pretreated and Enzymatically Hydrolyzed Distillers’ Grains.” Bioresource Technology 99, no. 12 (August 2008): 5243–49. https://doi.org/10.1016/j.biortech.2007.09.041.

Ranathunga, S. D., K. F. Kalscheur, A. R. Hippen, and D. J. Schingoethe. “Replacement of Starch from Corn with Nonforage Fiber from Distillers’ Grains and Soyhulls in Diets of Lactating Dairy Cows.” Journal of Dairy Science 93, no. 3 (March 2010): 1086–97. https://doi.org/10.3168/jds.2009-2332.

Rausch, Kent D., Ronald L. Belyea, Vijay Singh, and M. E. Tumbleson. “Corn Processing Co-products from Ethanol Production.” AgEcon Search, 2007. https://doi.org/10.22004/ag.econ.48775.

Rew, H. J., M. H. Shin, H. R. Lee, C. Jo, S. K. Lee, and B. D. Lee. “Effects of Corn Distiller’s Dried Grains with Solubles on Production Performance and Economics in Laying Hens.” Korean Journal of Poultry Science 36, no. 1 (2009): 15–21.

Rodriguez, B., Y. Vazquez, M. Valdivie, and M. Herrera. “Evaluation of Maize Distillers’ Dried Grains with Solubles in the Feeding of White Leghorn L-33 Laying Hens.” Cuban Journal of Agricultural Science 50, no. 4 (2016): 543–48.

Rodríguez, Luis F., Changying Li, Madhu Khanna, Aslihan D. Spaulding, Tao Lin, and Steven R. Eckhoff. “An Engineering and Economic Evaluation of Quick Germ-Quick Fiber Process for Dry-Grind Ethanol Facilities: Analysis.” Bioresource Technology 101, no. 14 (July 2010): 5282–89. https://doi.org/10.1016/j.biortech.2010.01.140.

Rosentrater, K.A., and E. Kongar. “Costs of Pelleting to Enhance the Logistics of Distillers’ Grains Shipping,” 137–47, 2009. https://www.scopus.com/inward/record.uri?eid=2-s2.0-79955623431&partnerID=40&md5=5d56e686123cdd8cb1834ba23844b3c4.

Rosentrater, Kurt A. “Expanding the Role of Systems Modeling: Considering By-product Generation from Biofuel Production.” Ecology and Society 11, no. 1 (2006). https://www.jstor.org/stable/26267824.

Sándor, Z.J., N. Révész, D. Varga, F. Tóth, L. Ardó, and G. Gyalog. “Nutritional and Economic Benefits of Using DDGS (Distiller’ Dried Grains Soluble) as Feed Ingredient in Common Carp Semi-Intensive Pond Culture.” Aquaculture Reports 21 (2021). https://doi.org/10.1016/j.aqrep.2021.100819.

Schmit, T. M., R. N. Boisvert, D. Enahoro, and L. Chase. “Dairy Farm Management Adjustments to Biofuels-Induced Changes in Agricultural Markets.” Working Paper - Department of Applied Economics and Management, Cornell University, no. WP 2008-16 (2008): 31 pp.

Schmit, T. M., R. N. Boisvert, D. Enahoro, and L. E. Chase. “Optimal Dairy Farm Adjustments to Increased Utilization of Corn Distillers’ Dried Grains with Solubles.” Journal of Dairy Science 92, no. 12 (December 2009): 6105–15. https://doi.org/10.3168/jds.2009-2213.

Schmit, Todd M., Leslie J. Verteramo, and William G. Tomek. “Implications of Growing Biofuels Demands on Northeast Livestock Feed Costs.” AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.37595.

Sesmero, Juan P., Richard K. Perrin, and Lilyan E. Fulginiti. “A Variable Cost Function for Corn Ethanol Plants in the Midwest.” Canadian Journal of Agricultural Economics/Revue Canadienne d’agroeconomie 64, no. 3 (September 1, 2016): 565–87. https://doi.org/10.1111/cjag.12097.

Shipman, Frank. “Distilled Spirit.” Encyclopædia Britannica. Encyclopædia Britannica, inc., September 19, 1998. https://www.britannica.com/topic/distilled-spirit.

Sihag, Sajjan, Z. S. Sihag, Jyoti Shunthwal, and Sushil Kumar. “Efficacy of Dried Distiller’s Grains with Solubles as a Replacement for Soybean Meal in the Rations of Growing Goats.” Indian Journal of Animal Nutrition 34, no. 4 (2017): 408–13. https://doi.org/10.5958/2231-6744.2017.00065.2.

Skinner, Stewart, Alfons Weersink, and Cornelius F. deLange. “Impact of Dried Distillers’ Grains with Solubles (DDGS) on Ration and Fertilizer Costs of Swine Farmers.” Canadian Journal of Agricultural Economics 60, no. 3 (September 2012): 335–56.

Soliman, A. Z. M., F. G. Ahmed, M. A. F. El-Manylawi, and F. T. F. Abd-El-Ghany. “Effect of Corn Distiller’s Dried Grains with Solubles (DDGS) on Growing Rabbit Performance.” Egyptian Journal of Rabbit Science 20, no. 1 (2010): 31–48.

Springer, N. P., and J. Schmitt. “The Price of By-products: Distinguishing Co-products from Waste Using the Rectangular Choice-of-Technologies Model.” Resources, Conservation and Recycling 138 (2018): 231–37. https://doi.org/10.1016/j.resconrec.2018.07.034.

Srinivasan, R., B. Lumpkins, E. Kim, L. Fuller, and J. Jordan. “Effect of Fiber Removal from Ground Corn, Distillers’ Dried Grains with Solubles, and Soybean Meal Using the Elusieve Process on Broiler Performance and Processing Yield.” Journal of Applied Poultry Research 22, no. 2 (2013): 177–89. https://doi.org/10.3382/japr.2012-00544.

Srinivasan, R., V. Singh, R. L. Belyea, K. D. Rausch, R. A. Moreau, and M. E. Tumbleson. “Economics of Fiber Separation from Distillers’ Dried Grains with Solubles (DDGS) Using Sieving and Elutriation.” Cereal Chemistry 83, no. 4 (2006): 324–30. https://doi.org/10.1094/CC-83-0324.

Stockton, Matt. “The Economics of Dry Distillers’ Grain as a Creep Feed for Yearling Cattle.” AgEcon Search, November 8, 2006. https://doi.org/10.22004/ag.econ.306478.

Stockton, Matthew C., and Leslie Aaron Stalker. “The Economics of Bunk Feeding Distillers’ Grains to Feeder Steers on Pasture.” AgEcon Search, March 1, 2012. https://doi.org/10.22004/ag.econ.306751.

Strydom, D. B., F. Meyer, P. R. Taljaard, and B. J. Willemse. “The Impact of Maize-Based Ethanol Production on the Competitiveness of the South African Animal Feed Industry.” Agrekon 49, no. 3 (September 2010): 267–92.

Strydom, D. B., P. R. Taljaard, and B. J. Willemse. “Ethanol Blending Policies and the South African Animal Feed Industry.” Agrekon 49, no. 2 (June 2010): 255–65.

Suh, Dong Hee, and Charles B. Moss. “Decompositions of Corn Price Effects: Implications for Feed Grain Demand and Livestock Supply.” Agricultural Economics 48, no. 4 (July 2017): 491–500.

Suh, Dong Hee, and Charles B. Moss. “Dynamic Adjustment of Demand for Distiller’s Grain: Implications for Feed and Livestock Markets.” AgEcon Search, 2014. https://doi.org/10.22004/ag.econ.162454.

Suh, Dong Hee, and Charles B. Moss. “Dynamic Interfeed Substitution: Implications for Incorporating Ethanol By-products into Feedlot Rations.” Applied Economics 48, no. 19–21 (April 2016): 1893–1901.

Taheripour, Farzad, Thomas W. Hertel, and Wallace E. Tyner. “Implications of Biofuels Mandates for the Global Livestock Industry: A Computable General Equilibrium Analysis.” Agricultural Economics 42, no. 3 (May 1, 2011): 325–42. https://doi.org/10.1111/j.1574-0862.2010.00517.x.

Tejeda, Hernan A. “Time-Varying Price Interactions and Risk Management in Livestock Feed Markets – Determining the Ethanol Surge Effect.” AgEcon Search, 2012. https://doi.org/10.22004/ag.econ.124956.

Thaeripour, Farzad, Thomas W. Hertel, Wallace E. Tyner, Jayson F. Beckman, and Dileep K. Birur. “Biofuels and Their By-Products: Global Economic and Environmental Implications.” AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.6452.

Tidwell, J. H., S. D. Coyle, A. VanArnum, C. Weibel, and S. Harkins. “Growth, Survival, and Body Composition of Cage-Cultured Nile Tilapia Oreochromis Niloticus Fed Pelleted and Unpelleted Distillers’ Grains with Solubles in Polyculture with Freshwater Prawn Macrobrachium Rosenbergii.” Journal of the World Aquaculture Society 31, no. 4 (2000): 627–31. https://doi.org/10.1111/j.1749-7345.2000.tb00912.x.

Tokgoz, Simla. “The Impact of Energy Markets on the EU Agricultural Sector.” AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.44241.

Tonsor, Glynn T. “Hedging in Presence of Market Access Risk.” AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.37621.

Troyer, B. C., H. L. Greenwell, A. K. Watson, J. C. MacDonald, and K. H. Wilke. “Relative Value of Field Pea Supplementation Compared with Distillers’ Grains for Growing Cattle Grazing Crested Wheatgrass.” Applied Animal Science 36, no. 5 (2020): 615–21. https://doi.org/10.15232/aas.2020-02026.

USDA-NASS. USDA/NASS QuickStats Ad-hoc Query Tool, 2021. https://quickstats.nass.usda.gov/.

United States Department of Agriculture National Institute of Food and Agriculture (USDA NIFA). “What Are Corn Condensed Distillers’ Solubles?” Beef Cattle. Extension Foundation, September 3, 2019. https://beef-cattle.extension.org/what-are-corn-condensed-distillers’-solubles/.

Van Winkle, Tyler W., and Ted C. Schroeder. “Spatial Price Discovery, Dynamics, and Leadership in Evolving Distiller’s Grain Markets.” AgEcon Search, 2008. https://doi.org/10.22004/ag.econ.6933.

Voegele, Erin. 2020. *Pacific Ethanol focuses on high-quality alcohol, co-products.* August 12. http://ethanolproducer.com/articles/17455/pacific-ethanol-focuses-on-high-quality-alcohol-co-products.

Wang, L. J., M. A. Hanna, C. L. Weller, and D. D. Jones. “Technical and Economical Analyses of Combined Heat and Power Generation from Distillers’ Grains and Corn Stover in Ethanol Plants.” Energy Conversion and Management 50, no. 7 (2009): 1704–13. https://doi.org/10.1016/j.enconman.2009.03.025.

Wang, Michael, Hong Huo, and Salil Arora. “Methods of Dealing with Co-products of Biofuels in Life-Cycle Analysis and Consequent Results within the U.S. Context.” Energy Policy 39, no. 10 (October 2011): 5726–36.

Weseen, Simon, Jill Hobbs, and William A. Kerr. “Reducing Hold-up Risks in Ethanol Supply Chains: A Transaction Cost Perspective.” International Food and Agribusiness Management Review 17, no. 2 (May 1, 2014): 83–106.

Wood, C., K.A. Rosentrater, and K. Muthukumarappan. “Techno-Economic Modeling of Co-product Processing in a Corn Based Ethanol Plant in 2012,” 2:1185–1214, 2013. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84881649811&partnerID=40&md5=a6638ebe6eb0f0cb71f6c4a59b441449.

Wood, C., P. Aubert, K.A. Rosentrater, and K. Muthukumarappan. “Techno-Economic Modeling of a Corn Based Ethanol Plant in 2011,” 3:1812–46, 2012. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84871759832&partnerID=40&md5=0c279c3805471c553229d04f21067e40.

Wright, Andrew P., Donna Mitchell, and Darren Hudson. “An Estimation of the Demand for Dried Distiller Grains by the Cattle Feeding Industry: A Combination of Survey Methods and Market Projections.” AgEcon Search, 2012. https://doi.org/10.22004/ag.econ.119947.

Wu, Felicia, and Gary P. Munkvold. “Mycotoxins in Ethanol Co-products: Modeling Economic Impacts on the Livestock Industry and Management Strategies.” Journal of Agricultural and Food Chemistry 56, no. 11 (June 11, 2008): 3900–3911. https://doi.org/10.1021/jf072697e.

Xiang, Z. Y., and T. Runge. “Coproduction of Feed and Furfural from Dried Distillers’ Grains to Improve Corn Ethanol Profitability.” Industrial Crops and Products 55 (2014): 207–16. https://doi.org/10.1016/j.indcrop.2014.02.025.

Yildiz, E., N. Todorov, and K. Nedelkov. “Comparison of Different Dietary Protein Sources for Dairy Cows.” Bulgarian Journal of Agricultural Science 21, no. 1 (2015): 199–208.

Yu, Tun-Hsiang (Edward), and Chad E. Hart. “Impact of Biofuel Industry Expansion on Grain Utilization and Distribution: Preliminary Results of Iowa Grain and Biofuel Survey.” AgEcon Search, January 16, 2009. https://doi.org/10.22004/ag.econ.46847.

Zhang, W., and K.A. Rosentrater. “Techno-Economic Analysis (TEA) of Using a Destoner to Fractionate Distillers’ Dried Grains with Solubles (DDGS),” 7:5239–57, 2014. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84911478106&partnerID=40&md5=ca24c11f8cd3672c68357558f45e2115.

Supporting Figures

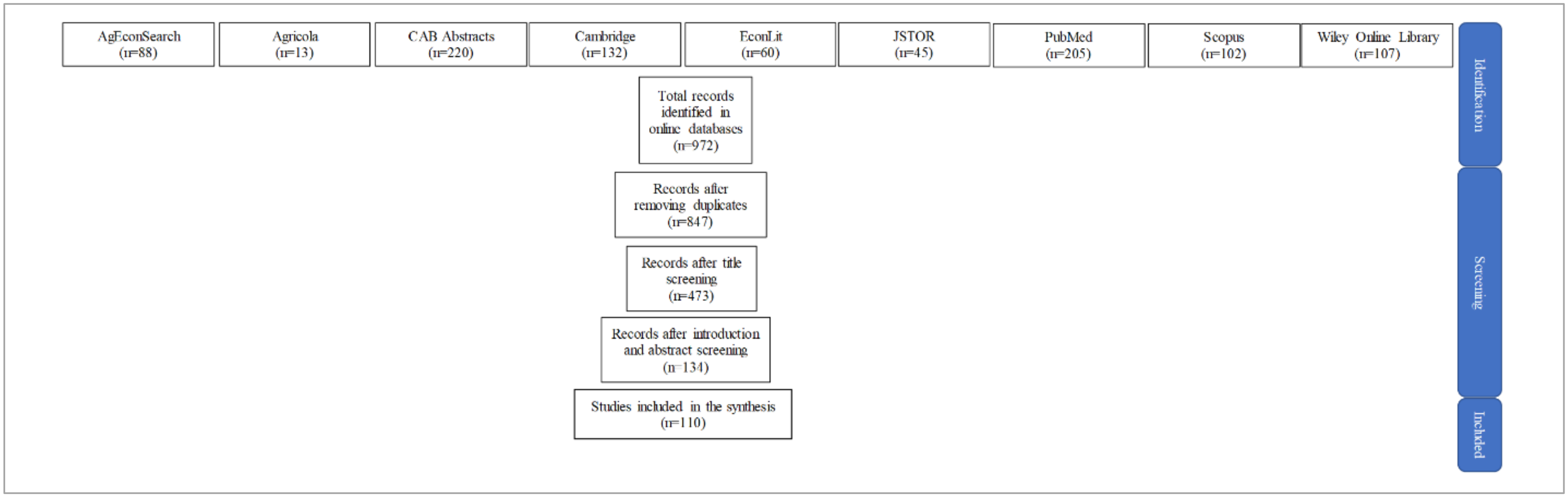

Figure 1: Search, Filtering, and Selection Process for Articles Used in the Synthesis Review
Source: Authors' compilation

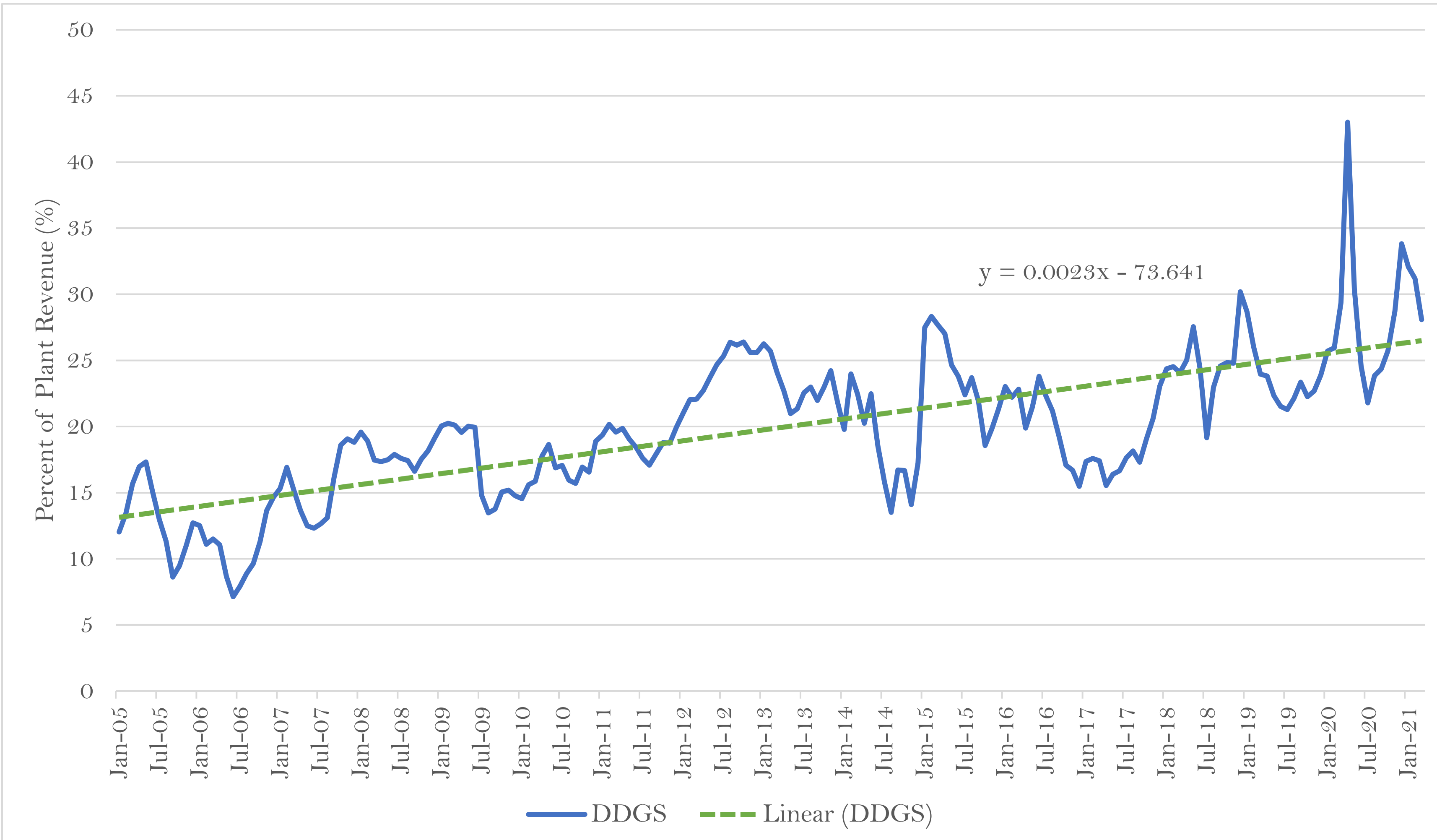

Figure 2. Monthly DDGS Percent of Ethanol Plant Revenue, 2005-2021

Source: Authors' calculations using Iowa Ethanol Plant Profitability Model (https://www.extension.iastate.edu/agdm/energy/html/d1-10.html

Supporting Tables

Table 1. Summary of Literature Review Results.

