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Author(s)	Knapp, Edward
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The Economics of Dairy Feed Systems: Risks and Opportunities for Irish Farms

Edward Knapp

Thesis submitted for the Degree of Doctor of Philosophy
J.E. Cairnes School of Business and Economics,
National University of Ireland, Galway

Supervisors: Prof. Cathal O'Donoghue, Dr. Stephen O'Neill and Trevor Donnellan.

Declaration

I declare that this thesis has not previously been submitted as an exercise for a degree at the National University of Ireland, or any other University, and I further declare that the work embodied in it is my own.

Edward Knapp

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Nomenclature

AEOS: Agri-Environment Options Scheme

Bord Bia: the Irish Food Board

CAP: European Union common agricultural policy

DP: direct payments of the CAP

EC: European Commission

EPA: the Environmental Protection Agency of Ireland

EU: European Union

Eurostat: Statistical Office of the European Union

EVI: Enhanced Vegetation Index

FAI-EUT: full asset integration – expected utility theory

FADN: Farm Accountancy Data Network

FAO: United Nations Food and Agriculture Organization

GLAS: Green Low-Carbon Agri-Environment Scheme

LU: Livestock unit

NAI-EUT: non asset integration – expected utility theory

NDVI: Normalised Difference Vegetation Index

NFS: Teagasc National Farm Survey

PAI-EUT: partial asset integration – expected utility theory

REPS: Rural Environmental Protection Scheme

Teagasc: Ireland’s Agriculture and Food Development Agency

UAA: Utilised agricultural area

Abstract

Pasture-based feed systems offer significant economic benefits such as reduced feed costs and environmental impacts to farmers, but also pose agroclimatic and income risks. While grassland dairy farmers avoid the need to purchase grain-based concentrate feeds, their reliance on seasonal weather variations for feed and milk output offers its own challenges. This thesis evaluates important sources of economic uncertainty for dairy farmers while quantifying the opportunities for improved economic viability that would result from improved grass growth. This Irish case study is valuable as Irish farmers, like many others around the world, face the threats of competitive globalised markets and increased climatic volatility. These threats push farmers to improve economic and environmental efficiency in order to remain viable. The abolition of milk quotas has provided an avenue for farmers to seek economies of scale and boost the milk output of their enterprises. While increasing the input of grain-based concentrates is one method to boost milk production under land constraints, it comes with significantly higher feed costs. Grass based feeding is an alternative solution which reduces the need to purchase feeds produced outside the farm while simultaneously providing environmental benefits such as reduced lifecycle greenhouse gas emissions. In order for farmers and policy makers to embrace grass feeds the hazards and advantages of this feeding system must be quantified at the disaggregated level. This study uses three models to empirically analyse this problem: (a) a risk model that compares the income risk faced by dairy farmers with that of three alternative farm types; (b) a grass growth model that measures the impact of geoclimatic variables on localised grass growth conditions over time; (c) an international comparison model that compares the on farm profitability of the grass-based feed systems with granivore feed systems across six dairy producing nations in north-western Europe. Together these models illustrate an economic pathway towards resilient dairy farming.

Publications and Presentations

Publications related to this work:

Knapp, E., & Loughrey, J. (2017). The single farm payment and income risk in Irish farms 2005–2013. *Agricultural and Food Economics*, *5*(1), 9.

Knapp, E., Magnan, A., O'Donoghue, C., Donnellan, T., & Green, S. (2018). Watching grass grow: a spatial and geoclimatic analysis of grass growth in Ireland. In *Sustainable meat and milk production from grasslands. Proceedings of the 27th General Meeting of the European Grassland Federation, Cork, Ireland, 17-21 June 2018* (pp. 866-868). Teagasc, Animal & Grassland Research and Innovation Centre.