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Markham (2005)	2005	USA	DDGS	Corn, soymeal, livestock	Domestic	No	No
Elobeid et al. (2006)	2006	USA	DDGS, MWDG	Grain, oilseed, livestock	Domestic	Yes	Yes
Rosentrater (2006)	2006	USA	DDGS	Ethanol	Domestic	Yes	Yes
Srinivasan et al. (2006)	2006	United States	DDGS	Fiber	Domestic	Yes	Yes
Stockton (2006)	2006	USA	DDGS	Cattle	Domestic	Yes	Yes
Jones et al. (2007)	2007	USA	DDGS, MWDG, WDG	Cattle	Domestic	Yes	Yes
Rausch et al. (2007)	2007	USA	DDGS	Ethanol	Domestic	Yes	Yes
Tidwell et al. (2007)	2007	USA	DDGS	Tilapia, catfish diet	Domestic	Yes	Yes
Babcock et al. (2008)	2008	Global	DDGS, MWDG, WDG	Livestock, poultry	Domestic & Export	Yes	No
Buckner et al. (2008)	2008	USA	DDGS	Beef cattle, corn	Domestic	Yes	Yes
Clemens and Babcock (2008)	2008	USA	DDGS, MWDG	Cattle	Domestic	Yes	Yes
Dooley (2008)	2008	USA	DDGS	Livestock	Domestic	No	No
Dooley (2008)	2008	USA	DDGS, MWDG, WDG	Dairy, hogs, beef, poultry	Domestic	No	No
Fabiosa (2008)	2008	USA	DDGS, MWDG, WDG	Hogs	Domestic	No	No
Fabiosa (2008)	2008	USA	DDGS	Hogs	Domestic	No	No
Klopfenstein et al. (2008)	2008	USA	DDGS, WDG	Beef cattle, corn	Domestic	No	Yes

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Perkis et al. (2008)	2008	United States	Hydrolyzed Distillers' Grains	Ethanol	Domestic	Yes	Yes
Schmit et al. (2008)	2008	USA	DDGS	Corn, soybean meal, livestock	Domestic	Yes	Yes
Schmit et al. (2008)	2008	USA	DDGS	Dairy cattle, corn, soybean meal	Domestic	Yes	Yes
Taheripour et al. (2008)	2008	USA, EU, Brazil	DDGS	Cereal grains, oilseeds	Domestic & Export	Yes	Yes
Tonsor (2008)	2008	USA	DDGS, WDG	Cattle, soybean oil, winter wheat	Domestic	Yes	Yes
Van Winkle and Schroeder (2008)	2008	USA	DDGS	Corn, soybean meal	Domestic	Yes	Yes
Wu and Munkvold (2008)	2008	United States	DDGS	Corn, swine	Domestic	Yes	Yes
Brinker et al. (2009)	2009	USA	DDGS, Corn Oil	Corn, soybean meal	Domestic	Yes	Yes
Fabiosa (2009)	2009	USA	DDGS	Hogs	Domestic	No	No
Fabiosa (2009)	2009	USA	DDGS	Crude oil, livestock	Domestic	Yes	Yes
Fabiosa et al. (2009)	2009	China	DDGS	Livestock	Export	Yes	Yes
Hubbs et al. (2009)	2009	USA	DDGS	Hogs	Domestic	No	No
Roberts (2009)	2009	USA	DDGS	Laying Hens	Domestic	Yes	Yes
Rosentrater and Kongar (2009)	2009	USA	Pelletized DDGS	Ethanol	Domestic	Yes	Yes
Schmit et al. (2009)	2009	United States	DDGS	Dairy cattle, corn, soybean meal	Domestic	Yes	Yes
Tokgoz (2009)	2009	EU	DDGS	Crude oil, grain, ethanol	Export	No	No

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Wang et al. (2009)	2009	United States	DDGS	Corn stover, industrial gas	Domestic	Yes	Yes
Yu and Hart (2009)	2009	USA	DDGS	Corn	Domestic	Yes	Yes
Bailey and Kallenbach (2010)	2010	USA	DDGS	Beef cattle, hay	Domestic	Yes	Yes
Beckman et al. (2010)	2010	USA	DDGS	Corn, soybeans	Domestic	Yes	Yes
Gadberry et al. (2010)	2010	USA	DDGS	Beef cattle, hay	Domestic	Yes	Yes
Hoffman and Dohlman (2010)	2010	USA	DDGS	Livestock, poultry	Domestic	No	No
Kumar et al. (2010)	2010	United States	DDGS	Corn stover, industrial gas	Domestic	Yes	Yes
Murguia and Lawrence (2010)	2010	USA	DDGS	Corn, soybean meal	Domestic	Yes	Yes
Ranathunga et al. (2010)	2010	United States	DDGS	Dairy cattle, soyhulls, corn	Domestic	Yes	Yes
Rodriguez et al. (2010)	2010	USA	DDGS	Ethanol	Domestic	Yes	Yes
Strydom et al. (2010)	2010	South Africa	DDGS	Livestock, maize	Export	Yes	Yes
Strydom et al. (2010)	2010	South Africa	DDGS	Livestock, ethanol, maize	Export	Yes	Yes
Taheripour et al. (2010)	2010	Global	DDGS	Livestock	Domestic & Export	Yes	Yes
Bremer et al. (2011)	2011	United States	DDGS, MWDG, WDG	Corn, dairy cattle, beef cattle, hogs	Domestic	Yes	Yes
Ferris (2011)	2011	USA	DDGS	Biodiesel	Domestic	Yes	Yes

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Wang et al. (2011)	2011	USA	DDGS	Ethanol	Domestic	Yes	Yes
Wood et al. (2011)	2011	United States	DDGS, WDG	Ethanol	Domestic	Yes	Yes
Abou-Zied et al. (2012)	2012	Egypt	DDGS	Tilapia, fish meal	Export	Yes	Yes
Harris et al. (2012)	2012	USA	DDGS	Hogs, soybean meal, pea chips	Domestic	Yes	Yes
Jewison and Gale (2012)	2012	USA Export to China	DDGS, MWDG, WDG	Livestock producers	Export	No	No
Masa'deh et al. (2012)	2012	USA	DDGS	Pullets, soybean meal, corn	Domestic	Yes	Yes
Skinner et al. (2012)	2012	USA	DDGS	Corn, hogs	Domestic	Yes	Yes
Stockton and Stalker (2012)	2012	USA	DDGS	Cattle	Domestic	No	No
Tejada (2012)	2012	USA	DDGS	Corn, sorghum, soybean meal	Domestic	No	No
Wood et al. (2012)	2012	United States	DDGS, WDG	Ethanol	Domestic	Yes	Yes
Wright et al. (2012)	2012	USA	DDGS	Cattle	Domestic	Yes	Yes
Youssef et al. (2012)	2012	Egypt	DDGS	Rabbits	Export	Yes	Yes
Conley (2013)	2013	USA	DDGS	Ethanol, corn	Domestic	Yes	Yes
Ferris (2013)	2013	USA	DDGS	Grains, oilseeds, biodiesel	Domestic	Yes	Yes
Irwin and Good (2013)	2013	USA	DDGS, MWDG, WDG	Corn	Domestic	No	No
Srinivasan et al. (2013)	2013	United States	DDGS	Broilers	Domestic	Yes	Yes

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Coble et al. (2014)	2014	USA	DDGS	Hogs	Domestic	Yes	Yes
El-Rahman et al. (2014)	2014	Egypt	DDGS	Beef cattle, black cumin seed	Export	Yes	Yes
Kubas and Firman (2014)	2014	USA	DDGS, low/high fat DDGS	Broilers, yellow grease	Domestic	Yes	Yes
Suh and Moss (2014)	2014	USA	DDGS	Livestock	Domestic	Yes	Yes
Weseen et al. (2014)	2014	Canada	DDGS, WDG	Corn, ethanol	Export	Yes	Yes
Zhang and Rosentrater (2014)	2014	United States	DDGS	DDGS nutrients	Domestic	Yes	Yes
El-Hack et al. (2015)	2015	Egypt	DDGS	Laying hens	Export	Yes	Yes
Etienne and Hoffman (2015)	2015	USA	DDGS	Corn, soybean meal	Domestic	Yes	Yes
Good (2015)	2015	USA Export	DDGS	Corn, ethanol	Export	No	No
Irwin and Good (2015)	2015	USA	DDGS, Corn Oil	Ethanol	Domestic	No	No
Johnson et al. (2015)	2015	USA	DDGS	Corn, soybean meal	Domestic	Yes	Yes
Kubas and Firman (2015)	2015	USA	DDGS, low/high fat DDGS	Turkey, yellow grease	Domestic	Yes	Yes
Nunez et al. (2015)	2015	United States	DDGS	Beef cattle, corn	Domestic	Yes	Yes
Yildiz et al. (2015)	2015	Bulgaria	DDGS	Dairy cattle, SFM, rapeseed meal, soybean meal	Export	Yes	Yes
Good (2016)	2016	USA Export	DDGS	Ethanol	Export	No	No

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Good (2016)	2016	USA Export	DDGS	Corn, ethanol	Export	No	No
Lowe II et al. (2016)	2016	United States	DDGS, WDG	Dairy cattle, grasses, corn silage	Domestic	Yes	Yes
Rodriguez et al. (2016)	2016	Cuba	DDGS	Laying hens, soybean	Export	Yes	Yes
Sesmero et al. (2016)	2016	USA	DDGS, MWDG	Ethanol	Domestic	Yes	Yes
Suh and Moss (2016)	2016	USA	DDGS, WDG	Livestock, poultry	Domestic	Yes	Yes
Bekkerman and Tejada (2017)	2017	USA	DDGS	Ethanol, corn	Domestic	Yes	Yes
DeOliveira et al. (2017)	2017	USA Export	DDGS	Ethanol, corn	Export	No	No
Etienne et al. (2017)	2017	USA	DDGS	Corn, soybean meal	Domestic	Yes	Yes
Sajjan et al. (2017)	2017	India	DDGS	Goats, soybean meal	Export	Yes	Yes
Suh and Moss (2017)	2017	USA	DDGS	Corn, cattle, chicken, pork	Domestic	Yes	Yes
Alvaran et al. (2018)	2018	Philippines	DDGS	Dairy buffaloes	Export	Yes	Yes
De Matteis et al. (2018)	2018	Argentina	DDGS	Hogs, corn	Export	Yes	Yes
De Matteis et al. (2018)	2018	USA Export	DDGS, MWDG, WDG	Corn, soybean meal, livestock	Export	Yes	Yes
Hubbs (2018)	2018	USA Export	DDGS	Corn, ethanol	Export	No	No
Paine et al. (2018)	2018	USA	DDGS	Goats, soybean meal	Domestic	Yes	Yes
Springer and Schmitt (2018)	2018	United States	DDGS	Ethanol	Domestic	Yes	Yes

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Changan et al. (2019)	2019	India	WDG	Dairy cattle	Export	Yes	Yes
Dahlgran and Gupta (2019)	2019	USA	DDGS	Corn, ethanol	Domestic	Yes	Yes
DeRose et al. (2019)	2019	United States	WDG	Renewable fuels	Domestic	Yes	Yes
Diogenes et al. (2019)	2019	Portugal	DDGS	Gilthead seabream, soybean meal	Export	Yes	Yes
Olson and Capehart (2019)	2019	USA	DDGS, MWDG	Livestock	Domestic	No	No
Allam et al. (2020)	2020	Egypt	DDGS	Catfish, fish meal	Export	Yes	Yes
El-Deek et al. (2020)	2020	Egypt	DDGS	Broilers, sunflower meal, corn gluten meal, soybean meal	Export	Yes	Yes
Gertner and Dennis (2020)	2020	USA	DDGS	Cattle, meat, oil	Domestic	No	No
Gertner and Dennis (2020)	2020	USA	DDGS	Ethanol, feed substitutes, cattle	Domestic	No	No
O'Brien et al. (2020)	2020	United States	DDGS	Corn stover, industrial gas	Domestic	Yes	Yes
Oliveira et al. (2020)	2020	United States	DDGS	Aquaculture, soybean meal	Domestic	Yes	Yes
Troyer et al. (2020)	2020	United States	DDGS	Beef cattle, field peas, wheatgrass	Domestic	Yes	Yes
Barnharst et al. (2021)	2021	United States	WDG	Mucor indicus, Rhizopus oryzae	Domestic	Yes	Yes
Corassa et al. (2021)	2021	Brazil	DDGS	Hogs	Export	Yes	Yes
Kurambhatti et al. (2021)	2021	United States	DDGS	Hogs	Domestic	Yes	Yes

Table 1. Continued

Study	Year Published	Location	Products Examined	Product	Domestic or Export Market	Peer Reviewed (Y/N)	Economic/Cost-Benefit Analysis
Sandor et al. (2021)	2021	Hungary	DDGS	Carp	Export	Yes	Yes

CHAPTER 2 - THE IMPACT OF COVID-19 ON THE U.S. DISTILLERS' GRAINS MARKET

Abstract:

Distillers' grains play an important role in both maintaining ethanol plant profit margins and providing affordable, nutritious feed to livestock producers. The arrival of COVID-19 to the United States introduced a series of shocks to distillers' grains markets. This paper estimates the magnitudes of and relationships between distillers' grains price changes in response to the COVID-19 market shock using panel fixed effect models. The price fluctuations indicate that livestock producers favored the flexibility provided by dried distillers' grains (DDGS) and, therefore, drove those prices upward more significantly than modified wet distillers' grains (MDGS) and wet distillers' grains (WDGS) prices. Modified and wet distillers' grains price responses, though, were more pronounced in areas whose livestock production industries demanded fixed feeding schedules, such as the dairy industry in Wisconsin. The disparate price responses by grain type and location offer some insight into how markets may respond in the event of future market shocks. Consequently, the results from this analysis can assist both ethanol plants and livestock producers in better preparing for future market shocks.

Introduction

Distillers' grains play an important role in both maintaining ethanol plant profit margins and providing affordable, nutritious feed to livestock feedlots. Distillers' grains are produced as necessary by-products of the fuel ethanol production process, and therefore rely on an input grain – most commonly corn in the United States – and fuel ethanol in their production (USDA ERS 2021). As a result, the primary tenets of the supply structure in the distillers' grains market In the United States are fuel ethanol and corn, while livestock operations in need of feed products comprise the majority of distillers' grains demand structure.

Since distillers' grains are by-products to ethanol production, they rely on corn availability and prices and compete with corn as imperfect substitutes in livestock feed rations. Distillers' grains also compete with other, non-corn substitute feed products in the market, such as soybean meal. The quantity of distillers' grains demanded is, therefore, also influenced by the prices of those substitute feeds. Because of this relationship to the corn, ethanol, and livestock feed markets, distillers' grains are uniquely susceptible to market shocks.

The purpose of this paper is to explore the distillers' grains price response to the COVID-19 shock in the United States, which introduced a series of unique market situations that allowed for disparate responses by location and type of distillers' grain. To our knowledge, no research has yet quantified the price impacts of the COVID-19 market shock to the distillers' grains market. To assist academic and industry participants in processing the impacts of COVID-19 on distillers' grains markets, this paper conducts an analysis of the price impacts of COVID-19 supply and demand shocks in the distillers' grains industry. Results show that price responses to the COVID-19 shock varied by location and type of grain and may be attributed, in part, to the unique market structures of each state. Longer-term implications of the market shocks to the distillers' grains industry introduced by the pandemic are also discussed.

Background on Distillers' Grains

Distillers' grains are produced via the dry-grind ethanol production process. The aim of the dry-grind process is to ferment the highest possible percentage of the corn kernel. The starch in the kernel is converted to ethanol and carbon dioxide, while the remaining protein, lipids, fiber, minerals, and vitamins are converted into co-products – the most common of which are distillers' grains (Liu 2011).

Wet Distillers' Grains (WDG) are the distiller grains that are left over after the dry-grind process and consist of approximately 32.5% dry matter. Ethanol plants often re-add solubles (syrup) to WDG to create wet distillers' grains with solubles (WDGS) and can either sell the resulting grains directly as WDGS or create other distillers' grains through drying WDGS. Modified Wet Distillers' Grains with Solubles (MDGS) have 48.8% dry matter and are created by drying WDGS once and Dried Distillers' Grains with Solubles (DDGS), with 90% dry matter, are created by drying WDGS twice (Stewart and Duggin 2010).

Ethanol plants sell these different types of distillers' grains to livestock feeding operations, since their high protein content accelerates weight gain (Halfman 2020) and offers other favorable nutritional properties.[1] While both MDGS and WDGS offer

[1] For example, using distillers' grains in cattle feeding rations allows operators to use a lower quality forage such as wheat or corn stalks in the ration compared to a corn-based diet that requires a higher quality forage such as grass hay or alfalfa.

slightly higher feeding values than DDGS due to elevated digestibility from higher moisture contents, their moisture contents and weights make them difficult to ship beyond a limited radius (Nuttelman et al. 2011). As a result, WDGS and MDGS are purchased by producers generally within a 100-mile radius of an ethanol plant, whereas DDGS, the most common form of distillers' grains nationally, can be shipped practically anywhere domestically or internationally (DeOliveira et al. 2017). Each type of distillers' grain offers desirable nutritional properties compared to corn due to lower starch content, higher total digestible nutrients, and higher crude protein content (Jenkins 2016). Thus, one tradeoff for livestock feeders is the relative price, on a dry matter basis, of distillers' grains to corn. In markets for which distillers' grains are primarily a protein feed substitute, such as the hog, poultry, and dairy markets, livestock producers may also account for the relative prices of distillers' grains versus soybean meal or other high-protein feeds. For ease of comparison between products and location, those other possible feed substitutes are not accounted for in this analysis. Instead, the focus remains on the relationship between corn and distillers' grains on a dry-matter basis.

Livestock producer demand for distillers' grains has helped ethanol plants market distillers' grains as co-products rather than as by-products. This has assisted in forming a market for distillers' grains that is mostly separate from non-production-related aspects of the ethanol sector (Morgan 2020). This strategy of building a standalone market for distillers' grains has largely been successful. Low crude oil prices and relatively steady corn prices over the past half decade made for a thin and volatile ethanol profit margin. According to estimates from Iowa State University's ethanol plant profitability model, total distillers' grains' percent of plant profit has increased from approximately 10% to

27% in the past 15 years (Hofstrand 2021). Thus, distillers' grains and other co-products of ethanol production have increased ethanol plant profitability, maintained strong plant cash flows[2], and created additional incentives for plants to produce ethanol (Irwin 2020).

COVID-19 and the Distillers' Grains Market

When the first COVID-19 case was officially detected in the United States, the resulting government and industry responses led to shocks in the distillers' grains industry. Stay-at-home orders reduced consumer travel, and demand for gasoline and fuel ethanol fell, causing some ethanol plants to temporarily reduce capacity and/or idle (Snodgrass 2020). Since distillers' grains are co-products of ethanol production, diminished ethanol production decreased the availability of distillers' grains, subsequently raising the price of distillers' grains.

From a distillers' grains demand perspective, homebound consumers demanded higher levels of grocery store food while greatly reducing their food service purchases (Dong and Zeballos 2021). The influx of at-home food demand caused a series of rapidly changing supply and demand conditions along the livestock and meat complex. Meat and livestock products destined for restaurants were repacked and reprocessed for compatibility in grocery stores (Kang and Bunge 2020). Meat packing plants continued to try to process harvest-ready animals, but a growing number of positive cases among plant workers forced idling, reduced plant utilizations, and – in some cases – led to temporary closures (Gallagher 2020). This created a transitory supply surplus situation for livestock

[2] Over the past decade, ethanol plants have developed new value-added products such as pelletized distillers' grains, de-oiled distillers' grains, and corn oil. This has been done to create additional revenue streams and to protect profit margins from adverse price trends in the ethanol market (Voegele 2020).

producers while creating a meat shortage for retailers. Wholesale cutout prices rose, and livestock cash prices dropped, forcing some producers to sell livestock far below breakeven prices. These hiccups created uncertainty in the livestock supply chain, which typically relies heavily on distillers' grains to accelerate weight gain. Many producers responded by slowing their herds' weight gain by – in some cases – limiting the use of distillers' grains in animal feeding diets (Gertner and Dennis, 2020).

Despite a demand structure for distillers' grains that is largely separate from ethanol's, the production of distillers' grains directly depends on the amount of ethanol produced. While the closure of meatpacking plants most directly impacted the demand for distillers' grains, their effect on distillers' grains production was far outweighed by the effect of unprecedentedly low demand for gasoline. Meatpacking plants closed sporadically and for only a few weeks at a time, while global gasoline demand remained low for months (Domonoske 2020). As is evident in Figure 1,the impact of ethanol production slowdowns on co-product production was stark: From March to May of 2020, the production of types of distillers' grains experienced unprecedented reductions. Since data regarding monthly distillers' grains production by state are not publicly available, Figure 1 estimates distillers' grains production in some of the nation's top ethanol-producing states by multiplying national distillers' grains production by each state's percentage of total ethanol operating production in 2018 (Nebraska Energy Office 2018). During the period initial COVID-19 market shock, 73 ethanol plants in the United States idled and 71 more significantly reduced operations to deal with the impact of COVID-19 on ethanol demand (Snodgrass 2020).

Prices for both ethanol and distillers' grains have made significant recoveries since the initial market shocks in the early days of the pandemic. Renewed demand for travel, re-opened restaurants and meatpacking plants, vaccines, and a general adjustment to a world with COVID-19 have contributed to this recovery in distillers' grains prices. The markets in which specific ethanol plants operate also influenced the strength of price recoveries for ethanol and distillers' grains. Still, the mechanisms behind the price movements in the distillers' grains industry have not, to our knowledge, been examined via economic analysis since the arrival of COVID-19 in the United States.

A model was developed that explores the price impacts of COVID-19 on distillers' grains markets in various states. These results are then analyzed by type of distillers' grain, relationship between distillers' grains, and location.

Data

Weekly prices for corn, DDGS, MDGS, and WDGS in Iowa, Nebraska, South Dakota, and Wisconsin were obtained from the Livestock Marketing Information Center (LMIC). These data were reported by USDA's Agricultural Marketing service and compiled by LMIC. The distillers' grains prices represent an aggregation of weekly spot bids that ethanol plants reported in dollars per ton. These bids were reported as free on board (FOB) origin, which means that the buyer is at risk once the seller ships the product. The corn prices represent daily US #2 spot bids at ethanol plants and are reported in dollars per bushel. Volume estimates were not available. The report dates are restricted to between January 2018 to August 2021 to limit periods where prices are not reported. Missing prices are filled in with a linear-interpolation method. The lockdown measures to control the spread of COVID-19 began to occur between February and May 2020 and began to be lifted at various times during the summer and fall of 2020. The data provides significant pre-Covid, Covid, and post-Covid periods, allowing for proper identification of any significant price changes within and between each time frame.

The states Iowa, Nebraska, South Dakota, and Wisconsin were strategically chosen. First, ethanol production is not ubiquitous in every state in the US. This lack of production – or lower levels of production – results in some states having sporadic reporting of prices by USDA-AMS (compiled by LMIC) across all three distillers' grains. The objective of this paper is to examine the impact of COVID-19 on each type of distillers' grains, rather than just DDGS. This created a subset of states containing, in part, Iowa, Nebraska, South Dakota, and Wisconsin. Together, these four states comprise roughly 50% of the nation's ethanol nameplate capacity and operating production, meaning they are some of the primary players in the domestic distillers' grains market (NEO 2018).

Iowa, Nebraska, South Dakota, and Wisconsin are also all located in the Upper Midwest – the center of domestic ethanol and distillers' grains production – while each maintains unique demand structures and livestock industries. These unique demand structures can be used to make an inference about how the different livestock industries were affected by adverse price movements to provide context to the varying price responses by type of grain and location. Livestock production in Iowa, Nebraska, South Dakota, and Wisconsin is dominated by different livestock sectors. In Iowa, the livestock and livestock products industries in the state generated over $14 billion in direct cash receipts in 2019. During that year, cattle production, hog production, and dairy production contributed roughly 28%, 55%, and 7% of the total livestock-related cash receipts in the state, respectively. Nebraska's livestock and livestock products industries generated over $11 billion in direct cash receipts in 2019, with cattle, hog, and dairy production contributing to 89%, 7%, and 2% of those receipts. South Dakota's livestock production and animal products industries received over $4 billion in direct cash receipts in 2019, of which 67%, 14%, and 12% were comprised by cattle, hog, and dairy production. Finally, Wisconsin's livestock and livestock products industries generated over $7 billion in direct cash receipts in 2019, with cattle, hog, and dairy production contributing to 21%, 2%, and 72% of those receipts, respectively (Economic Research Service 2020).

Several modifications were made to the data to reflect current livestock feeding decisions and allow for appropriate price comparisons. First, distillers' prices were reported in dollars per ton, and corn prices were reported in dollars per bushel. To remove these different units of measurement, all prices were converted to a dry matter basis. Second, livestock producers – especially beef cattle producers – make decisions about rations based, in part, on the relative prices of corn and distillers' grains. As distillers' grains become more expensive relative to corn, livestock producers substitute away from distillers' grains and toward corn. To capture these movements simultaneously, all dry-matter prices were converted to percent-corn, dry matter prices. Thus, the dependent variable of interest is the price ratio of distillers' grains dry matter to corn dry matter by location, not the nominal price levels.

Figure 2 plots distillers' grains prices as a percentage of corn prices from January 2018 to August 2021. As is evident, prices for dried, modified, and wet distillers' grains as a percent of corn all increased simultaneously in the early part of 2020, when COVID-

19 first arrived in the United States and created the series of market responses discussed earlier. Although the magnitude of the response varied by type of grain and location, all types of distillers' grains briefly became more expensive relative to corn. The exact nature of these responses will be later discussed.

Most ethanol plants offer at least two types of distillers' grains to purchase. Livestock producers can choose between distillers' grains by adjusting their feeding rations given price differences between distillers' grains relative to corn. Figure 3 plots price ratio differences between distillers' grains by location. Unlike Figure 2, the responses to COVID-19 are less clear in the differences between percent-corn grain prices than the percent-corn grain prices themselves. In general, modified wet distillers' grains briefly became less expensive relative to wet distillers' grains across all locations, while dried distillers' grains became more expensive relative to modified wet distillers' grains. The differences between dried and wet distillers' prices varied by location, and locations took distinct amounts of time to return to baseline relationships. Possible explanations for these responses are discussed in the results section.

Empirical Strategy

The optimal model was determined to be a panel fixed effects model in which the percent-corn price of each type of distillers' grains was regressed on a COVID-19 dummy variable that was specific to each state's optimal COVID-19 start and end date. State and month-year-trend variables were the fixed effects variables, and the error term was clustered by state. Given that the start and end dates were similar across states for percent-corn prices, as shown in Table 1, the start and end dates were not forced to be the same across all states or within each type of distillers' grain. Instead, the model was allowed to self-select optimal start and end dates according to the highest adjusted R^2 value.

The basic empirical specification to estimate the impact of COVID-19 measures on the corn-to-distillers' grains price ratio is as follows:

1) $$Y_{djwy} = \beta_0 + \beta_1 COVID_{djt} + \lambda_j + \theta_{myt} + \varepsilon$$

For each distillers' grain d in state j in week w and year t, the coefficient of interest, β_1, estimates the within distillers' grain price impact of COVID by comparing weeks with and without COVID impacts. The variable $COVID_{djqy}$ equals 1 if the corn-distillers' price ratio occurs in week t identified as having an abnormally high price ratio and 0 otherwise. The general specification also includes state dummies, λ_j, and month-year-trend dummies, θ_{myt}. The state dummies are omitted in the state-specific models. The error term, ε, is clustered by state in the general model specifications and is not clustered in the state-specific models.

The panel fixed effect empirical specification used to estimate the impact of COVID-19 measures on the corn-to-distillers' grains price spread ratio is identical:

2) $$Y_{djwy} = \beta_0 + \beta_1 COVID_{djt} + \lambda_j + \theta_{myt} + \varepsilon$$

where, in this case, d refers to the type of distillers' grains price spread and the coefficient of interest, β_1, estimates the within distillers' grain price spread impact of COVID by comparing weeks with and without COVID impacts.[3]

Identification of Pandemic Start and End Dates

[3] The sample is limited to price ratios after 2017 to eliminate frequent weeks where prices were not reported for distillers' grain prices in select states.

To answer the question of when the initial COVID-19 impact started and ended in the distillers' grains market, the models shown in Appendix Tables 1-3 were specified, and the data was iterated through each model by type of distillers' grain and distillers' grain spread. Various start and end dates were also iterated through the models, both increasing by increments of one week in each subsequent loop. The best-fitting models were determined by the highest adjusted R^2 value for each location and distillers' grains. Adjusted R^2 values can be found in Table 1. Consequently, the optimal start and end dates – along with the optimal model specification – were determined by the models' performances over the course of the loops, rather than by an arbitrary selection process. The average start date of March 14, 2020 and end date of May 16, 2020 selected by the individual percent-corn distillers' grains models aligns with the general understanding of the initial COVID-19 shock. Mid-March to mid-May 2020 saw 42 US states and territories issue mandatory stay-at-home orders, which led to many of the market impacts discussed earlier in this paper, such as reduced gasoline demand, ethanol plant closures and slowdowns, processing plant issues, and limited food service demand (Moreland et. al, 2020).

The same model specification (found in the Empirical Model section above and specification (4) in Appendix Tables 1-3) produced the highest adjusted R^2 for each measure, but the optimal start and end dates vary by type of distillers' grains and location. The results of these optimal models can be found in Tables 2-4.

Results

Price Impacts by Type of Distillers' Grains

Table 2 reports the percent-corn price impacts of the COVID-19 shock. The value of the COVID-19 coefficient is the average percentage increase of distillers' grains percent-corn prices during the COVID-19 impact from pre- and post-shock levels. In decreasing order of magnitude, the COVID-19 shock caused the DDGS, WDGS, and MDGS percent-corn prices to rise by 35%, 30%, and 24% respectively. All values were significant at the 95% confidence level.

Several reasons help explain the different price responses by type of distillers' grain. One explanation is the nature of the markets for each type of distillers' grain. Dried distillers' grains can be shipped anywhere around the world because of their low moisture content (Iowa State University 2020). Although the DDGS demand structure offers more flexibility in distributing price impacts, the supply structure was significantly disrupted during COVID. For example, while DDGS is more easily shipped and stored than MDGS or WDGS, the global logistics of finding available containers and trucks proved extremely difficult (Twinn et. al, 2020). Additionally, drying distillers' grains costs money, and ethanol plants, whose margins were squeezed during the initial shock, may have chosen to direct that money elsewhere and, instead, sell MDGS or WDGS.

Modified and wet distillers' grains can only be affordably shipped within a certain radius of an ethanol plant, usually about 100 miles for MDGS and 50 miles for WDGS (Dooley and Martens 2008). Helping boost their prices during market uncertainty are the superior nutritional qualities provided by their higher moisture contents (Duckworth 2020). Wet distillers' grain's price response was likely elevated in comparison to MDGS's due to the same root cause of DDG's price increase: If ethanol plants were, in fact, reducing the amount of distillers' grains going through the dryer, MDGS would have been a natural middle ground for ethanol plants to produce and feedlots to demand. They offer more flexibility than WDGS in shipping and storing, and they require less drying than DDGS. This likely led to a relative abundance of MDGS in the marketplace and kept price reactions muted when compared to DDGS and WDGS prices. Since WDGS can only be shipped about 50 miles from an ethanol plant, they often enjoy a stable demand from local farms and feedlots. Prices, therefore, were likely supported by the continuation of that demand paired with reduced availability due to production slowdowns.

Price Impacts by Type of Distillers' Grains and Location

Table 3 displays the magnitude of the COVID-19 percent-corn prices shock by type of distillers' grain and state. The four states examined were Iowa, Nebraska, South Dakota, and Wisconsin. The magnitude of impacts varied both (1) across states but within the same distillers' grain type and (2) across distillers' grain type but within the same state. For example, Nebraska DDGS prices as a percent of corn were, on average, 44% higher during the COVID shock, while Wisconsin DDGS percent-corn prices were only 21% higher. Conversely, Wisconsin WDGS prices as a percent of corn averaged 35% higher than non-COVID shock periods, while Nebraska percent-corn WDGS prices were only 18% above average non-COVID values. All impacts discussed in this section were found to be significant at the 99% confidence level.

Total availability of distillers' grains in each state – measured by distillers' grains production – helps to account for some of the variation within types of distillers' grains. Another likely explanation for the diverse responses to the COVID-19 impact on distillers' grains markets relates to the nature of the dominant livestock industries in each state and how each industry uses distillers' grains in their operations.

The dominant livestock industries in each state are relevant because they affect how producers around regional ethanol plants respond to distillers' grains price changes. Beef cattle, dairy cattle, and hog production occur on tight schedules from birth to slaughter, but beef cattle producers, especially, have some power to influence the pace of those schedules by either slowing or accelerating weight gain according to market conditions (Clark 2019). Dairy producers, on the other hand, have little say over whether their cattle produce milk; biologically, milk production occurs regardless of market conditions (Minson 1990).

These relationships are apparent in the varying price reactions within distillers' grain type and between states. The states with the highest proportions of beef cattle production, Nebraska and South Dakota, experienced the largest DDGS price increases as a percent of corn during the initial COVID-19 shock. Larger impacts on dried products in beef cattle-heavy states likely occurred because beef cattle producers have some measure of flexibility in their feeding rations. When plants began to close or idle and producers anticipated higher prices on the horizon, dried distillers' products were in highest demand because producers had the ability to store the feed beyond the purchase date. Since livestock operations within a roughly 100-mile radius can fairly easily switch between DDGS, MDGS, and WDGS, the flexibility provided by DDGS was likely attractive to those operations. The influx of demand for product to use not only in the present period but for a few weeks or months in the future (as a hedge against the uncertainty the market was facing) likely drove prices upward. This ability was unique to beef cattle producers because the production timeframe can be adjusted more easily than in hog or dairy production, where producers must follow rigid production cycles. The relative price of soybean meal versus distillers' grains would have also played a larger role in hog and dairy operations than beef cattle operations.

In non-beef-cattle-centric states, on the other hand, producers enjoyed less flexibility in manipulating their animals' feed rations. Dairy producers, in particular, were bound by biology to feed their animals a consistent, stable ration regardless of market conditions. This issue of steady demand for feed inputs even during poor market conditions was evidenced by the milk dumping seen in the early days of the COVID-19 pandemic. Despite nearly nonexistent demand for dairy producers' end products, their dairy cattle kept producing milk (Schneider 2020). Wisconsin, which is heavily dominated by dairy production, revealed dairy producers' need for a steady feed source in the MDGS and WDGS percent-corn price reactions during the COVID-19 shock, where Wisconsin experienced some of the largest increases. Since dairy producers require a dependable feed source, they have long served as a convenient outlet for the difficult-to-ship and difficult-to-store MDGS and WDGS co-products of local ethanol plants. When ethanol production began to falter, the dairy cows still required their usual MDGS and WDGS feedstuffs, so producers were forced to pay higher prices to feed their animals. Since few, if any, hog producers feed MDGS or WDGS, the relative increase in those prices in Iowa was likely driven by other livestock industries or by a shortage of those products relative to DDGS.

The livestock industries in each state played an incomplete role in determining the price impacts of the COVID-19 shock, but the unique dynamics of each livestock type help to place the price shocks in real-world context. Other factors, such as the extent to which ethanol plants idled or closed in each state, also impacted price reactions, but the lack of public, state-level data makes the exact effects of those shocks difficult to quantify.

Price Spread Impacts by Type of Distillers' Grains

Only one of the non-state specific price spread relationships using optimal dates – DDG-WDGS – experienced a significant impact during the COVID-19 shock. On average, the DDGS and WDGS price spread as a percent of corn was about 19.3% greater than average during the COVID-19 shock at the 95% confidence level. DDGS percent-corn prices were elevated compared to WDGS percent-corn prices likely due to the flexibility offered by DDGS in a period when feedlots and producers faced significant uncertainty about the markets for their animals. With food service sales significantly reduced and processing plants around the country limiting capacity and temporarily idling, purchasing DDGS allowed producers to better adapt to changing situations than WDGS, which must be fed in a short time frame. As will be explored in the next section, though, whether this dynamic can be attributed to COVID-19 can be debated, given the significant amount of noise in the data far beyond what is generally understood as the initial COVID-19 impact.

Price Spread Impacts by Type of Distillers' Grains and Location

The price spread impacts by state and type of distillers' grains can be found in Table 4, which includes results from the models that solved for the optimal COVID-19 dates and the models that imposed the start and end dates on the models. As can be seen in Table 1, the optimal dates selected by the models do not consistently align with the dates selection by the percent-corn price models. Figure 3 helps to explain this discrepancy, as a significant amount of noise extends beyond what is generally understood as the initial COVID-19 shock. Consequently, start and end dates based on the average optimal start and end dates from the individual, percent-corn distillers' grains models were imposed. Those dates were March 14, 2020 and May 16, 2020, respectively. This allowed for a more straightforward examination of the behaviors of distillers' grains price spreads during the initial COVID-19 shock.