Oral Presentations:

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Chapter 1. Introduction

This thesis has its origins in 2015 at a national dairy conference conducted by Teagasc, Ireland's Agriculture and Food Development Authority. Dairy farmers from around Ireland had come to attend workshops hosted by agronomists, animal scientists, and farm advisors in order to learn novel methods to improve their farm businesses. Most of these workshops were centred around strategies farmers could implement to grow more grass feed. The message from Teagasc to farmers was clear: pasture-based agriculture is the way to go environmentally and economically. However, at the end of every workshop, farmers' hands would shoot up to make comments like: "That sounds like a great idea, but it won't work on my farm"; "My farm is in the wet and windy west of Ireland"; "My soil quality is poor"; "I can't afford to make improvements". These comments from farmers inspired an effort to quantify what these farmers were saying and to use an economic approach towards understanding and solving the problems grassland farmers face.

1.1 Context of the thesis

This introductory chapter will place this thesis in the context of the Irish and international agricultural economy. It will make the argument that grassland feed systems are an important research area that deserves further study if their economic and environmental potential is to be unleashed. It will explain the importance of agriculture to the Irish economy and the crucial nature of grasslands to Irish pastoral agriculture. While pasture-based agriculture makes a significant contribution to the Irish economy it is also a tremendous part of Irish cultural heritage and environmental value.

The agri-food sector represents seven percent of Ireland's gross value added (Teagasc, 2017). This is high compared to other developed nations and is particularly large relative to the two percent of European Union gross value added as a whole (Eurostat, 2021). Ireland's agricultural system is an important native industry in an economy that otherwise relies heavily on foreign direct investment and on multinational corporations for employment.

This economic structure has left Ireland increasingly exposed to global economic shocks, most recently the 2008 financial crisis. During this economic shock and subsequent recession, Ireland saw unemployment rise to as much as 14.7 percent in 2012, increased outward migration and "brain drain", and severe budget deficits which rose to 32.1 percent of GDP (CSO, 2022b; Eurostat, 2020). During this difficult period agriculture remained a key industry which sustained employment and investment particularly in rural areas. The largely rural western and northern regions of Ireland suffered tremendous drops in employment in the hospitality and construction industries. Between 2007 and 2011 the hospitality sector lost 18,700 jobs, a decline of 14 percent. Even more affected was the construction sector which lost 174,300 jobs, representing a decline of 64 percent from 2007 to 2012 (CSO, 2022a). In comparison, the agriculture, forestry, and fishing sector lost 21,600 jobs from 2007 to 2012, a decline of 19.9 percent ((CSO, 2022a). In order for the Irish economy as whole, and in particular the Irish rural economy, to weather future global economic storms native industries that support rural communities must be supported.

Agriculture is one such industry which supports rural economies and employment. Still agriculture faces its own economic and environmental headwinds. Changing European Union and national policies have exposed farmers to competitive global markets while requiring ever more stringent standards for environmental protection. The policy environment will be further explored in section 1.2 of this thesis while the environmental background will be illustrated in section 1.3. One way in which some Irish farmers have been facing the twin pressures of increasing competition and higher environmental standards is through increased use of grass-based feeding systems.

Ireland's agricultural sector is primarily comprised of dairy and beef production which represents over 61 percent of the sectoral output as a whole (Teagasc, 2017). Dairy farms in Ireland are composed mainly of small and medium size family farms with the average dairy farm covering an area of 60 hectares often on non-contiguous fields of grassland (Dillon et al., 2021). Cattle rearing and other cattle farms (such as cattle finishing operations) are even smaller in area, averaging 31 and 37 hectares respectively (Dillon et al., 2021). Grazed grass comprises a large proportion of animal feed and because of this pasture represents 50.7 percent of Ireland’s land area and 77 percent of Ireland’s agricultural area (CIA, 2022). Grass is essentially Ireland’s most important crop and its prominent place in Irish animal agriculture deserves further study.