Within each type of distillers' grain price spread, general trends are more difficult to identify. For the DDG-MDGS price spread, all impacts are significant at the 90% confidence level, and all the impacts are positive. For the DDG-WDGS price spread, only the Nebraska response is significant, and it is positive and significant at the 99% confidence level. Finally, three of the four MDGS-WDGS price spread responses are significant, all at the 95% confidence level or higher, with Iowa and South Dakota's responses negative and Nebraska's response positive. The positive DDG-MDGS and DDG-WDGS relationship was addressed for DDG-WDGS in the section above and holds here, as well. The negative MDGS-WDGS relationship in Iowa and South Dakota and positive MDGS-WDGS relationship in Nebraska indicates that WDGS were preferred to MDGS in Iowa and South Dakota, but MDGS was preferred to WDGS in Nebraska during the COVID-19 shock. Modified distillers' grains were likely preferred to WDGS in Nebraska during the initial shock due to the large number of cattle feedlots in the state who wanted some level of flexibility in storing their feedstuffs while they responded to market conditions. Modified distillers' grains offered slightly more flexibility than WDGS in storage and transportation, which helps to explain the relationship. Plus, since WDGS are generally more common in the marketplace than MDGS, the limited availability of MDGS relative to WDGS at a time when some of the traits of MDGS were desired also likely drove MDGS higher relative to WDGS prices.

Robustness Checks

In this section, possible factors that could confound the estimates resulting from the model are explored, such as endogeneity or issues in the error term. Several alternative models are tested to demonstrate the robustness of the main effect.

Endogeneity occurs when, for whatever reason, the error term is correlated with the independent variable in an econometric model. Possible causes of endogeneity are selection bias, reverse causality, measurement error, or omitted variables. The existence of endogenous variables can make the results of a model incorrect and/or untrustworthy and limit the robustness of the model. In this analysis, given the nature of the research question and data, the most likely causes of endogeneity would be omitted variables or measurement error. Potential omitted variables could include month, quarter, week, or year fixed effect variables or quarter-year trend variables. Results from models including these variables can be found in Tables A1 and A2. As is evident, these models more poorly represented the data according to the R^2 and adjusted R^2 values, indicating those variables do not belong in the actual model.

Another possible cause of endogeneity would be measurement error. Measurement error occurs when there is inaccuracy in the values observed as opposed to the realized values in the market. In this case, measurement error would occur if USDA inaccurately measured and reported distillers' grains and/or corn prices, or if LMIC incorrectly aggregated those prices. Whether or not this may be the case is beyond the scope of this paper and, if true, would complicate the results of many prior research projects.

The results in Tables A1 and A2 indicate that the models selected for this analysis best represented the data of the available models. Consequently, there are no clear confounding factors that would cause one to distrust the models used or the results of this analysis.

Post-Pandemic Implications

Long-term Impacts on the Distillers' Grains Market

The purpose of this section is to provide examples of shocks in which the analysis used in this paper could be applied to quantify the impacts of non-pandemic market disturbances. Both supply and demand shock scenarios will be introduced, and potential implications of those shocks are discussed. Considering these scenarios reveals that the impacts introduced by the pandemic are not limited to a once-in-a-century virus. Instead, producers who rely heavily on distillers' grains in their livestock feed rations regularly expose themselves to these potential risks. To better prepare for the future, producers may, consequently, consider changing their relationship to distillers' grains in the coming years.

One potential shock to the distillers' grains industry is a weather-related disruption. This disruption could come in the form of a drought, flood, or severe storm, any of which would serve to limit the supply of corn. Ceteris paribus, a negative impact to the corn supply would place upward pressure on distillers' grains prices. In turn, ethanol and distillers' grains would become more expensive to produce, which would limit the quantity of distillers' grains supplied to the marketplace. A market shock unrelated to the natural world that would affect the market for distillers' grains would be the removal of governmental support for the ethanol industry. This removal of support would most likely come in the form of a relaxation of the ethanol blending requirement for oil refineries. With lower minimum blending requirements, the demand for ethanol from oil refineries would fall, which would negatively impact ethanol prices and plants' demand for corn. Lower demand for corn from plants would lower corn prices, all else equal, and would also negatively affect distillers' grains prices. Finally, a third possible market shock is the spread of a livestock disease in the United States or abroad. Disease would reduce the number of animals, which would lower the demand for corn and distillers' grains, all else equal. As a result, corn and distillers' grains prices would fall. Cheaper corn would make ethanol less expensive to produce, but the decline in distillers' grains prices would place downward pressure on plant revenues

The effects of market shocks like COVID-19 on the distillers' grains industry would likely take two forms: adjustments to distillers' supply and adjustments to distillers' demand. On the supply side, ethanol plants would likely continue their effort to distinguish their distillers' grains products by further specializing and differentiating their feed products. Pelletized distillers' grains, high protein distillers' grains, and de-oiled distillers' grains are examples of these value-added (or value-subtracted, depending on the customer) products currently in the marketplace. By further differentiating their product lines, ethanol plants can create demand structures less reliant on only one or two livestock species while receiving a premium for the products they sell.

On the demand side, livestock producers may begin to consider how to avoid the price volatility in distillers' grains by making permanent shifts away from distillers' grains. Small, operation-specific grain milling, corn crushing, and corn flaking operations is an example of how this shift is already starting to occur. Although the upfront investment is high, if producers feel confident they can lock in a lower, more consistent feed cost over the long run by investing in their own feeding infrastructure, they may begin to shift their resources away from distillers' grains. A large-scale shift away from distillers' grains would likely have a significant negative impact on the ethanol industry, barring the development of other non-feed ethanol co-products.

Summary and Conclusions

The market conditions introduced by the pandemic and subsequent government and industry responses created a unique set of shocks unparalleled in their volume and magnitude and led to simultaneous disruptions in supply, demand, and derived demand in the distillers' grains market.

This paper aimed to quantify the price impacts of the market shock of COVID-19 on DDGS, MDGS, and WDGS prices and price spreads in Iowa, Nebraska, South Dakota, and Wisconsin. A panel fixed effect model was used to measure both the timing and magnitude of price movements. The model revealed varying responses by location and types of distillers' grains, indicating the importance of local distillers' grains market structures in determining prices. The price fluctuations seemed to indicate that livestock producers favored the flexibility provided by DDGS and, therefore, drove those prices upward more significantly than MDGS and WDGS prices. MDGS and WDGS price responses, though, were more pronounced in areas whose livestock production industries demanded fixed feeding schedules, such as the dairy and hog industries in Wisconsin and Iowa.

The disparate price responses by grain type and location offer some insight into how markets may respond in the event of future market shocks. Depending on the type of shock, ethanol plants will be differently equipped to weather market impacts based, in part, on their location and grain production patterns. Additionally, the results can provide livestock producers with insight into how distillers' grains prices may respond in different market scenarios and, therefore, help them to prepare accordingly in the case of another impact to the distillers' grains market. As a result, the distillers' grains market responses to COVID-19 can help both ethanol plants and livestock producers better prepare for future market shocks.

References

Clark, Teresa. 2019. *Flexibility making stocker cattle more popular.* July 26. https://www.thefencepost.com/news/flexibility-making-stocker-cattle-more-popular/.

DeOliveira, Vanessa, Kate Brooks, and Lia Nogueira. "A Short Introduction to the Distillers' Dried Grains Export Market." Cornhusker Economics, February 8, 2017. https://agecon.unl.edu/cornhusker-economics/2017/distillers-dried-grain-export-market#:~:text=Distillers'%20dried%20grains%20with%20soluble,alternative%20feedstuff%20in%20livestock%20rations.&text=U.S.%20Exports%20of%20DDGS%20have,tons%2C%20a%201%2C439%25%20increase.

Domonoske, Camila. 2020. Oil Demand Has Collapsed, And It Won't Come Back Any Time Soon. September 15. https://www.npr.org/2020/09/15/913052498/oil-demand-has-collapsed-and-it-wont-come-back-any-time-soon.

Duckworth, Barbara. 2020. *New distillers' grains introduced to feed market.* February 27. https://www.producer.com/2020/02/new-distillers'-grains-introduced-to-feed-market/.

Dong, Xiao, and Elianna Zeballos. Ms. *COVID-19 Working Paper: The Effects of COVID-19 on Food Sales*. Economic Research Service, n.d. https://www.ers.usda.gov/webdocs/publications/100426/ap-088.pdf?v=8064.5.

Dooley, Frank J, and Bobby J Martens. "Transportation and Logistics in Distillers Grains Markets." Center for Agricultural and Rural Development. Iowa State University, 2008. https://www.card.iastate.edu/products/books/distillers_grains/pdfs/chapter9.pdf. Economic Research Service. 2020. *Cash receipts by commodity, 2011-2020F.* September 2. https://data.ers.usda.gov/reports.aspx?ID=17845&AspxAutoDetectCookieSupport=1#Pdd18c1d9ae9747ac96bccc22002e0b37_6_17iT0R0x49.

"Feedgrains Sector at a Glance." USDA ERS, June 28, 2021. https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/feedgrains-sector-at-a-glance/.

Gallagher, Dianne. "Meat Processing Plants across the US Are Closing Due to the Pandemic. Will Consumers Feel the Impact?" CNN. Cable News Network, April 27, 2020. https://www.cnn.com/2020/04/26/business/meat-processing-plants-coronavirus/index.html.

Gertner, Daniel and Elliott Dennis. "Impact of COVID-19 on Demand for Distillers' Grains from Impact of COVID-19 on Demand for Distillers' Grains from Livestock Operations Livestock Operations." AgEcon Search, May 27, 2020. https://doi.org/10.22004/ag.econ.309740.

Halfman, William. 2020. *Considerations for slowing feedlot cattle growth due to the COVID-19 pandemic.* April 24. https://fyi.extension.wisc.edu/wbic/2020/04/24/considerations-for-slowing-feedlot-cattle-growth-due-to-the-covid-19-pandemic/.

Hofstrand, Don. "Tracking Ethanol Profitability: Ag Decision Maker." Tracking Ethanol Profitability. Iowa State University, September 14, 2021. https://www.extension.iastate.edu/agdm/energy/html/d1-10.html.

Iowa State University. 2020. *Distillers' Grains.* April. https://distillers'grains.org/distillers'-grains/.

Irwin, Scott. 2020. 2019 Ethanol Production Profits: Just How Bad Was It? January 29. https://farmdocdaily.illinois.edu/2020/01/2019-ethanol-production-profits-just-how-bad-was-it.html.

Jenkins, Karla H. 2016. *Understanding the Difference between Corn and Corn Distillers' Grains as Energy Supplements for Pasture Cattle.* August. https://beef.unl.edu/difference-between-corn-and-corn-distillers'-grains-as-energy-supplements-for-pasture-cattle.

Kang, Jaewon, and Jacob Bunge. "Supermarkets Adjust Meat Sections as Coronavirus Cuts Supply." The Wall Street Journal. Dow Jones & Company, April 16, 2020. https://www.wsj.com/articles/supermarkets-adjust-meat-sections-as-coronavirus-cuts-supply-11587051995.

Kelly, Stephanie, and Jarrett Renshaw. "EXCLUSIVE EPA to Urge U.S. Biofuel BLENDING Mandates below 2020 Levels, Sources Say." Reuters. Thomson Reuters, August 20, 2021. https://www.reuters.com/business/energy/us-epa-recommend-lower-biofuel-blending-mandates-below-2020-levels-sources-2021-08-20/.

"Meat Price Spreads." USDA ERS - Meat Price Spreads. Accessed November 11, 2021. https://www.ers.usda.gov/data-products/meat-price-spreads/.

Minson, Dennis J. 1990. "Milk Production - An Introduction." *Forage in Ruminant Nutrition.*

Moreland, Amanda, Christine Herlihy, Michael Tynan, Gregory Sunshine, Russell McCord, Charity Hilton, Jason Poovey, et al. "Timing of State and Territorial Covid-19 Stay-at-Home Orders and Changes in Population Movement - United States, March 1–MAY 31, 2020." Centers for Disease Control and Prevention. Centers for Disease Control and Prevention, September 3, 2020. https://www.cdc.gov/mmwr/volumes/69/wr/mm6935a2.htm#:~:text=During%20March%201%E2%80%93May%2031%2C%2042%20states%20and%20territories%20issued,by%20California%20(March%2019).

Morgan, Tyne. 2020. Ethanol Plants Could Soon Start Producing for DDGs, Not Ethanol. March 27. https://www.drovers.com/article/ethanol-plants-could-soon-start-producing-ddgs-not-ethanol.

Nebraska Energy Office (NEO). 2018. Ethanol Facilities Capacity by State and Plant. May. https://neo.ne.gov/programs/stats/inf/122.htm.

Nuttelman, Brandon L., Will A. Griffin, Josh R. Benton, Galen E. Erickson, and Terry J. Klopfenstein. 2011. *Comparing Dry, Wet, or Modified Distillers' Grains Plus Solubles on Feedlot Cattle Performance.* Lincoln, Nebraska: The Board of Regents of the University of Nebraska

Olson, David W., and Thomas Capehart. "Dried Distillers' Grains (DDGs) Have Emerged as a Key Ethanol Coproduct." Amber Waves:The Economics of Food, Farming, Natural Resources, and Rural America 2019, no. 9 (October 1, 2019). https://doi.org/10.22004/ag.econ.302876.

Renshaw, Jarrett, and Stephanie Kelly. "Midwest Floods Hammer U.S. Ethanol Industry, Push Some Gasoline Prices toward 5-Year High." Reuters. Thomson Reuters, April 8, 2019. https://www.reuters.com/article/usa-ethanol-floods/rpt-midwest-floods-hammer-u-s-ethanol-industry-push-some-gasoline-prices-toward-5-year-high-idUSL1N21P06D.

Schneider, Leighton. 2020. *Dairy farmers dumping milk amid COVID-19: Pandemic's impact on the dairy industry.* April 21. https://abcnews.go.com/US/dairy-farmers-dumping-milk-amid-covid-19-pandemics/story?id=70268302.

Snodgrass, Alex. 2020. 73 US ethanol plants now idled, 71 significantly reducing operations. April 20. https://www.icis.com/explore/resources/news/2020/04/20/10498185/73-us-ethanol-plants-now-idled-71-significantly-reducing-operations.

Stewart, Lawton, and Jason Duggin. "Using Distillers Grains in Beef Cattle Diets." University of Georgia Extension, September 1, 2010. https://extension.uga.edu/publications/detail.html?number=B1482&title=Using+Distillers+Grains+in+Beef+Cattle+Diets.

Twinn, Ian, Navaid Qureshi, Maria López Conde, Carlos Garzón Guinea, and Daniel Perea Rojas . "The Impact of COVID-19 on Logistics." International Finance Corporation (blog). World Bank Group, June 2020. https://www.ifc.org/wps/wcm/connect/2d6ec419-41df-46c9-8b7b-96384cd36ab3/IFC-Covid19-Logistics-final_web.pdf?MOD=AJPERES&CVID=naqOED

Voegele, Erin. 2020. Pacific Ethanol focuses on high-quality alcohol, co-products. August 12. http://ethanolproducer.com/articles/17455/pacific-ethanol-focuses-on-high-quality-alcohol-co-products.

Supporting Tables

Table 1. Optimally Solved Beginning and Ending Dates of COVID-19 by Type of Distillers' Grain by State

	State	Adjusted R^2	Start Date	End Date
Panel (a): Distillers' Grain				
DDGS	Iowa	0.801	3/14/2020	5/2/2020
DDGS	Nebraska	0.780	3/14/2020	5/16/2020
DDGS	South Dakota	0.848	3/14/2020	5/9/2020
DDGS	Wisconsin	0.918	3/14/2020	5/30/2020
MDGS	Iowa	0.756	3/14/2020	5/9/2020
MDGS	Nebraska	0.733	3/14/2020	5/16/2020
MDGS	South Dakota	0.822	3/14/2020	5/16/2020
MDGS	Wisconsin	0.882	3/14/2020	5/16/2020
WDGS	Iowa	0.738	3/14/2020	5/2/2020
WDGS	Nebraska	0.748	3/14/2020	5/16/2020
WDGS	South Dakota	0.802	3/14/2020	5/16/2020
WDGS	Wisconsin	0.810	3/14/2020	5/2/2020
Panel (b): Distillers' Grain Spread				
DDGS-MDGS	Iowa	0.477	3/14/2020	9/12/2020
DDGS-MDGS	Nebraska	0.743	3/14/2020	5/2/2020
DDGS-MDGS	South Dakota	0.490	3/14/2020	4/18/2020
DDGS-MDGS	Wisconsin	0.835	3/14/2020	5/23/2020
DDGS-WDGS	Iowa	0.467	3/14/2020	11/7/2020
DDGS-WDGS	Nebraska	0.614	3/14/2020	5/2/2020
DDGS-WDGS	South Dakota	0.565	3/14/2020	8/22/2020
DDGS-WDGS	Wisconsin	0.519	3/14/2020	4/25/2020
MDGS-WDGS	Iowa	0.464	3/14/2020	5/2/2020
MDGS-WDGS	Nebraska	0.414	2/15/2020	8/22/2020
MDGS-WDGS	South Dakota	0.638	3/14/2020	6/6/2020
MDGS-WDGS	Wisconsin	0.665	3/14/2020	5/23/2020

Table 2. Main Effects of COVID-19 On Distillers' Grains and Distillers' Grains Price Spreads

	Distiller Grains			Distiller Grains Spreads		
	DDG	*MWDG*	*WDG*	*DDG-MWDG*	*DDG-WDG*	*MWDG-WDG*
COVID-19	35.261***	24.097***	30.450**	3.244	-19.300**	0.488
Standard Error	(4.175)	(3.229)	(8.457)	(5.356)	(5.860)	(5.901)
Fixed Effects						
State x Month-Year Trend	Yes	Yes	Yes	Yes	Yes	Yes
Observations	748	748	748	748	748	748
Adjusted R^2	0.889	0.840	0.707	0.498	0.257	0.341
Residual Standard Error (df=701)	6.924	6.730	11.585	6.020	11.152	10.536

Note: **p<0.05; ***p<0.01

Table 3. Effect of COVID-19 by Type of Distillers' Grain and State

	Iowa	Nebraska	South Dakota	Wisconsin
Panel (a): DDG				
COVID-19	25.905***	44.275***	27.015***	21.296***
Standard Error	(4.773)	(5.071)	(3.966)	(5.612)
Fixed Effects				
State x Month-Year Trend	Yes	Yes	Yes	Yes
Observations	187	187	187	187
Adjusted R^2	0.908	0.887	0.927	0.950
Residual Standard Error (df=143)	5.943	7.081	5.538	4.860
Panel (b): MWDG				
COVID-19	18.118***	31.131***	18.008***	29.023***
Standard Error	(3.582)	(3.845)	(3.113)	(3.108)
Fixed Effects				
State x Month-Year Trend	Yes	Yes	Yes	Yes
Observations	187	187	187	187
Adjusted R^2	0.904	0.889	0.925	0.940
Residual Standard Error (df=143)	5.002	5.370	4.347	4.340
Panel (c): WDG				
COVID-19	42.520***	18.311***	33.364***	34.877***
Standard Error	(8.460)	(3.675)	(5.960)	(4.853)
Fixed Effects				
State x Month-Year Trend	Yes	Yes	Yes	Yes
Observations	187	187	187	187
Adjusted R^2	0.823	0.878	0.893	0.895
Residual Standard Error (df=143)	10.533	5.132	8.322	6.043