Domesticated cattle and sheep were introduced to the island of Ireland between 4000 and 2500 BC (Taylor et al., 2017). The mild and moist “temperate rainforest” climate of Ireland allowed these animals to thrive as forests were progressively transformed to open pastures by early farmers. Ireland’s climate is still conducive to grassland agriculture with a long, mild cattle grazing season of 240 days per year on average and 250 to 300 days per year possible (Bord Bia, 2022; Byrne et al., 2020). Annual rainfall is high and averages 1230mm across all of Ireland (Walsh, 2012). The rainiest months of the year, with monthly precipitation of approximately 130mm, are October through January, and the driest months include April, May, and June, when monthly total rainfall averages approximately 80mm (Met Eireann, 2022; Walsh, 2012). Temperatures in Ireland are highest inland during July and peak at 18 to 20 degrees centigrade (Walsh, 2012). Average annual temperatures range from 9 to 10 degrees centigrade with higher values along Ireland’s coast (Walsh, 2012). These agronomic conditions are highly favourable to grass growth and will be explored in further detail in Chapters 3 and 4. Ultimately these conditions have made and continue to make grassland agriculture an attractive agricultural system in Ireland.

Grass based agriculture is also attractive given its environmental benefits. These include reduced use of chemical fertilisers and pesticides compared to other feed stocks which are often imported from outside of Ireland and indeed from outside the European Union. Avoiding imports also eliminates the greenhouse gas impact of shipping feeds since the feed is produced, harvested, and consumed in the same location. Grassland also has a reduced carbon footprint relative to tilled field crops as it sequesters rather than releases soil carbon as tillage crops would. Grassland agriculture also provides the public amenity of a scenic, pastoral, and traditional landscape.

Ireland's scenic and uniquely green fields are attractive to tourists and locals alike and are a living symbol of the coexistence of environment and agriculture. Still, grass-based agriculture has some environmental costs relative to other forms of livestock production. One example of this is that animal waste and the associated nutrient load are more difficult to capture and control if animals are dispersed at pasture.

The economic benefits of pasture-based agriculture are also important to note. Chief among these are a reduction of the cost of feed and animal housing. Other economic benefits include reduced costs for labour as feeding and cleaning labour needs are reduced. Veterinary costs are reduced given that animals spend less time enclosed in close quarters with other animals in sheds and are less likely to transmit communicable diseases. Grassland agriculture may however require higher costs for land. The relative economic costs and benefits are outlined in further detail in Chapter 8.

A review of the economic benefits and costs of grassland agriculture is particularly relevant to the dairy industry. Dairy is a particularly critical component of the Irish agri-food economy supporting 17,500 family farms in rural Ireland (Bord Bia, 2022). The Irish dairy sector is highly export oriented and is the largest category of food and drink exports, with dairy exports totalling 4.4 billion euros as of 2019 (Bord Bia, 2022). The Irish dairy industry is also the leader among EU nations in terms of exports to non-EU nations. As of 2021, Ireland is the number one exporter of butter in the EU and is in the top five EU exporting nations for cheese, skim and whole milk powder, and whey powder (Eurostat, 2022). The primary export markets for Irish dairy products are the United States, the United Kingdom and China (Eurostat, 2022).

At the individual farm level, Irish specialist dairies have higher farm incomes than other Irish livestock production systems with dairy family farm incomes averaging 74,249 euros per year in 2020 versus a national average of only 25,615 euros (Dillon et al., 2020). The average Irish dairy farm is also less reliant on subsidies and is more market oriented than the average Irish farm with only 28 percent of family farm income coming from direct subsidy payments compared with a national average of 70 percent. While dairy farms are more economically viable than other forms of livestock production in Ireland, they still face challenges. As outlined in further detail in Chapter 2, Irish dairy farms face significantly more income risk than other production systems. This is attributable in large part to their role as price takers on global feed markets. Irish policy makers envision steady growth of the dairy industry over the next decade and have developed policy frameworks to support competitiveness and growth in the dairy industry. These policies will be analysed in further detail in section 1.2.

At an international level, the dairy industry is an important and growing segment of the global agricultural sector. As global population has increased from 6.1 to 7.8 billion since the turn of the twenty first century, food demand has risen steadily and dairy based foods are no exception to this trend (Thornton, 2010; World Bank, 2022). Developing countries such as China and India now have large and growing middle classes whose food tastes have changed as their incomes have risen. This has led to global production of milk rising 59 percent from 1988 to 2018 while consumption of milk products has risen 95 percent from 1980 to 2002 (FAO, 2022; Thornton, 2010).

The world's primary dairy producing nations include India, which accounts for 22 percent of global dairy production, as well as the United States of America, China, Pakistan, and Brazil (FAO, 2022). In terms of surplus dairy production, Ireland follows New Zealand, the United States of America, Germany, France, and Australia in the list of top exporting nations (FAO, 2022). While the Irish dairy sector is predominantly composed of pasture based, outdoor dairy systems, much of the world's dairy farms are large granivore or indoor systems. In the United States for example, 16 percent of dairy farms are considered concentrated animal feeding operations (CAFO) with greater than 1,000 housed livestock units on a single farm (Kellogg, 2002).

Farm feeding systems are a crucial economic component of dairy production as feed makes up a large proportion of total costs. What's more the choice of feed system also affects the requirements for and costs of labour, builidings, land, machinery, and nutrient management among other things. These cost differentials will be explored in detail in Chapter 6. In addition to cost differences, the risks associated with dairy feed systems also differ widely. While granivore dairy systems may face higher input market risk, grass based dairy farms face weather and climate risks which have the potential to restrict grass production. While both systems face output market risk, grass-based systems produce and market the bulk of their production in spring and summer during peak grass growth periods. Indoor dairy systems can produce a steady output of milk throughout the year, or, if local market conditions demand, they may increase production in winter to maintain a fresh milk supply when grass-based producers seasonally decrease production. The general structure of Irish grass based dairy production systems is outlined in further detail in section 1.5.

1.2 Policy environment

Ireland's agricultural system and in particular its dairy sector have been heavily influenced by governmental policies to boost production, support farm incomes, and to protect the environment. Policy evolution in this space can largely be traced to Ireland's accession to the European Union in 1973. In the 1970s farmers enjoyed a period of elevated agricultural prices. These prices were underpinned by the European Union's Common Agricultural Policy (CAP) which established a system of minimum prices for agricultural commodities. These prices were supported by mass purchases and storage of commodities when prices fell below predetermined levels.

The early form of the Common Agricultural Policy was successful from the farm income standpoint, but it struggled to achieve goals in other areas. Rapid increases in food production had resulted in environmental degradation and wasteful oversupplies of food commodities in storage. As supply surpluses mounted, the cost of guaranteeing minimum prices grew at an unsustainable rate. By the 1980s policy makers began the process of CAP reform in an effort to achieve the goal of supporting farmers and food production while reducing the economic and environmental costs. One reform that influenced European dairy production for decades was the system of milk quotas. In order to counter dairy surpluses, the EU set production quotas for farmers which limited production and opportunities to increase the scale of dairy farms.

Further reforms of the CAP in the 1990s under EU Agriculture Commissioner Ray McSherry replaced direct intervention in agricultural commodity markets with direct payments to farmers. These payments were based on the number of livestock units on the farm. Direct payments were also conditional on meeting minimum environmental quality standards and the provisioning of public goods such as biodiversity and scenic, pastoral, landscapes. While the combination of quotas and direct payments reduced the commodity surpluses of the 1970s and 1980s, direct subsidy payments to farmers were still a highly economic distortive measure. This market distortion was problematic from a trade standpoint as the 21st century brought with it a move towards globalisation and liberalised trade policies. Policy makers sought to replace the existing system of subsidy payments based on production and stocking rate with a new, less distortionary system decoupled from production, but still supportive of farm incomes.