Note: ***p<0.01

Table 4. Impacts of COVID-19 by Distillers' Grain Spread and State

	Iowa		Nebraska		South Dakota		Wisconsin	
Panel (a): DDG-MWDG								
COVID-19	8.401**	5.751*	16.180***	13.144***	16.444***	8.817***	8.179***	8.371***
Standard Error	(3.464)	(3.313)	(3.069)	(2.781)	(3.229)	(2.989)	(2.453)	(2.160)
Fixed Effects								
State x Month-Year Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Forced Start/End Dates	No	Yes	No	Yes	No	Yes	No	Yes
Observations	187	187	187	187	187	187	187	187
Adjusted R^2	0.621	0.614	0.777	0.77	0.718	0.687	0.871	0.875
Residual Standard Error (df=143)	4.582	4.627	3.821	3.883	3.955	4.174	3.054	3.016
Panel (b): DDG-WDG								
COVID-19	-23.367***	-8.63	34.271***	25.964***	-11.650**	-6.539	-0.462	-2.743
Standard Error	(7.142)	(6.454)	(5.062)	(4.709)	(5.605)	(4.959)	(5.421)	(3.354)
Fixed Effects								
State x Month-Year Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Forced Start/End Dates	No	Yes	No	Yes	No	Yes	No	Yes
Observations	187	187	187	187	187	187	187	187
Adjusted R^2	0.615	0.592	0.693	0.665	0.779	0.775	0.796	0.797
Residual Standard Error (df=143)	8.747	9.013	6.302	6.576	6.864	6.925	4.695	4.684
Panel (c): MWDG-WDG								
COVID-19	-24.108***	-14.381**	-8.163*	12.820***	-19.830***	-15.356***	-5.616	-5.050
Standard Error	(7.661)	(6.959)	(4.346)	(3.706)	(5.896)	(5.216)	(4.146)	(3.696)
Fixed Effects								
State x Month-Year Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Forced Start/End Dates	No	Yes	No	Yes	No	Yes	No	Yes
Observations	187	187	187	187	187	187	187	187
Adjusted R^2	0.556	0.539	0.539	0.564	0.796	0.792	0.758	0.758
Residual Standard Error (df=143)	9.538	9.718	5.322	5.175	7.221	7.283	5.162	5.161

Notes: Start date is fixed at 2020-03-14 and the End Date is fixed at 2020-05-16. These start and end dates are based on the average optimal start and end dates from individual distiller grains; *p<0.1; **p<0.05; ***p<0.01

Table A1. Different Model Specifications for Dried Distillers' Grains Using Optimal Start and End Dates

	DDG				
	(1)	(2)	(3)	(4)	(5)
COVID-19	45.486***	45.168***	42.713***	35.261***	42.302***
Standard Error	(2.525)	(2.295)	(2.518)	(4.175)	(2.584)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
R^2	0.585	0.806	0.663	0.896	0.687
Adjusted R^2	0.579	0.801	0.655	0.889	0.66
Residual Standard Error	13.487 (df = 737)	9.283 (df = 729)	12.220 (df = 729)	6.924 (df = 701)	12.121 (df = 689)

Note: ***p<0.01

Table A2. Different Model Specifications for Modified Wet Distillers' Grains Using Optimal Start and End Dates

	MWDG				
	(1)	(2)	(3)	(4)	(5)
COVID-19	31.508***	31.823***	28.542***	24.097***	27.767***
Standard Error	(2.233)	(3.210)	(2.096)	(3.229)	(1.996)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
R^2	0.558	0.741	0.642	0.850	0.665
Adjusted R^2	0.552	0.735	0.633	0.840	0.637
Residual Standard Error	11.260 (df = 737)	8.656 (df = 729)	10.189 (df = 729)	6.730 (df = 701)	10.134 (df = 689)

Note: ***p<0.01

Table A3. Different Model Specifications for Wet Distillers' Grains Using Optimal Start and End Dates

	MWDG				
	(1)	(2)	(3)	(4)	(5)
COVID-19	49.149***	44.181***	48.174**	30.450**	48.788**
Standard Error	(7.933)	(6.624)	(9.621)	(8.457)	(9.895)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
R^2	0.509	0.648	0.552	0.725	0.571
Adjusted R^2	0.502	0.639	0.541	0.707	0.535
Residual Standard Error	15.093 (df = 737)	12.854 (df = 729)	14.495 (df = 729)	11.585 (df = 701)	14.586 (df = 689)

Note: **p<0.05; ***p<0.01

Table A4. Different Model Specifications DDGS-MDGS Spread Using Optimal (Non-Forced) Start and End Dates

	DDGS-MDGS				
	(1)	(2)	(3)	(4)	(5)
COVID-19	9.618	7.428	9.563	3.244	9.513
Standard Error	(4.876)	(5.975)	(4.744)	(5.356)	(4.842)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Forced Start/End Dates	No	No	No	No	No
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
Adjusted R^2	0.325	0.436	0.339	0.498	0.317
Residual Standard Error	6.982 (df = 737)	6.384 (df = 729)	6.910 (df = 729)	6.020 (df = 701)	7.021 (df = 689)

Table A5. Different Model Specifications DDGS-WDGS Spread Using Optimal (Non-Forced) Start and End Dates

	DDGS-WDGS				
	(1)	(2)	(3)	(4)	(5)
COVID-19	-15.188*	-15.776*	-16.215*	-19.300**	-16.659*
Standard Error	(5.982)	(5.626)	(5.954)	(5.860)	(5.764)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Forced Start/End Dates	No	No	No	No	No
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
Adjusted R^2	0.143	0.218	0.164	0.257	0.14
Residual Standard Error	11.976 (df = 737)	11.443 (df = 729)	11.830 (df = 729)	11.152 (df = 701)	12.000 (df = 689)

Note: *p<0.1

Table A6. Different Model Specifications MDGS-WDGS Spread Using Optimal (Non-Forced) Start and End Dates

	MDGS-WDGS				
	(1)	(2)	(3)	(4)	(5)
COVID-19	-14.498	-7.127	-15.118	0.488	-15.374
Standard Error	(7.629)	(7.513)	(8.840)	(5.901)	(8.904)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Forced Start/End Dates	No	No	No	No	No
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
Adjusted R^2	0.212	0.306	0.212	0.341	0.186
Residual Standard Error	11.522 (df = 737)	10.811 (df = 729)	11.527 (df = 729)	10.536 (df = 701)	11.711 (df = 689)

Table A7. Different Model Specifications DDGS-MDGS Spread Using Optimal (Forced) Start and End Dates

	DDGS-MDGS				
	(1)	(2)	(3)	(4)	(5)
COVID-19	12.027**	11.644**	12.173**	9.021***	12.429**
Standard Error	(3.089)	(2.936)	(2.963)	(1.533)	(2.986)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Forced Start/End Dates	Yes	Yes	Yes	Yes	Yes
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
Adjusted R^2	0.344	0.462	0.355	0.507	0.334
Residual Standard Error	6.883 (df = 737)	6.233 (df = 729)	6.824 (df = 729)	5.968 (df = 701)	6.935 (df = 689)

Note: **p<0.05; ***p<0.01

Table A8. Different Model Specifications DDGS-WDGS Spread Using Optimal (Forced) Start and End Dates

	DDGS-WDGS				
	(1)	(2)	(3)	(4)	(5)
COVID-19	-4.666	-0.149	-6.542	2.013	-7.754
Standard Error	(9.619)	(7.889)	(10.670)	(8.082)	(10.919)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Forced Start/End Dates	Yes	Yes	Yes	Yes	Yes
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
Adjusted R^2	0.070	0.145	0.088	0.176	0.059
Residual Standard Error	12.479 (df = 737)	11.962 (df = 729)	12.359 (df = 729)	11.745 (df = 701)	12.549 (df = 689)

Table A9. Different Model Specifications MDGS-WDGS Spread Using Optimal (Forced) Start and End Dates

	MDGS-WDGS				
	(1)	(2)	(3)	(4)	(5)
COVID-19	-18.255*	-11.997	-20.265*	-5.492	-22.058*
Standard Error	(6.976)	(6.817)	(8.171)	(6.535)	(8.257)
Fixed Effects					
State	Yes	Yes	Yes	Yes	Yes
Year	Yes	No	Yes	No	No
Quarter	Yes	No	No	No	No
Month	No	No	Yes	No	No
Week	No	No	No	No	Yes
Forced Start/End Dates	Yes	Yes	Yes	Yes	Yes
Trend					
Quarter-Year	No	Yes	No	No	No
Month-Year	No	No	No	Yes	No
Observations	748	748	748	748	748
Adjusted R^2	0.228	0.321	0.234	0.343	0.217
Residual Standard Error	11.407 (df = 737)	10.697 (df = 729)	11.363 (df = 729)	10.521 (df = 701)	11.487 (df = 689)

Note: *p<0.1

Table A10. Prices Pre, During, and Post COVID-19 by State and Type of Distillers' Grain

	Pre COVID-19					COVID-19					Post COVID-19				
	Obs.	Mean	St. Dev.	Min	Max	Obs.	Mean	St. Dev.	Min	Max	Obs.	Mean	St. Dev.	Min	Max
Iowa															
DDG	115	1.113	0.133	0.809	1.424	7	1.703	0.221	1.277	1.919	65	1.126	0.198	0.680	1.468
MWDG	115	0.942	0.100	0.711	1.204	8	1.440	0.206	1.130	1.690	64	0.977	0.158	0.645	1.202
WDG	115	1.038	0.145	0.678	1.305	7	1.928	0.303	1.415	2.337	65	1.024	0.227	0.571	1.527
Nebraska															
DDG	115	1.144	0.126	0.877	1.385	9	1.783	0.218	1.419	2.046	63	1.138	0.203	0.712	1.495
MWDG	115	1.033	0.112	0.787	1.251	9	1.433	0.107	1.230	1.530	63	0.982*	0.165	0.669	1.294
WDG	115	1.052	0.111	0.750	1.254	9	1.424	0.153	1.16	1.642	63	1.016	0.132	0.724	1.298
South Dakota															
DDG	115	1.121	0.130	0.837	1.367	8	1.741	0.226	1.288	2.001	64	1.153	0.205	0.710	1.543
MWDG	115	1.050	0.105	0.759	1.189	9	1.1458	0.151	1.170	1.640	63	1.060	0.171	0.693	1.349
WDG	115	1.003	0.172	0.721	1.467	9	1.846	0.215	1.378	2.022	63	1.091*	0.195	0.756	1.632
Wisconsin															
DDG	115	1.138	0.11	0.895	1.380	11	1.827	0.231	1.355	2.052	61	1.176	0.188	0.719	1.405
MWDG	115	1.013	0.144	0.712	1.277	9	1.146	0.159	1.110	1.625	63	0.993	0.156	0.622	1.275
WDG	115	1.036	0.115	0.743	1.353	7	1.689	0.232	1.331	1.928	65	1.029	0.165	0.648	1.428

Notes: The COVID-19 timeframe is defined by the optimal (non-forced) cutoff dates for each location and measure; * indicates post COVID-19 mean is statistically different compared to the pre COVID-19 level at the 95% confidence level.

Table A11. Prices Pre, During, and Post COVID-19 by State and Distillers' Grain Spread

	Pre COVID-19					COVID-19					Post COVID-19				
	Obs.	Mean	St. Dev.	Min	Max	Obs.	Mean	St. Dev.	Min	Max	Obs.	Mean	St. Dev.	Min	Max
Iowa															
DDGS-MDGS	115	0.170	0.073	0.033	0.363	26	0.206	0.062	0.13	0.398	46	0.124*	0.067	0.025	0.283
DDGS-WDGS	115	0.075	0.120	-0.262	0.352	34	-0.017	0.159	-0.418	0.228	38	0.149*	0.142	-0.141	0.486
MDGS- WDGS	115	-0.095	0.097	-0.397	0.128	7	-0.469	0.234	-0.798	-0.138	65	-0.042*	0.139	-0.353	0.332
Nebraska															
DDGS-MDGS	115	0.112	0.050	-0.014	0.231	7	0.380	0.137	0.190	0.541	65	0.159*	0.068	-0.010	0.279
DDGS-WDGS	115	0.093	0.077	-0.064	0.273	7	0.410	0.144	0.251	0.601	65	0.124	0.121	-0.154	0.332
MDGS- WDGS	111	-0.018	0.075	-0.191	0.164	27	-0.031	0.085	0.085	0.187	49	-0.029	0.082	-0.169	0.122
South Dakota															
DDGS-MDGS	115	0.070	0.066	-0.077	0.263	5	0.314	0.127	0.118	0.432	67	0.09*	0.053	-0.026	0.264
DDGS-WDGS	115	0.118	0.128	-0.157	0.469	23	-0.127	0.086	-0.280	0.011	49	0.108	0.126	-0.072	0.437
MDGS- WDGS	115	0.048	0.133	-0.350	0.339	12	-0.355	0.078	-0.476	-0.208	60	-0.018*	0.122	-0.241	0.297
Wisconsin															
DDGS-MDGS	115	0.125	0.055	0.004	0.220	10	0.378	0.110	0.186	0.497	62	0.189*	0.061	0.073	0.314
DDGS-WDGS	115	0.102	0.087	-0.018	0.393	6	0.112	0.121	0.017	0.322	66	0.189*	0.107	0.050	0.570
MDGS- WDGS	115	-0.023	0.108	-0.209	0.299	10	-0.230	0.122	-0.401	0.042	62	-0.026	0.056	0.056	0.090

Notes:

1) The COVID-19 timeframe is defined by the optimal (non-forced) cutoff dates for each location and measure.
2) A * next to Post COVID-19 mean indicates a statistically significant difference compared to the Pre COVID-19 level at at least the 95% confidence level.

Supporting Figures

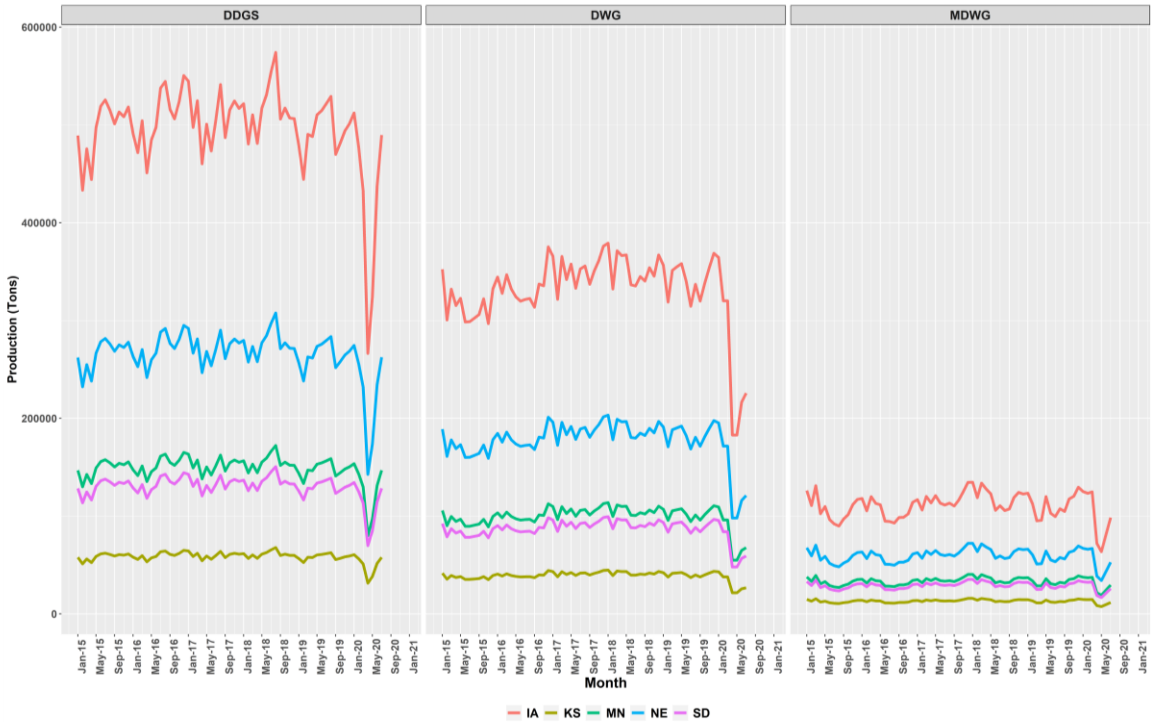

Figure 1. Total Production by Type of Distillers' Grains by State, Jan 2015 – Jan 2021

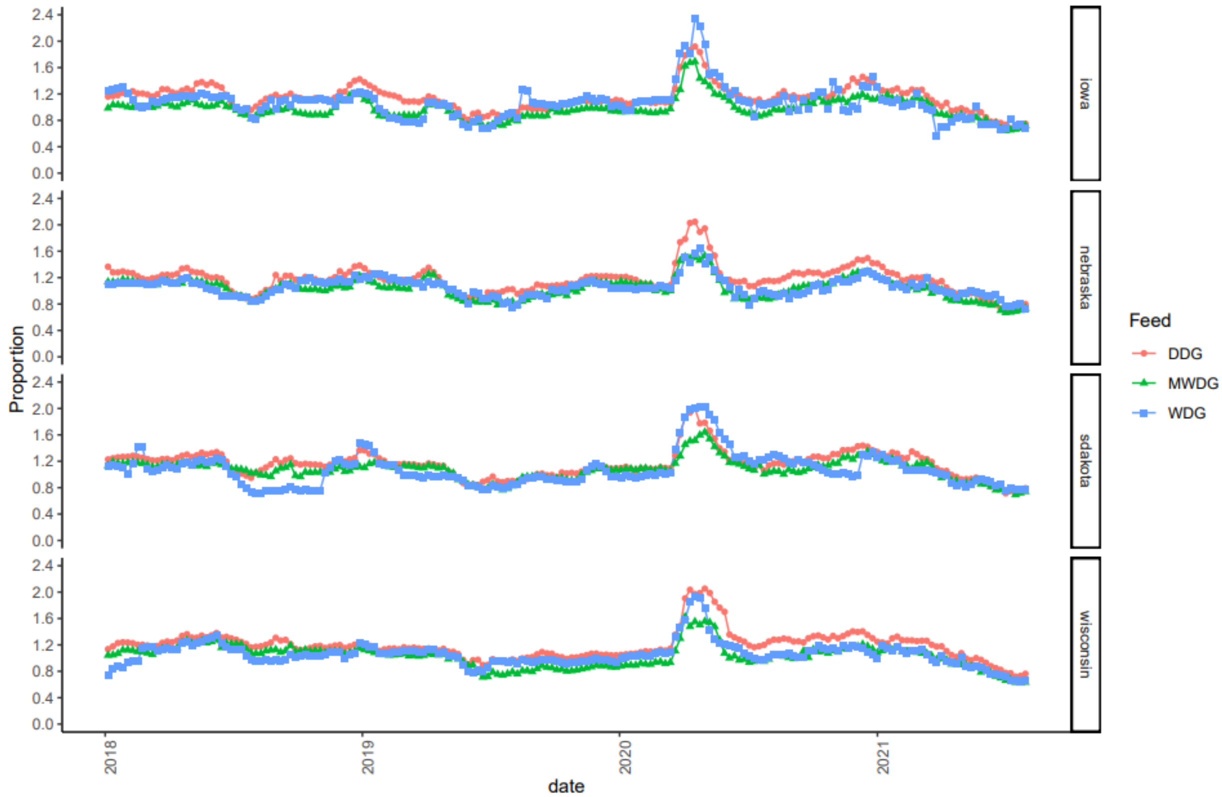

Figure 2. Weekly Percent-Corn Prices for DDG, MDGS, and WDGS in Iowa, Nebraska, South Dakota, and Wisconsin – 2018-2021.