Decoupled payments were introduced in 2003 whereby the receipt of subsidies or “entitlements” became dependant, in the case of Ireland, on historical production on a given farmland area. This reform allowed Ireland and the rest of the EU to access global food markets with reduced trade barriers. This liberalisation also increased competitive pressures on farmers to reduce costs in order to compete on global markets. While subsidy payments still had a positive effect on farm incomes, farm incomes in Ireland became increasingly volatile as farmers faced less stable input and output prices. Many farmers also faced increased business risk as they capital investments to improve efficiency or increase scale.

During this process of increased farm innovation and expansion, dairy farms were hamstrung by output quotas. Purchasing additional quotas and production rights was costly for farmers and the scope for increases in scale were limited. By this time, the vast surpluses of the 1970s and 1980s were a distant memory and in 2015 the system of dairy quotas was finally abolished. Irish dairy farmers were now freely able to increase milk production for sale on growing global markets.

In order to manage and encourage growth in the Irish agricultural sector in general and in particular in the dairy industry, policy makers developed a framework for expansion of the sector and improved competitiveness. These policies were first summarised in the policy document Food Harvest 2020 which planned for sectoral growth from 2015 to 2020. Food Harvest 2020 planned for an increase in milk production of 50 percent relative to the 2007-2009 average production (Miller et al., 2014). This increase was projected to be worth 800 million euros to the Irish agro-economy (Miller et al., 2014).

While Food Harvest 2020 was ambitious from an economic standpoint it was seen by some as failing to consider the environmental repercussions of agricultural expansion. The successor policy document to Food Harvest 2020 was Food Wise 2025 which sought to address environmental concerns in addition to dairy expansion goals. One of the primary messages of Food Wise 2025 was that output could be increased through efficiency improvements and technological innovation rather than simply increasing the land footprint and animal numbers of farms. This message was summarised as “better before bigger”. By focusing on efficiency improvements such as improved animal genetic merit and increased grass production, farms could become more competitive and productive with limited adverse environmental impacts.

1.3 Environmental background

The role of agriculture is not merely economic and this is particularly the case for Ireland where agriculture plays a major role in the provisioning of public goods. Since the majority of Ireland’s land area is under agricultural management, farmers and farm management practices a critical to maintaining a healthy environment. Increasingly, farmers have a role to play beyond food production. Policymakers recognise the potential for farmers to preserve unique natural, pastoral, and biodiverse landscapes. In addition, properly managed agricultural land can improve water quality and, in the case of grasslands, sequester atmospheric carbon. To encourage the provisioning of these public goods, policymakers have utilised various measures and programmes to reward farmers for high environmental quality while reducing subsidy levels for farms that do not meet environmental standards.

The introduction of direct payments in 2003 coincided with a policy of "greening the CAP". In order for farmers to receive their subsidy payments they would be required to meet minimum environmental standards such as crop rotation, "set-aside" land for grasslands, and managing nutrient loads. While farmers often incurred significant compliance costs associated with these environmental regulations, later rural development and environmental programmes such as AEOS and GLAS provided farmers with additional compensation in order provide environmental services. These services included preserving and enhancing habitats for threatened species as well as protecting watercourses from nutrient runoff. Still the conflicting pressures of increasing food production and increasingly stringent environmental standards have been difficult for farmers to achieve in tandem. This is particularly the case with regard to agricultural atmospheric carbon emissions.

In the face of global climate change, Ireland and all other nations have evaluated their respective greenhouse gas emission contributions with a view towards stabilising and reducing their emission impact. In the case of Irish greenhouse gas emissions, the agricultural sector comes to the fore. This is because Ireland's agriculture industry accounts for 37.5 percent of total carbon dioxide equivalent emissions as of 2021 (EPA, 2022). Ireland's large and export-oriented livestock sector accounts for a disproportionate amount of emissions due to the fact that it is dominated by cattle and sheep. These ruminants produce methane, a far more potent greenhouse gas than carbon dioxide, through enteric fermentation and account for 60.7 percent of Irish agricultural carbon equivalent greenhouse gas emissions (EPA, 2022). While industries such as electricity generation and ground transportation look forward to emission free replacements, livestock production does not have such replacements on the technological horizon. In this case, the goals of reduced animal emissions seem to be diametrically opposed to the Irish government's stated goal of increased animal numbers and animal product output. However, partial solutions lie in increased food output per animal as well as a reduction in the carbon footprint of animal feeds, the primary input for animal agriculture.

1.4 Objectives and structure of the thesis

The primary objectives of this study include:

1. Evaluating the income risk associated with different farm systems in Ireland in order to highlight the elevated risk levels borne by dairy farmers. This econometric analysis prompts questions about the environmental and economic factors that make the dairy sector different from other agricultural systems and why the case of the Irish dairy feed system deserves special study.

2. Developing a heterogeneous, disaggregated model of agroclimatic conditions for grass growth in Ireland. This model allows the relationship between agroclimatic conditions and ground level vegetation growth to be quantified over time and for the agronomic effects of climatic shocks to be spatially and temporally evaluated in a quantitative manner.

3. Comparing the on-farm profitability outcomes of grass based dairy feed systems with those of indoor or grain-based feed systems. This objective is accomplished through a farm level international comparison of Irish grassland dairies with similarly scaled granivore dairy systems located in the primary milk producing nations of north-western Europe. The Oaxaca-Blinder decomposition method is employed to isolate the profitability differences attributable to farm endowments from unobserved farm management skills characteristics. This allows for an accurate evaluation the relative farm level economic costs of alternative feed systems.

In order to meet these objectives, a heterogeneous, farm level analysis is applied to novel datasets synthesising the individual farm risk structure, system, and management characteristics as well as localised pedoclimatic[1] conditions. This allows for the economic outcomes of alternative farm systems to be evaluated on the basis of both “nature” and “nurture” simultaneously. This methodology contributes to the existing body of microeconomic farm system literature, which typically relies solely on single point agronomic models to quantify the effects of the natural environment on farm outcomes. The purely agronomic approach collects data in the setting of a research or “model” farm, but fails to represent the highly heterogeneous distribution of farms which are located across a wide spectrum of pedoclimatic conditions. Other purely economic models struggle to account for the environmental characteristics which surveyed farmers grapple with. Only by bringing together environmental and economic data can the complex interactions between the natural environment and farm management characteristics be effectively modelled.

The data involved in this study includes both pedoclimatic and farm survey data. The pedoclimatic data utilised includes meteorological models of farm level and local area rainfall and temperature across Ireland, spatially disaggregated soils data and satellite measurements of vegetation growth at the two hundred fifty metre scale. Farm survey data is drawn from the Teagasc National Farm Survey, a detailed rolling panel survey which is nationally representative of all farms in Ireland.

The methodologies employed to meet the objectives of this thesis consist econometric, spatial, and statistical modelling to significantly explain the impacts of environmental, policy, and management characteristics on farm outcomes. These methodologies include the use of fixed effects models on detrended panel data to evaluate and compare the income risk profiles of disparate farm systems. In order to measure the relationship between agroclimatic conditions and vegetation growth random effects models were employed to control for the effects of soil and weather conditions on grass growth over time. This econometric approach is used in concert with the

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[1] Pedoclimatic conditions refer to the interaction effects of climate with unique soil characteristics such as soil texture.

statistical methodology of data clustering in order to classify farms into an agronomic taxonomy. In this way farms with similar agroclimatic conditions can be grouped together while demonstrating that the statistically significant relationship between environmental conditions and grass growth outcomes holds even in the most disparate pedoclimatic regions.   The profitability comparison of farm level feed systems is facilitated by the Oaxaca-Blinder decomposition method which allows farms' profitability to be compared on the basis of feed system differences while separating the impact of farm scale and other farm characteristics.

This thesis is structured as seven chapters. The remainder of Chapter 1 will include a general structural description of the grass based dairy feed system in Ireland, specifically highlighting the important role of feed in the production system. It will also specifically introduce the primary research questions and will underscore how this thesis informs the existing body of international literature. Chapter 1 will be concluded with final comments synthesising the message that this thesis offers to farmers and policy makers in Ireland and around the world.