Figure 3. Weekly Percent-Corn Price Differences for Distillers' Grains in Iowa, Nebraska, South Dakota, and Wisconsin – 2018-2021.

CHAPTER 3 - A MARKET MODEL TO MEASURE IMPACTS IN THE DISTILLERS' GRAINS MARKET

Abstract:

Distillers' grains are co-products of the fuel ethanol production process and are commonly marketed to livestock operations as important components to livestock feed rations. The purpose of this paper is to estimate the impacts of different market shocks on the ethanol and distillers' grains sectors. Specifically, this paper develops an equilibrium displacement model (EDM) of the U.S. ethanol industry to estimate the short-run impacts of different market shocks on prices and quantities of ethanol, WDGS, MDGS, and DDGS. The results of the equilibrium displacement analysis indicate that the responses of ethanol and each type of grain to market shocks rely heavily on the relationships between the products. Applying this analysis to real-world events may help both plants and producers in adjusting their operations to minimize the impacts of market shocks.

Introduction

Distillers' grains are co-products of the fuel ethanol production process and are commonly marketed to livestock operations as important components to livestock feed rations. In the United States, the vast majority of ethanol and, therefore, distillers' grain is produced from corn – roughly 40% of the total US corn crop goes to ethanol production each year (USDA ERS 2021). Consequently, distillers' grains use corn as a primary input in production while also serving as an imperfect substitute to corn for livestock feedlot operations.

Since distillers' grains are necessary co-products to ethanol production and rely on corn prices while also competing with corn as end products in the marketplace, they are uniquely susceptible to a wide variety of market shocks. These shocks can come in form of supply shocks, demand shocks, or some combination of the two. Despite the importance of distillers' grains to both the ethanol and livestock industries, the nature of the responses from different distillers' grains (dried distillers' grains (DDGS), modified wet distillers' grains (MDGS), and wet distillers' grains (WDGS)) and the ethanol system due to various shocks are largely unknown.

The purpose of this paper is to estimate the impacts of different market shocks on the ethanol sector. Specifically, this paper develops an equilibrium displacement model (EDM) of the U.S. ethanol industry to estimate the short-run impacts of different market shocks on prices and quantities of ethanol, WDGS, MDGS, and DDGS. The model incorporates vertical linkages from ethanol production through the creation of different distillers' grains. The model assumes a fixed proportion Leontief structure and that ethanol plants face three decisions for distillers' grains in the production process: They decide whether to (1) sell all wet distillers' grains, (2) dry the WDGS to produce and sell MDGS, or (3) dry MDGS to produce and sell DDGS. To our knowledge, no existing papers have attempted to address this topic.

The results of the equilibrium displacement analysis indicate that the responses of ethanol and each type of grain to market shocks rely heavily on the relationships between the products. For example, a reduction in the quantity of livestock demanding distillers' grains results in unequal declines in the demand for each type of distillers' grain. This difference is due to the substitution effects between each type of distillers' grain. The equilibrium displacement analysis results are important to both ethanol plants and livestock producers for understanding the ways in which certain market shocks may impact their operations.

The objective of this paper is to propose an equilibrium displacement framework to measure the impacts of market shocks to the distillers' grains' prices and quantities. By incorporating the relationships between dried, modified, and wet distillers' grains in the market, this model framework allows users to observe the relative distribution of different market shocks to each distillers' grain product. Applying this analysis to real-world events may help both plants and producers in adjusting their operations to minimize the impacts of market shocks.

Ethanol Plant Production

In the United States, distillers' grains are most often produced by the dry-grind ethanol production process. The purpose of the dry-grind production process is to ferment as much of the corn kernel as possible while leaving little to waste. In this process, the starch in the kernel is converted to ethanol and carbon dioxide, and the residual proteins, fats, and fiber are converted into thin stillage and wet distillers' grains co-products. The thin stillage is then often concentrated into condensed distillers' solubles, which is mixed with wet distillers' grains to become wet distillers' grains with solubles (WDGS) and then dried to become modified wet distillers' grains with solubles (MDGS) or dried distillers' grains with solubles (DDGS) (Liu 2011).

When distillers' grains first began to experience widespread availability in the marketplace, they were primarily sold to local livestock operations as WDGS with 60%-65% moisture and were considered a protein feed due to their high crude protein contents (25%-35%). They were consequently priced as an alternative to soybean meal, whose crude protein content is 45%-50%. But as supply grew, distillers' grains shifted to being primarily viewed as alternatives to corn in livestock feed rations.

Today, distillers' grains products are most commonly sold as WDGS, MDGS, and DDGS. Both MDGS and WDGS contain high moisture contents that limit the distance they can be shipped, although they both offer slightly higher feeding values than DDGS (Nuttelman et al. 2011). As a result, DDGS are the most common form of distillers' grains nationally, comprising roughly 50% of the total distillers' grains market (USDA-NASS 2021). Each type of distillers' grain features lower starch and fiber content, higher protein, and higher levels of digestible nutrients than corn, making the nutritional properties of all types of distillers' grains preferred to corn in most cases (Liu 2011). These properties helped build a market for distillers' grains which complements that of the ethanol sector in its importance to ethanol plant revenue (Morgan 2020).

Model of U.S. Ethanol Industry

An equilibrium displacement model for a representative ethanol plant that produces ethanol and wet, modified, and dried distillers' grains was constructed. A Leontief production function is assumed in which the proportions of the ethanol plant technology to produce ethanol and wet distillers' grains remain fixed. This is largely supported by the fact that one bushel of corn produces 2.8 gallons of ethanol and 17-18 lbs. of distillers' grains, and little can be done to alter that ratio.[4] Using this hypothetical plant, the effects of different supply, demand, and combined supply and demand shocks to ethanol and distillers' grains market are demonstrated.

Structural Model

The industry cost function is assumed to be representative of a cost function for a typical ethanol plant.

<u>Quantity Constraint</u>

The total quantity of distillers' grains can be represented by:

$$Q_w^s \times 0.325 = Q_w^D \times 0.325 + Q_m \times 0.475 + Q_d \times 0.9$$

where Q_w^s is the quantity of wet distillers' grains supplied prior to any drying decision, and Q_w^D, Q_m, Q_d are the quantities of wet, modified, and dried distillers' grains supplied to the market following the drying decisions. Each coefficient represents the average dry matter percentage of each type of grain.

First, the initial share of distillers' grain dry matter going to Q_w^D, Q_m, and Q_d needs to be calculated.

1) $\alpha_1 Q_w^S = \sum_j \alpha_j Q_j$

[4] Other co-products can also comprise a portion of plant revenue, such as corn oil and carbon dioxide. These co-products are not included here to maintain the simplicity of the model.

The log differential of Equation 1 is as follows:

$$a_1 dQ_1 = \sum_j \alpha_j dQ_j$$

$$a_1 \frac{dQ_1}{Q_1} = \sum_j \alpha_j \frac{Q_j}{Q_1}\frac{dQ_j}{Q_j}$$

$$a_1 dlnQ_1 = \sum_j \alpha_j s_j dlnQ_j$$

$$dlnQ_1 = \frac{\sum_j \alpha_j s_j dlnQ_j}{\alpha_1}$$

where α_1 is the percent dry matter in each type of distillers' grain, Q_1 is the total quantity of wet distillers' grains produced prior to any drying decisions, Q_j is the quantity of distillers' grain post-drying decision $j = \{WDGS, MDGS, DDGS\}$, and s_j is the share the distillers' grain j. The shares of each grain were calculated using the five-year average shares of production of DDGS, MDGS, and WDGS, according to data from the United States Department of Agriculture's National Agricultural Statistics Service. Those shares are 53%, 12%, and 35% for DDGS, MDGS, and WDGS, respectively.

Following the log differential of Equation 1 using the previously specified dry matter and market share percentages retrieves:

$$d \ln Q_w^S = 0.35 \times d \ln Q_w^D + 0.18 \times d \ln Q_m + 1.47 \times d \ln Q_d$$

Supply Function Specification

Let the cost function $C(Q_w, Q_e; P_c, P_{elec}, P_{nat}, P_o)$ describe the technology of the ethanol plant, where:

$$Q_w = quantity\ of\ WDGS\ produced$$

$$Q_e = quantity\ of\ ethanol\ produced$$

$$P_c = price\ of\ corn$$

$$P_{elec} = price\ of\ electricity$$

$$P_{nat} = price\ of\ natural\ gas$$

$$P_o = price\ of\ other\ ethanol\ plant\ inputs$$

Then, WDGS supply is set equal to a share of ethanol supply as specified by the Leontief structure. This retrieves:

2) $Q_w^S = \alpha Q_e^S$, leading to: $d \ln Q_w = d \ln Q_e$

Likewise, the ethanol supply is given by $P_e^s = C_e$. Once again taking the logarithmic differential of the ethanol supply function to get it in terms of elasticities gets[5]:

3) $d\ ln\ P_e^s = \varepsilon_{ew} d\ ln\ Q_w^s + \varepsilon_{ee} d\ ln\ Q_e + \varepsilon_{ec} d\ ln\ P_c + \varepsilon_{eelec} d\ ln\ P_{elec} +$
$\varepsilon_{enat} d\ ln\ P_{nat} + \varepsilon_{eo} d\ ln\ P_o$

The assumption that $d \ln Q_w = d \ln Q_e$ is because it is assumed that WDGS and ethanol are jointly produced in an ethanol plant (i.e. by producing one you also produce the other) whose technology is the same, and the proportions of that technology remain fixed regardless of the quantity produced.

After the initial distilling process, the ethanol plant must decide whether to sell WDGS or convert them into either MDGS by drying them once or DDGS by drying them twice. For simplicity, it is assumed the ethanol plant uses different technology to create WDGS, MDGS, and DDGS, and the plant must account for the prices in the other distillers' grain before each decision to create a drier product. This follows that the cost

[5] Considering roughly 40% of the United States' corn supply goes to ethanol production, it may be the case that corn should be endogenous to the supply of ethanol in this model. Doing so was beyond the scope of this paper, but it may be worth considering in future analyses.

function $C(Q_m, Q_w; P_w, P_{elec}, P_{nat}, P_{add})$ describes the technology used to make MDGS and the cost function $C(Q_d, Q_m; P_m, P_{elec}, P_{nat}, P_{add})$ describe the technology used to make DDGS. Then the MDGS supply function is given by $P_m^s = C_m$ and the DDGS supply function is given by $P_d^s = C_d$, where:

$$Q_w = quantity\ of\ WDGS$$

$$Q_m = quantity\ of\ MDGS$$

$$Q_d = quantity\ of\ DDGS$$

$$P_w = price\ of\ WDGS$$

$$P_m = price\ of\ MDGS$$

$$P_d = price\ of\ DDGS$$

$$P_{elec} = price\ of\ electricity$$

$$P_{nat} = price\ of\ natural\ gas$$

$$P_{add} = price\ of\ additional\ drying\ inputs$$

Once again taking the logarithmic differential of the MDGS and DDGS supply function, respectively, to get both in terms of elasticities retrieves:

4) $d\ ln\ P_m^s = \varepsilon_{mm} d\ ln\ Q_m + \varepsilon_{mw} d\ ln\ P_w + \varepsilon_{melec} d\ ln\ P_{elec} + \varepsilon_{mnat} d\ ln\ P_{nat} + \varepsilon_{madd} d\ ln\ P_{add}$

5) $d\ ln\ P_d^s = \varepsilon_{dd} d\ ln\ Q_d + \varepsilon_{dm} d\ ln\ P_m + \varepsilon_{delec} d\ ln\ P_{elec} + \varepsilon_{dnat} d\ ln\ P_{nat} + \varepsilon_{dadd} d\ ln\ P_{add}$

This assumes a sort of cascading production from WDGS to MDGS to DDGS. In other words, it is assumed DDGS can only be produced from MDGS and not from WDGS.

Demand Specification

Let the demand function for ethanol be given as $Q_e^d = f(P_e, P_g, K)$, where:

$$P_e = price\ of\ ethanol$$

$$P_g = price\ of\ pump\ gasoline\ prices$$

$$K = government\ policies$$

Then, taking the logarithmic differential of the ethanol demand function to get it in terms of elasticities gets:

6) $d\ ln\, Q_e^d = \eta_{ee} d\ ln\, P_e + \eta_{eg} d\ ln\, P_g + \eta_{ek} d\ ln\, K$

Let the demand function for WDGS be given as $Q_w^d = f(P_w, P_m, P_d, P_c, P_s, Q_{lof})$ where:

$$P_w = price\ of\ WDGs$$

$$P_m = price\ of\ MWDGs$$

$$P_d = price\ of\ DDGs$$

$$P_c = price\ of\ corn$$

$$P_s = price\ of\ other\ subsitute\ feeds$$

$$Q_{lof} = quantity\ of\ livestock\ on\ feed$$

Then, taking the logarithmic differential of the WDGS demand function to get it in terms of elasticities retrieves:

7) $d\ ln\, Q_w^d = \eta_{ww} d\ ln\, P_w + \eta_{wm} d\ ln\, P_m + \eta_{wd} d\ ln\, P_d + \eta_{wc} d\ ln\, P_c + \eta_{ws} d\ ln\, P_s + \eta_{wlof} d\ ln\, Q_{lof}$

The demand specification for MDGS follow the same as WDGS as $Q_m^d = f(\cdot)$. Taking the logarithmic differential of the MDGS demand function to get it in terms of elasticities gets:

8) $d\ ln\, Q_m^d = \eta_{mw} d\ ln\, P_w + \eta_{mm} d\ ln\, P_m + \eta_{md} d\ ln\, P_d + \eta_{mc} d\ ln\, P_c + \eta_{ms} d\ ln\, P_s + \eta_{mlof} d\ ln\, Q_{lof}$

The DDGS demand specification allows for export market conditions (M) to influence domestic DDGS demand. Thus, the demand specification is $Q_d^d = f(P_w, P_m, P_d, P_c, P_s, Q_{lof}, M)$. Taking the logarithmic differential of the DDGs demand function to get it in terms of elasticities retrieves:

9) $$d\,ln\,Q_d^d = \eta_{dw} d\,ln\,P_w + \eta_{dm} d\,ln\,P_m + \eta_{dd} d\,ln\,P_d + \eta_{dc} d\,ln\,P_c + \eta_{ds} d\,ln\,P_s + \eta_{dlof} d\,ln\,Q_{lof} + \eta_{dm} d\,ln\,M$$

Equilibrium Conditions

We now take equations (1)-(9) and put them in a matrix format with the endogenous variables on the left-hand side and the exogenous on the right-hand side. These yield:

10)

$$\begin{array}{c} - \\ \boldsymbol{WDG\ Market\ Clearing} \\ \boldsymbol{Q_w = Q_e} \\ \boldsymbol{Ethanol\ Supply} \\ \boldsymbol{MWDG\ Supply} \\ \boldsymbol{DDG\ Supply} \\ \boldsymbol{WDG\ Demand} \\ \boldsymbol{Ethanol\ Demand} \\ \boldsymbol{MWDG\ Demand} \\ \boldsymbol{DDG\ Demand} \end{array} \begin{bmatrix} \boldsymbol{d\ln Q_w^s} & \boldsymbol{d\ln Q_w^d} & \boldsymbol{d\ln Q_e} & \boldsymbol{d\ln Q_m} & \boldsymbol{d\ln Q_d} & \boldsymbol{d\ln P_w} & \boldsymbol{d\ln P_e} & \boldsymbol{d\ln P_m} & \boldsymbol{d\ln P_d} \\ -1 & 0.35 & 0 & 0.18 & 1.47 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \varepsilon_{ew} & 0 & \varepsilon_{ee} & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & \varepsilon_{mm} & 0 & \varepsilon_{mw} & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & \varepsilon_{dd} & 0 & 0 & \varepsilon_{dm} & -1 \\ 0 & -1 & 0 & 0 & 0 & \eta_{ww} & 0 & \eta_{wm} & \eta_{wd} \\ 0 & 0 & -1 & 0 & 0 & 0 & \eta_{ee} & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & \eta_{mw} & 0 & \eta_{mm} & \eta_{md} \\ 0 & 0 & 0 & 0 & -1 & \eta_{dw} & 0 & \eta_{dm} & \eta_{dd} \end{bmatrix}$$

$$= \begin{bmatrix} \boldsymbol{d\ln P_c} & \boldsymbol{d\ln P_o} & \boldsymbol{d\ln P_{elec}} & \boldsymbol{d\ln P_{nat}} & \boldsymbol{d\ln P_{add}} & \boldsymbol{d\ln P_s} & \boldsymbol{d\ln P_g} & \boldsymbol{d\ln Q_{lof}} & \boldsymbol{d\ln M} & \boldsymbol{d\ln K} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\varepsilon_{ec} & -\varepsilon_{eo} & -\varepsilon_{eelec} & -\varepsilon_{enat} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\varepsilon_{melec} & -\varepsilon_{mnat} & -\varepsilon_{madd} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\varepsilon_{delec} & -\varepsilon_{dnat} & -\varepsilon_{dadd} & 0 & 0 & 0 & 0 & 0 \\ -\eta_{wc} & 0 & 0 & 0 & 0 & -\eta_{ws} & 0 & -\eta_{wlof} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\eta_{eg} & 0 & 0 & -\eta_{ek} \\ -\eta_{mc} & 0 & 0 & 0 & 0 & -\eta_{ms} & 0 & -\eta_{mlof} & 0 & 0 \\ -\eta_{dc} & 0 & 0 & 0 & 0 & -\eta_{ds} & 0 & -\eta_{dlof} & -\eta_{dM} & 0 \end{bmatrix}$$

Eq. (10) can be rewritten as:

$$\begin{bmatrix} Q_w^S \\ Q_w^D \\ Q_e \\ Q_m \\ Q_d \\ P_w \\ P_e \\ P_m \\ P_d \end{bmatrix} = \underbrace{A^{-1}}_{9x9} \underbrace{B}_{9x10} \begin{bmatrix} P_c \\ P_o \\ P_{elec} \\ P_{nat} \\ P_{add} \\ P_s \\ P_g \\ Q_{lof} \\ M \\ K \end{bmatrix}$$

where A is equal to the left-hand matrix in Eq. (10) and B is equal to the right-hand matrix in Eq. (10).

Model Parameterization

Solutions for the Y variable in equation (10) require elasticity estimates for the elements of A and parameter estimates for the elements of B. Elasticity measures the responsiveness of changes in one measure to changes in another measure. For example, price elasticity of demand measures the change in quantity demanded resulting from a change in price. Elasticities can be directly interpreted as percentages, so a price elasticity of -2 would mean that quantity would decrease by 2% in response to a 1% increase in price. When possible, elasticity estimates are obtained from the extant literature. Table 2 lists the elasticities used in the model.

Hypothetical Shocks

In this section, potential market shocks to the distillers' grains industry are explored. The purpose of this section is to provide applications of the analysis in this paper to examples of real-world market disturbances. For the sake of simplicity, all shocks introduced here will be explored at the 10% magnitude – either positive or negative – in the equilibrium displacement model. Both supply and demand shock scenarios are introduced, and results of these shocks are discussed in next section, followed by possible long-term implications. As will be evident by these results, livestock producers who heavily rely on distillers' grains in their livestock feed rations regularly expose themselves to these potential risks in the market. To better manage distillers' grains price volatility, producers may, consequently, consider changing their relationship to distillers' grains in the coming years, while ethanol plants may explore ways to limit the price fluctuations in the distillers' grains marketplace.

Supply Shocks

The first shock explored is a supply shock in the corn market. This disruption could be in the form of a weather-related disruption, a corn-specific plant disease, or an insect infestation that would specifically limit corn supply (i.e., corn borer). Since corn is the primary input in ethanol production, a negative impact to the corn supply would be expected to limit the supply of distillers' grains by making ethanol and distillers' grains more expensive to produce. The exact impact on distillers' grains prices is less clear since distillers' grains serve as substitutes to corn in the livestock feed market. One historical example of this type of shock is the 2019 floods throughout much of the Midwestern United States. These floods impacted corn supply, reduced ethanol production by roughly 13%, and raised gasoline prices (Renshaw and Kelly, 2019).

The second shock is an increase in the price of natural gas. Since natural gas is an input in ethanol and distillers' grains production, an increase in natural gas prices would raise input costs and negatively impact the supply of ethanol and distillers' grains. Natural gas would comprise a different share of production costs for WDGS versus DDGS, thus the impact varies by type of distillers' grain. This is because natural gas is an input in both the ethanol production and distillers' grains drying processes. A real-world example of this is currently unfolding in the marketplace. Natural gas prices in the United States this year have risen over 80% versus the same period last year (Eaton and Blunt 2021).

The third shock is an increase in crude oil and gasoline prices. Fuel ethanol is a complementary product to gasoline in domestic markets because of the minimum fuel blending requirements. However, it can also act, in some cases, as an imperfect substitute to gasoline, since vehicles have varying levels of flexibility in the percentage of ethanol in gasoline blends that their engines can handle. As a result, the direction of the impacts of an increase in gasoline prices on the ethanol and distillers' grains industry is unclear. A recent example of this impact has been price of gasoline surging 6.1% in October 2021 versus October 2020 (Mutikani 2021).

Demand Shocks

The fourth shock is anything that would serve to reduce the quantity of livestock demanding feed in the United States. This could range from the introduction of more stringent environmental regulations that would reduce the total number of livestock in the United States to the spread of a livestock disease that would cause animal mortality or morbidity and would, therefore, reduce the quantity of feed consumed. All else equal, fewer livestock would mean lower demand for distillers' grains, and this could hold true in both the short-run and the long-run.

Lower demand for livestock feed would not only impact distillers' grains demand – it would also impact the markets for corn and other livestock feeds. Therefore, ceteris paribus, animal feed prices would be expected to decline. This decline in feed prices would serve to lower the cost of production for ethanol, since corn would be less expensive to purchase. The effect on the distillers' grains market would be ambiguous. On one hand, lower input costs would make distillers' grains less expensive to produce, but reduced demand would disincentivize distillers' grains production. Consequently, the quantity of distillers' grains produced would likely rely on the state of the ethanol market. If ethanol production is proving profitable for ethanol plants, they would produce ethanol and, therefore, distillers' grains, regardless of whether a robust market for distillers' grains exists. On the other hand, if ethanol production is less profitable, ethanol plants would likely reduce the production of ethanol in an attempt to support both ethanol and distillers' grains prices.

There are few historical examples of a shock of this type in the United States. Internationally, spread of African Swine Fever in China certainly affected the country's demand for feed crops, but the direct impact to US distillers' grains markets were difficult to identify beyond a general reduction in demand for US feed exports. A spread of a similar magnitude in one of the major US livestock industries, though, would likely hamper domestic distillers' grains and livestock feed markets in a manner similar to the one discussed above.

Supply and Demand Shock

The fifth shock would be an impact to governmental regulations, such as the removal of government support for the ethanol industry or the introduction of minimum quality standards for distillers' grains. An introduction of minimum quality or nutrition standards to the distillers' grains market would likely impact both the supply and demand of distillers' grains. If, for example, certain types of distillers' grains were required to contain specified minimum levels of protein, fat, and oil, livestock producers would be better able to ensure the quality of the feed they were providing their livestock. All else equal, the minimum quality or nutrition standards would likely increase the demand for distillers' grains from livestock producers, as they would increase confidence in product quality and predictability of livestock performance. On the supply side, these standards would likely impose additional costs on ethanol plants, since plants would need to ensure their products met the minimum requirements. Ceteris paribus, an increase in costs would decrease the production of distillers' grains. The exact impact on the distillers' market would depend on the relative increase in demand versus the rise in input costs, since elevated demand would incentivize additional production, while higher input costs would have the opposite effect.

Results

For the five proposed scenarios, a 10% shock is assumed. In other words, positive 10% shocks to the corn price, natural gas price, and gasoline price were introduced to the model in separate scenarios. A negative 10% shock to livestock on feed and government policies were applied in the fourth and fifth scenarios.

The changes in the prices and quantities for each commodity in the system is reported in Table 1. All the positive 10% shocks resulted in the same directional responses for the supply and demand of each product – although the magnitude varied by product. The positive 10% shocks to corn, natural gas, and gasoline prices, for example, all resulted in negative impacts to ethanol supply but positive impacts to ethanol demanded. These results can be interpreted in percentage terms. For example, a 10% increase in the price of natural gas resulted in a 3.6% decline in ethanol supply in this model. Distillers' grains demand, on the other hand, experienced negative responses to the positive shocks, all likely the result of the higher prices of distillers' grains caused by the positive price shocks.

Conversely, the negative 10% price shocks generally resulted in opposite directional responses for each measure, dependent on whether the shock was applied to livestock on feed or government policies. Predictably, a negative shock to livestock on feed led to a decline in demand for distillers' grains, while a negative shock to government policies led to increases in demand for distillers' grains. In this case, the concept of a negative shock to government policies is more unclear. It could be best described as a pullback in government regulations. With fewer government regulations, inefficiency would be decreased in the markets, which could help explain the subsequent increase in distillers' grains demand.

Discussion and Conclusions

This equilibrium displacement model serves as a useful tool in quantifying impacts to the ethanol and distillers' grains industry, the results it produces are of little practical use without an examination of their potential long-term impacts on the market. In general, the long-term effects of these market shocks on the distillers' grains industry would be expected to take two forms: adjustments to distillers' supply and adjustments to distillers' demand.

The equilibrium displacement model only reflects adjustments to these factors in the short run, since the model inherently holds everything else equal while applying a single shock. Over the long-run, ethanol plants and livestock producers have more time to adjust their decision-making to reach new equilibriums in the market.

A long-term adjustment to these market shocks on the supply-side of the distillers' grains market would likely come in the form of ethanol plants continuing their effort to distinguish their distillers' grains products by further specializing and differentiating their feed products. Pelletized distillers' grains, high protein distillers' grains, and de-oiled distillers' grains are examples of these value-added (or value-subtracted, depending on the customer) products currently in the marketplace. These differentiated product lines further divide the distillers' grains market and would serve to insulate each faction from market shocks in an adjacent distillers' grain type.

On the demand side, livestock producers may look to avoid distillers' grains market volatility entirely by making permanent shifts away from their reliance on distillers' grains. To do this, livestock producers may absorb the upfront cost to invest in small, operation-specific grain milling or corn crushing operations to replace distillers' grains in their livestock feed rations. Despite the upfront cost, the prospect of more consistent and manageable feed costs over the long run may incentivize the shift away from distillers' grains. A large-scale shift away from distillers' grains would likely cripple the ethanol industry, barring the development of ethanol co-products for primarily non-feed purposes. Beef cattle operations, where most of these grain milling and corn crushing operations are being considered, comprise roughly 63% of the domestic distillers' grains market (Hoffman and Baker 2010). So, losing even a portion of beef cattle demand for distillers' grains would introduce series demand issues for the distillers' grains industry.

To understand market shocks to the ethanol and distillers' grains industry, an equal consideration of both short-run and long-run responses is needed. This paper provides an equilibrium displacement framework for quantifying the short-run impacts of market shocks and uses those results to inform a discussion of possible long-run adjustments. Most of the work in this space to date has focused on dynamic adjustments to distillers' grains supply or demand rather than conducting comparative statics analysis in the distillers' grains market (Schmit et al. 2008; Schmit et al. 2009; Suh and Moss 2014). A comparative statics analysis allows for a closer look at how changes in one supply or demand component affect the entire industry and can be easily updated to reflect longer-term market shifts. The results found in this paper suggest that both distillers' grains supply and demand are susceptible to market shocks. Ethanol plants and livestock producers must, therefore, strategically plan to minimize the impacts of these shocks to their operation

References

Eaton, Collin, and Katherine Blunt. “Natural-Gas Exports Lift Prices for U.S. Utilities Ahead of Winter.” The Wall Street Journal. Dow Jones & Company, November 7, 2021. https://www.wsj.com/articles/natural-gas-exports-lift-prices-for-u-s-utilities-ahead-of-winter-11636281000.

Hoffman, Linwood, and Allen Baker. “Market Issues and Prospects for U.S. Distillers’ Grains Supply, Use, and Price Relationships.” Economic Research Service. United States Department of Agriculture, December 2010. https://www.ers.usda.gov/mediaImport/107533/fds10k01_1_.pdf.

Hofstrand, Don. “Tracking Ethanol Profitability: Ag Decision Maker.” Tracking Ethanol Profitability. Iowa State University, September 14, 2021. https://www.extension.iastate.edu/agdm/energy/html/d1-10.html.

Kelly, Stephanie, and Jarrett Renshaw. “EXCLUSIVE EPA to Urge U.S. Biofuel BLENDING Mandates below 2020 Levels, Sources Say.” Reuters. Thomson Reuters, August 20, 2021. https://www.reuters.com/business/energy/us-epa-recommend-lower-biofuel-blending-mandates-below-2020-levels-sources-2021-08-20/.

Khachatryan, Hayk, Jia Yan, and Ken Casavant. “Spatial Differences in Price Elasticityof Demand for Ethanol.” *Journal of the Transportation Research Forum*, 2011. https://doi.org/10.5399/osu/jtrf.50.3.4130.

Liu, KeShun. “Chemical Composition of Distillers’ Grains, a Review.” Journal of Agricultural and Food Chemistry 59, no. 5 (2011): 1508–26. https://doi.org/10.1021/jf103512z.

Luchansky, Matthew S., and James Monks. “Supply and Demand Elasticities in the U.S. Ethanol Fuel Market.” Energy Economics 31, no. 3 (2009): 403–10. https://doi.org/10.1016/j.eneco.2008.12.005.

Mathews, Kenneth H., and Michael J. McConnell. “The Market for U.S. Livestock Feed Proteins.” Applied Economic Perspectives and Policy 34, no. 4 (2012): 555–69. https://doi.org/10.1093/aepp/pps030.

Morgan, Tyne. 2020. Ethanol Plants Could Soon Start Producing for DDGs, Not Ethanol. March 27. https://www.drovers.com/article/ethanol-plants-could-soon-start-producing-ddgs-not-ethanol.

Mutikani, Lucia. “Surging Gasoline, Food Prices Fan U.S. Inflation.” Reuters. Thomson Reuters, November 10, 2021. https://www.reuters.com/business/us-consumer-prices-surge-weekly-jobless-claims-fall-2021-11-10/.

Nuttelman, Brandon L., Will A. Griffin, Josh R. Benton, Galen E. Erickson, and Terry J. Klopfenstein. 2011. *Comparing Dry, Wet, or Modified Distillers’ Grains Plus Solubles on Feedlot Cattle Performance.* Lincoln, Nebraska: The Board of Regents of the University of Nebraska

Renshaw, Jarrett, and Stephanie Kelly. “Midwest Floods Hammer U.S. Ethanol Industry, Push Some Gasoline Prices toward 5-Year High.” Reuters. Thomson Reuters, April 8, 2019. https://www.reuters.com/article/usa-ethanol-floods/rpt-midwest-floods-hammer-u-s-ethanol-industry-push-some-gasoline-prices-toward-5-year-high-idUSL1N21P06D.

Schmit, T. M., R. N. Boisvert, D. Enahoro, and L. Chase. “Dairy Farm Management Adjustments to Biofuels-Induced Changes in Agricultural Markets.” Working

Paper - Department of Applied Economics and Management, Cornell University, no. WP 2008-16 (2008): 31 pp.

Schmit, T. M., R. N. Boisvert, D. Enahoro, and L. E. Chase. “Optimal Dairy Farm Adjustments to Increased Utilization of Corn Distillers’ Dried Grains with Solubles.” Journal of Dairy Science 92, no. 12 (December 2009): 6105–15. https://doi.org/10.3168/jds.2009-2213.

Suh, Dong Hee & Moss, Charles B., 2014. "Dynamic Adjustment of Demand for Distiller's Grain: Implications for Feed and Livestock Markets," 2014 Annual Meeting, February 1-4, 2014, Dallas, Texas 162454, Southern Agricultural Economics Association.

Taheripour, Farzad, Thomas W. Hertel, Wallace E. Tyner, Jayson F. Beckman, and Dileep K. Birur. “Biofuels and Their by-Products: Global Economic and Environmental Implications.” Biomass and Bioenergy 34, no. 3 (2010): 278–89. https://doi.org/10.1016/j.biombioe.2009.10.017.

USDA ERS. “Feedgrains Sector at a Glance.” United States Department of Agriculture Economic Research Service, June 28, 2021. https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/feedgrains-sector-at-a-glance/.

USDA-NASS. USDA/NASS QuickStats Ad-hoc Query Tool, 2021. https://quickstats.nass.usda.gov/.

Supporting Tables

Table 1. Results of Equilibrium Displacement Model Shocks.

Equation #	Equation	*Variable Impacted*	**Positive 10% Shock**			**Negative 10% Shock**	
			Price of Corn	*Price of Natural Gas*	*Price of Gasoline*	*Livestock on Feed*	*Government Policies*
			Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1	WDG Market Clearing	$d\ln Q_w^s$	-0.229	-0.036	-0.284	0.000	0.100
2	Qw=Qe	$d\ln Q_w = d\ln Q_e$	0.881	0.052	0.409	0.387	-0.144
3	Ethanol Supply, MCe	$d\ln P_e^s$	-0.229	-0.036	-0.284	0.000	0.100
4	MWDG Supply, MCm	$d\ln P_m^s$	0.505	0.025	0.201	0.241	-0.071
5	DDG Supply, MCd	$d\ln P_d^s$	-0.427	-0.040	-0.315	-0.122	0.111
7	WDG Q Demanded	$d\ln Q_w^D$	-1.611	-0.058	-0.891	-0.627	0.314
6	Ethanol Q Demanded	$d\ln Q_e^D$	0.070	0.011	0.000	0.000	0.000
8	MWDG Q Demanded	$d\ln Q_m^D$	-1.289	-0.035	-0.713	-0.502	0.251
9	DDG Q Demanded	$d\ln Q_d^D$	-1.031	-0.017	-0.570	-0.401	0.201

Table 2. Estimated Elasticities in Equilibrium Displacement Model.

Elasticity	Estimate	Source
ε_{ew}	0	Substitution constraints in Leontief production
ε_{ee}	0	Substitution constraints in Leontief production
ε_{mm}	0	Substitution constraints in Leontief production
ε_{mw}	0.8	Estimate of WDGS cost share in MDGS production
ε_{dd}	0	Substitution constraints in Leontief production
ε_{dm}	0.8	Estimates of MDGS cost share in DDGS production
η_{ww}	-1.3	Author estimate
η_{wm}	0.06	Author estimate
η_{wd}	1.24	Share-weighted symmetry constraint
η_{ee}	-3.27	Khachatryan et al. 2011
η_{mw}	0.18	Share-weighted symmetry constraint
η_{mm}	-1.8	Author estimate
η_{md}	1.63	Share-weighted symmetry constraint
η_{dw}	0.82	Share-weighted symmetry constraint
η_{dm}	0.37	Share-weighted symmetry constraint
η_{dd}	-1.19	Share-weighted symmetry constraint
ε_{ec}	0.7	Five-year average of corn's contribution to ethanol's cost of production (Hofstrand 2021).
ε_{eo}	0.14	Estimated cost share
ε_{eelec}	0.05	Estimated cost share
ε_{enat}	0.11	Five-year average of natural gas's contribution to ethanol's cost of production (Hofstrand 2021).
ε_{melec}	0.0025	Estimated cost share
ε_{mnat}	0.11	Five-year average of natural gas's contribution to ethanol's cost of production (Hofstrand 2021).
ε_{madd}	0.0675	Author estimate
ε_{delec}	0.0225	Estimated cost share
ε_{dnat}	0.11	Five-year average of natural gas's contribution to ethanol's cost of production (Hofstrand 2021).
ε_{dadd}	0.0675	Author estimate
η_{wc}	1.4245	Suh and Moss 2014
η_{ws}	0.024	Matthews and McConnel 2011
η_{wlof}	-1	Author estimate
η_{eg}	-2.843	Luchansky and Monks 2009
η_{ek}	-1	Author estimate
η_{mc}	1.4245	Suh and Moss 2014
η_{ms}	0.024	Matthews and McConnel 2011
η_{mlof}	-1	Author estimate
η_{dc}	1.4245	Suh and Moss 2014
η_{ds}	0.9	Taheripour et al. 2010
η_{dlof}	-1	Author estimate
η_{dM}	-1	Author estimate

CHAPTER 4 - DIRECTIONS FOR FUTURE DISTILLERS' GRAINS RESEARCH

Abstract:

Previous papers published in the economic distillers' grains literature have offered an overview of the existing research, analyzed the domestic distillers' grains market, and explored some theoretical and realized impacts that shocks can have on the market. This paper proposes potential paths for the future direction of distiller grains research in economics and explores the potential contributions of non-distillers' ethanol co-product economic research to the literature. This paper concludes that the ethanol and distillers' grains markets seem poised to remain the subject of interest in the academic literature for the foreseeable future. The potential for future research in the ethanol co-products space is full of opportunities for innovative studies of new and existing products, and the research paths discussed in this paper would be valuable contributions to the literature, providing much-needed insights to industry participants.

Introduction

The previous sections have offered an overview of the economic distillers' grains literature, analyzed the domestic distillers' grains market, and explored some theoretical and realized impacts that shocks can have on the market. This section discusses the future direction of distiller grains research in economics. I also explore the potential contributions of non-distillers' ethanol co-product economic research to the literature. The paper is structured as follows:

1) Each section begins with a broad overview of the area identified as potentially under-researched or in need of re-exploration.
2) A more detailed exploration of the specifics of the research area, including types of data needed, locations of interest, and contribution to the literature. This format is repeated by topic.
3) A summary concludes the paper.