Chapter 2 is concerned with the development of a theoretical framework to underpin this study. The theoretical framework of this study is based on the balance between risk and reward that is faced by all businesses, especially farm enterprises. Chapter 2 concludes by setting this study in the theoretical context of production economics. In this way, the feed system, as a critical component of dairy production, can be modelled. The feed system itself is viewed through the lens of systems modelling theory.

Chapter 3 addresses the data employed in this thesis and in particular the data gap that exists with respect to empirical and distributional representative measures of farm level and local level grass growth. Chapter 3 explores and explains the current methods used to measure grass growth on farms in Ireland and internationally. The advantages and shortcomings of these current methods are assessed and a novel methodology is proposed to quantify grass growth in Ireland. Existing farm level grass growth data in Ireland is limited. A minority of Irish grassland farmers, typically those with technical, capital, and pedoclimatic advantages, manually measure grass growth in their fields on a regular basis. This is done in order to chart technical improvements and plan for future feed needs. Teagasc, Ireland’s Agriculture and Food Development Authority, collects some of this farm level data through its use of a custom software programme, Pasture Base Ireland. While this data is invaluable to those farmers who collect it, it is costly in labour terms to collect and is not representative of the full spectrum of grassland farms and farmers that exists in Ireland.

In order to avoid the time, labour, and financial costs of manually measured grass growth data, some researchers in this field have turned to remote sensing technologies in order to quantify grass growth from afar. The use of satellites, and in recent years, drone aircraft, has allowed farmers, commodity traders, researchers, and governments to track crop growth and condition in real time. The connection between satellite or drone imagery and actual crop yield estimates is made by statistical models which have been “ground-truthed” or based on ground measured harvest data. This presents a problem for grazed grass which is harvested by livestock who unfortunately do not collect accurate yield measurements. Thus remote sensing models are typically the domain of commodity field crops for which yields are accurately measured at harvest, often by the combine itself.

Research institute farms or “model” farms also make accurate grass growth measurements and have developed detailed agronomic models of grass production. While several of such models exist for Ireland, they fail to represent the spatial, agroclimatic, and management heterogeneity which exists between farms. As such, they are of limited use to farmers who operate on locations which are less agronomically favourable or who lack the technical and/or capital advantages often afforded to research farms. Policy makers also struggle to make use of such models in their efforts to support farms in less favoured areas. Still, single point agronomic grass growth models developed on research farms can be used to evaluate the key determinants of grass growth in general terms. Chapter 3 will conclude by detailing how such remote sensed data was collected and processed and by providing descriptive summary maps. The following chapters 4-6 conduct a detailed analysis of agroclimatic risk factors and their effects on grass growth potential such that the risks from grass-based feeding systems can be empirically compared with those of grain-based feeding systems.

Chapter 4 addresses how income risk is the key that can unlock improvements in investment, production, and ultimately income on farms. In order to be addressed, this risk needs to be quantitatively measured and explained so that its sources may be identified. Risk factors for Irish farms include market risk in terms of both inputs and outputs, policy risk, and agroclimatic risk. While all farm systems face certain degrees of risk, in the case of Ireland, dairy farms have a significantly higher market income risk than other farm systems such as sheep, beef, or field crops. The high feed usage of dairy farms in Ireland can be linked to both input market risk, in the case of purchased supplementary concentrate feeds, and agroclimatic risk, in the case of on farm grass production.

Localised meteorological data represents a set of key determinants of grass growth potential on farms. Chapter 5 will illustrate how weather data is collected in Ireland and the sources for such datasets. Daily data on mean temperature and total rainfall was collected from over seven hundred weather stations across Ireland. While this data is seen by Ireland's national meteorological office, MetEireann, to be nationally representative, spatial gaps do exist. In order to better represent localised weather conditions at farm level, microsimulation methodology is employed to model temperature and rainfall at over 91,000 farm locations and 3,500 electoral districts across Ireland. Chapter 4 will explain this method in detail and will provide summary maps of the model results.