Value-Added Co-Products

The economic distillers' grains literature to date has, generally, has focused on a rather limited subsection of the possible research paths. It has done so by prioritizing the types of distillers' grains that currently comprise the largest market share while omitting new and recently emerged value-added co-products (see Table 1 in the literature review in Chapter 1). Value-added distillers' grains products include high protein, pelletized, and de-oiled distillers' grains, among many other products. Papers that mention newer, value-added co-products or areas with potential for significant market expansion generally offer hypothetical scenarios but do not conduct a rigorous analysis of those products. These value-added co-products could fundamentally shift the distillers' grains landscape by providing features distinct from traditional ethanol co-products. A more systematic exploration of these lower-visibility yet high-potential products could provide insight into the potential trajectory of the distillers' grains industry. This Information, therefore, could assist both ethanol plants and livestock producers in effectively planning for the future of their operations. Some of the specific research questions related to each value-added product are explored below.

Contribution #1: High Protein Distillers' Grains

High protein distillers' grains differ from traditional distillers' grains in their nutritional composition, and many types of high protein distillers' grains exist. These grains can be produced using pre-treated hydrolyzed distillers' grains to increase protein contents, or they can be made by separating the fiber from traditional distillers' grains to producer higher-fat, higher-protein products – among many other production methods (Perkis et al. 2008; Srinivasan et al. 2006; Srinivasan et al. 2013). How does the subsequent nutritional change affect different livestock types, and are those variations in feeding value consistent across livestock types? What is the cost of producing high protein distillers' grains versus the premium or discount the products received in the marketplace? How do feeding high protein distillers' grains help livestock producers to minimize cost or maximize profit?

Contribution #2: Pelletized Distillers' Grains

Pelletizing dried distillers' grains does little to change the nutritional composition of the product (Tidwell et al. 2000). Instead, pelletized distillers' grains offer logistical benefits to traditional distillers' grains in their ease of transportation, storage, and feeding (Rosentrater and Kongar 2009). What price premium do these logistical benefits earn in the marketplace, and how does that premium compare to the cost of pelletizing distillers' grains? In what ways does purchasing pelletized distillers' grains provide value to livestock operations?

Contribution #3: De-Oiled

De-oiled distillers' grains are made by extracting the corn oil from distillers' grains and selling the corn oil and distillers' grains separately. These products are nearly ubiquitous in the marketplace and are generally sold under the traditional DDGS, MDGS, and WDGS umbrellas (Luebbe and Erickson 2013). This was not the case when many of the studies included in the literature review were conducted, and little is known about how de-oiled distillers' grains differ from traditional distillers' grains in their feeding value. If the feeding value of de-oiled distillers' grains differs from traditional distillers' grains, are livestock producers paying traditional distillers' grains prices for fundamentally different products? Should they, instead, be paying a premium or discount for these de-oiled products?

Economic Analysis

Access to private/company data is likely required to conduct an economic analysis of these lower-visibility, value-added distillers' grains products. USDA typically publishes distillers' grains data for only DDG(S), MDGS, and WDGS, and availability of data is sporadic by location. Data directly from ethanol plants would likely include cost, revenue, and customer base information related to value-added co-products. With this data, researchers could estimate the historical and future success of value-added products – and their relationship to more traditional co-products in the marketplace.

A different approach would be to look at value-added co-products from the customer perspective. The purpose would be to determine if the "value-added" is symmetric or if the share of value is primarily accrued at the ethanol plant level instead of an even split between ethanol plants and livestock operations. This would also describe substitution patterns between traditional co-products and new value-added co-products. Given that some co-products are hypothetical or not used by all producers, gathering this data would likely take the form of a choice experiment/survey sent to livestock producers in which they would rank the relative value of various products to their operation.

Industry Impact

These research questions would help to determine if these products are cost-effective and profitable for both plants and producers. Since ethanol plants continue to roll out new products to the market – and livestock producers remain interested in ways to improve their operations – a more rigorous examination of these products would help to shape the understanding of the future of the distillers' grains space. It would also help determine if these value-added products are independent of traditional co-products' market structures.

International Research

Another possible avenue to expand the existing distillers' grains research would be to conduct a more comprehensive analysis of the state of – and potential in – the international distillers' grains industry. In many cases, ethanol plants rely on international trade to weather unfavorable market conditions and/or to boost domestic prices by limiting the supply of distillers' grains in the United States (Fabiosa et al. 2009). Without a comprehensive understanding of the international distillers' grains market, ethanol plants limit themselves of potential price-boosting revenue streams, while livestock producers suffer from a lack of information to understand distillers' grains prices and, therefore, plan for the future. This international research could be conducted from both a US export perspective and an international production perspective.

Contribution #1: Internationally Produced

Studies on non-corn ethanol co-products were excluded from the literature review to allow for appropriate comparisons. However, international ethanol production has a greater variety of inputs than in the United States, with both wheat ethanol and sugarcane ethanol comprising significant shares of ethanol markets in certain countries (Sing et al. 2016). A significant amount of work could be conducted on how consumers view the substitutability or complementarity of, specifically, wheat ethanol co-products and if end user's profit margins would be affected by switching from traditionally-used corn distillers' co-products to other distillers' co-products.

Researchers could determine whether qualitative differences in the corn versus wheat and sugar co-products exist, the relative premium or discount rewarded to international plants for those differences, and whether that premium or discount is commensurate with the change in product quality. Researchers could also explore whether international livestock producers value co-products produced in the United States or abroad differently and whether the unique valuations benefit domestic or international ethanol plants. These analyses would provide a better understanding of the competition US ethanol plants face overseas and could offer insight as to whether an international investment is warranted.

Contribution #2: Potential Export Destinations for US Distillers Grains

Economic theory suggests that products flow between location A and location B if the cost in location A plus the transportation to location B is less than the cost in location B. There is a growing body of literature that examines the export destination factors that impact trade flows. In the distillers' grains literature, there is little research on the drivers of distiller grains' trade flow. Some of these export destination factors could include the livestock feeding population, alternative feedstuffs, ethanol profit margins, costs of other imported distiller grains, and government/market regulations on feed use. A better understanding of these factors would help determine viable export countries for U.S.-produced distillers' grains.

Economic Analysis

While some studies could simply replicate the methods of domestic research papers that use publicly available data, the accessibility of that data varies from country to country and may not be as comprehensive as the information available in the United States. For that reason, in many cases, the data would need to be retrieved from either domestic ethanol plants exporting products internationally, international ethanol plants producing their co-products, or international livestock producers purchasing co-products produced in their home country or from abroad. Data retrieved from international ethanol plants – especially those using non-corn ethanol feedstocks – could take the form of simple cost and revenue information regarding basic distillers' grains products. Or the data could be more advanced – such as products sold by customers and co-products in development. This data would provide researchers the opportunity to determine what differentiates internationally produced distillers' grains and their corresponding markets from domestic distillers' grains exported abroad.

Industry Impact

While numerous studies have analyzed distillers' grains economics from the vantage point of both plants and producers, the question of whether these results hold internationally – given varying production practices and unique regulations – has rarely been asked in the existing distillers' grains literature. The research questions detailed above would help provide insight into areas where domestic ethanol plants can further their international impact. Similarly, this research will help determine if certain international markets hold latent potential for export expansions. If the results of international studies indicate a negatively-trending market for distillers' grains overseas, they may offer insights on how – if possible – to prevent similar outcomes domestically. Either way, this research would provide valuable information regarding the state of the international and domestic distillers' grains market.

Governmental Regulations and Industry Challenges

Few topics of potential interest to distillers' grains economic research seem to undergo as much change, or face the potential for change, as the ever-evolving government regulations facing the ethanol and distillers' grains industries. Despite the continual specter of new or adjusted regulations and, concurrently, altered industry structures, few studies have examined the economic impact of these regulations directly on the distillers' grains industry. Most of the studies that do explore governmental regulations infer these impacts through the lens of regulations on the ethanol industry (Gallagher et al., 2000). For example, studies analyzing the impact of minimum fuel blending requirements inherently incorporate an impact on distillers' grains quantities regardless of whether they are explicitly included in the analysis.

Regulations that increase ethanol output will increase distillers' grains output, while those that decrease ethanol output will result in a commensurate decline in distillers' grains availability. These studies, therefore, occupy a well-explored section of the literature, even if more attention could be paid to the exact economic impacts of these increases or decreases in distillers' grains availability. However, areas with little-to-no existing economic research include regulations that directly impact distillers' grains products, such as nutrition or quality standards. This is because few regulations on distillers' grains nutrition and quality currently exist. But, as the industry continues to evolve and products are further refined to extract additional value, some effort to define what adequately constitutes various distillers' grains products may be undertaken. Studies examining the potential impact of these regulations would provide much-needed insight into the market.

Contribution #1: Nutrition Standards

Given the proliferation of new, value-added distillers' grains products, the definition of what constitutes certain distillers' grains beyond basic moisture content information can vary from day to day and from ethanol plant to ethanol plant. As a result, livestock producers can struggle to know the true value of the products they are purchasing, which puts them at a disadvantage in the ethanol plant-livestock producer relationship. The introduction of nutrition/composition standards to the distillers' grains industry could help close the information gap between an ethanol plant and livestock producer. If livestock producers knew the minimum protein, fat, and oil contents of various distillers' grains products, for example, they could more effectively measure the costs of purchasing the products versus the value they would provide to their operation.

On the other hand, mandating minimum nutrition or composition standards may impose new costs on ethanol plants. A full cost-benefit analysis would likely need to consider how any new regulations would outweigh the benefit to the marketplace.

Contribution #2: Quality Standards

The impact of quality standards/regulations of distillers' grains on the ethanol industry has not been explored. Quality standards could include rules relating to maximum levels of mycotoxins or phosphorus and require ethanol plants' products to meet those standards. While these standards would not likely impact the feeding value of distillers' grains in terms of nutritional composition, they would guarantee a safe product to end-users, thus improving animal health and limiting disease.

Economic Analysis

To analyze the impact of changing regulations on the distillers' grains industry, different hypothetical policy scenarios would need to be proposed. These studies would rely on existing or newly gathered data from ethanol plants on distillers' grains quality. This data is not currently being collected. Then, using different proposed nutrition and policy standards, the economic impacts could be examined. Of specific interest would be the costs of policy adherence to ethanol plants and the corresponding benefit of a guaranteed minimum product quality to livestock producers. The subsequent change in prices of distillers' grains – and the impact of those price changes on the market – would underpin most economic studies relating to distillers' grains regulations.

Industry Impact

It may be the case that governmental regulations play the single largest role in determining the future of the ethanol and distillers' grains industry in the United States.

With little research to back up that claim, though, little is known about the extent to which a change in regulations could impact the distiller co-product market. Adding this research to the existing literature would help both ethanol plants and livestock producers better plan if changes are ever introduced. It would also assist industry representatives in better articulating their arguments for or against certain changes. At the very least, distillers' grains policy analysis studies would provide regulators with additional insight into the impact of the policies they introduce and would help market participants to better understand the role these policies could play in shaping future distillers' grains markets.

Non-Traditional Co-Products

Nearly all the existing economic research has focused on the feed co-products of the ethanol production process. Little research has focused on non-feed ethanol co-products in the marketplace. When these products are excluded, it is often assumed that these non-traditional co-products are not valuable to ethanol plant profitability. This section is fundamentally different from the topics traditionally explored. Non-traditional co-products include products that cannot be used as livestock feed or for any similar use and, therefore, are entirely separate from distillers' grains markets. Their connection to distillers' grains is that they are both co-products of ethanol production and that the production of these other co-products impacts the quantity of distillers' grains in the market

A variety of products can be produced in the ethanol process aside from the most well-known co-products – distillers' grains and corn oil. Among the products also offered by ethanol plants are purified alcohol, CO2 and dry ice, hand sanitizer, concrete rejuvenator, and base materials for bioplastic production. These products currently comprise a small fraction of ethanol plants' revenue and overall production (Jessen 2021). This is because certain products can only be made in small amounts per every larger amount of ethanol. For example, one bushel of corn leads to, on average, 2.9 gallons of denatured fuel ethanol and 15.2 pounds of distillers' grains but only 0.8 pounds of corn oil and 1.1 pounds of carbon dioxide (RFA 2021). In other cases, it may be because a more established market already exists for co-products such as distillers' grains and, therefore, plants do not choose to allocate resources to the development of these other products. Regardless, there is a lack of understanding about these products in the economic literature.

Two of the non-traditional co-products that are likely to play an outsized role in the future of ethanol production are purified alcohol/hand sanitizer and bioplastic production. The production of the former by ethanol plants proliferated during the COVID-19 pandemic, while the latter will likely play a key role in the future of an industry concerned with sustainability.

Contribution #1: Purified Alcohol/Hand Sanitizer

Most ethanol plants producing purified alcohol and hand sanitizer products are fairly new to the process and do so in small amounts relative to total ethanol and other co-product production (Wells, 2020). Fundamental questions are still not well understood such as whether the introduction of these consumer-oriented products made more plants more profitable and what consumer preferences are for corn-ethanol-based vs. traditional hand sanitizers.

Contribution #2: Bioplastics

Bioplastics are a potential generator of plant revenue given the ever-growing concerns around sustainability. Since ethanol plants have found some technical success in producing biopolymers, a practical extension of the technical ability is discovering whether producing these products is economically viable (Drennan 2018). If not, what stands in the way of making these products economically feasible? Some factors to consider would be if cost constraints or end-user demand play a larger role in determining whether ethanol plants shift some capacity to bioplastic production, or if there would need to be a change in the market to incentivize additional production capacity.

Economic Analysis

Researchers would need cost, revenue, and research data from ethanol plants to determine whether alternative co-products offer a largely untapped opportunity for ethanol plants. Equally as important would be substitute/complement product data from potential end-users of these products. This data could come from – in the case of hand sanitizer – consumer research, or – in the case of bioplastics – surveys of plastic product manufacturers. Both the ethanol plant and end-user perspectives would be essential in determining the viability of these products in the marketplace

Industry Impact

These non-traditional co-products provide a unique opportunity for ethanol plants. Plants looking to efficiently allocate limited resources would be interested in what the profit-maximizing product portfolio looks like. These non-traditional products could complement traditional distillers' grains production or replace them entirely. The products could be a new frontier for the ethanol industry, or they could be permanent niche products that a limited amount of ethanol plants produce secondary to distillers' grains production. Without research on the subject, it will be difficult to know which is the case and whether increased attention should be paid to these products by industry participants.

Conclusion

Whether these research paths come to fruition relies, in large part, on the future of the ethanol and distillers' grains industries themselves. This future remains as uncertain today as at any point since the inception of the modern-day ethanol and ethanol co-product markets. With an increasing push toward more stringent environmental regulations – one that increasingly prioritizes battery-electric cars over flex-fuel vehicles – the long-term viability of fuel ethanol in the domestic market remains in question. It seems likely that ethanol plants will need to eventually find other end-users for fuel ethanol, or they will need to adapt their product offerings to achieve continued success in the market. Whether a change in those product offerings will measurably impact distillers' grains production remains uncertain. On the other hand, ethanol and biofuel production remains a key flashpoint in politically important states such as Iowa, Wisconsin, Michigan, and Ohio, which lowers the prospects for market overhauls that negatively impact the ethanol industry.

Regardless, the ethanol and distillers' grains markets seem poised to remain the subject of interest in the academic literature for the foreseeable future. The potential for future research in the ethanol co-products space is full of opportunities for innovative studies of new and existing products. Any of the research paths discussed above would be valuable contributions to the literature and would provide much-needed insights to industry participants. The directions taken by the industry and the paths pursued in research are likely to influence each other, given the potential turning point presently facing the industry. Therefore, it is more important than ever to continue to explore new frontiers in the ethanol and co-product literature. Doing so will prove critical in understanding complex markets at an even more complex time.

References

Drennan, Corinne. “A New Source of Renewable Plastics: Converting Ethanol to Butadiene in a Single Step.” Energy.gov, January 23, 2018. https://www.energy.gov/eere/bioenergy/articles/new-source-renewable-plastics-converting-ethanol-butadiene-single-step.

Fabiosa, Jacinto F., James M. Hansen, Holger Matthey, Suwen Pan, and Francis C. Tuan. “Assessing China’s Potential Import Demand for Distillers’ Dried Grain: Implications for Grain Trade.” AgEcon Search, 2009. https://doi.org/10.22004/ag.econ.55553.

Gallagher, P., D. Otto, and M. Dikeman. “Effects of an Oxygen Requirement for Fuel in Midwest Ethanol Markets and Local Economies.” Review of Agricultural Economics 22, no. 2 (2000): 292–311. https://doi.org/10.1111/1058-7195.00023.

Jessen, Holly. “Co-products Revenue Rising @Ethanolmagazine.” EthanolProducer.com, August 26, 2021. http://ethanolproducer.com/articles/18481/co-products-revenue-rising.

Luebbe, Matt, and Galen Erickson. “Feeding De-Oiled Distillers Grains in Growing and Finishing Diets.” Feeding De-Oiled Distillers Grains in Growing and Finishing Diets | Announce | University of Nebraska-Lincoln, April 1, 2013. https://newsroom.unl.edu/announce/beef/2155/12419.

Perkis, David, Wallace Tyner, and Rhys Dale. “Economic Analysis of a Modified Dry Grind Ethanol Process with Recycle of Pretreated and Enzymatically Hydrolyzed Distillers’ Grains.” Bioresource Technology 99, no. 12 (August 2008): 5243–49. https://doi.org/10.1016/j.biortech.2007.09.041.

Renewable Fuels Association (RFA). “Ethanol Co-Products.” Renewable Fuels Association. Accessed November 9, 2021. https://ethanolrfa.org/ethanol-101/ethanol-co-products.

Rosentrater, K.A., and E. Kongar. “Costs of Pelleting to Enhance the Logistics of Distillers Grains Shipping,” 137–47, 2009. https://www.scopus.com/inward/record.uri?eid=2-s2.0-79955623431&partnerID=40&md5=5d56e686123cdd8cb1834ba23844b3c4.

Singh, Anil Kumar, Neelima Garg, and Ajay Kumar Tyagi. “Viable Feedstock Options and Technological Challenges for Ethanol Production in India.” *Current Science* 111, no. 5 (2016): 815. https://doi.org/10.18520/cs/v111/i5/815-822.

Srinivasan, R., B. Lumpkins, E. Kim, L. Fuller, and J. Jordan. “Effect of Fiber Removal from Ground Corn, Distillers Dried Grains with Solubles, and Soybean Meal Using the Elusieve Process on Broiler Performance and Processing Yield.” Journal of Applied Poultry Research 22, no. 2 (2013): 177–89. https://doi.org/10.3382/japr.2012-00544.

Srinivasan, R., V. Singh, R. L. Belyea, K. D. Rausch, R. A. Moreau, and M. E. Tumbleson. “Economics of Fiber Separation from Distillers Dried Grains with Solubles (DDGS) Using Sieving and Elutriation.” Cereal Chemistry 83, no. 4 (2006): 324–30. https://doi.org/10.1094/CC-83-0324.

Tidwell, J. H., S. D. Coyle, A. VanArnum, C. Weibel, and S. Harkins. "Growth, Survival, and Body Composition of Cage-Cultured Nile Tilapia Oreochromis Niloticus Fed Pelleted and Unpelleted Distillers Grains with Solubles in Polyculture with Freshwater Prawn Macrobrachium Rosenbergii." Journal of the World Aquaculture Society 31, no. 4 (2000): 627–31. https://doi.org/10.1111/j.1749-7345.2000.tb00912.x.