Chapter 5 contributes to the objectives of this thesis by outlining the vital role of soils in a spatially heterogeneous agronomic model of grass production. This chapter begins by charting the evolution of soil mapping in Ireland over time. The existing body of spatial soil datasets is explained in terms of their data collection and taxonomic methodologies. While these national soil maps are not perfectly accurate measure of soil conditions at a field scale, they are an effective representation of how pedologic conditions vary widely across the landscape of Ireland. This disparity is visually illustrated in summary maps.

Chapter 6 compares the case study of the Irish dairy feed system to that of Ireland's neighbouring dairy producing nations in north-western Europe. Through the use of the Oaxaca-Blinder methodology the farm-level profitability potential of the grass-based feed system is compared with that of granivore feed systems.

Chapter 7 offers a discussion of this thesis's overall contribution to knowledge and understanding in the area of dairy feed system economics. The results and contributions of the specific studies of risks and opportunities from grass growth are summarised and their conclusions are used to offer alternative and international applications of this study's methodology. This chapter will also explore the scope for further development of the ideas included in this thesis as well as the limitations and caveats of the data and methods included herein.

1.5 Structure of grass based dairy production in Ireland

Before analysing and modelling the future potential for changes in the Irish dairy system it is useful to develop an understanding of the dairy system's structural underpinnings at the farm, national, and international levels. Irish dairy farming is generally characterised by export oriented seasonal milk production which relies upon favourable conditions for grass growth and high genetic merit animals as well as farmers who are both skilled in animal husbandry and grassland management. Irish dairy farms are typically labour-intensive operations employing 1.9 full time equivalent units of unpaid labour and 0.2 full time equivalent units of paid labour.

Land is also a major input into a typical Irish dairy farm since the average dairy farm has a land value equivalent to 17,516 euros per hectare although open market land sales are relatively rare. Rather land is transferred to one of the farmer's children. The Irish government has encouraged the use of farm transition agreements through favourable taxation structures in order to allow the next generation of farmers to have surety of income and career progression. However, most farms are still not transferred to a family member until the death of the existing farmer. This is primarily due to the income needs of farmers as they age and the direct payment entitlements support farmers income regardless of their current production levels.

Feed is another primary input for Irish dairy farms and is closely associated with milk production levels. Balancing the need to control feed costs while maintaining or increasing milk production is a primary concern for Irish dairy farmers. In a standard study herd of Irish dairy cows, each cow consumed an annual average of 9.8kg of grass dry matter per day which peaked in the month of June at 16.1 kg per day (Shalloo et al., 2004). In terms of concentrate feeds, only 1.0 kg per cow were consumed daily with no concentrate amount being consumed during the June through September months (Shalloo et al., 2004). This feed, along with silage allows the study cow to produce 6,421 kilograms of milk per year at an average protein content of 34 grams per kilogram of milk (Shalloo et al., 2004). This shows that grass feed is a key component of the Irish dairy system.

1.6 Conclusions

This introductory chapter serves to provide a basis and background for the theoretical framework (Chapter 2), data (Chapter 3), and analysis chapters (Chapters 4-6) which follow. This chapter also has introduced the primary research objectives of this thesis, namely, to model the income risk and agroclimatic conditions faced by Irish dairy farmers, while also comparing the profitability outcomes on an international and feed system scale. By achieving these objectives, this thesis uses economic analysis to alleviate the dissonance that exists between agronomists and the farmers they serve.

The context (1.1) policy (1.2), and environmental (1.3) sections of this introductory chapter shed light on the challenging, and ever evolving, external conditions which seriously impact dairy farmers in Ireland and around the world. Section 1.4 lays out a roadmap to achieving the objectives of this thesis, while section 1.5 focuses on the Irish dairy production system. Together this chapter provides the necessary context to understand the analyses contained in this thesis and the economic theoretical framework upon which these analyses are founded.

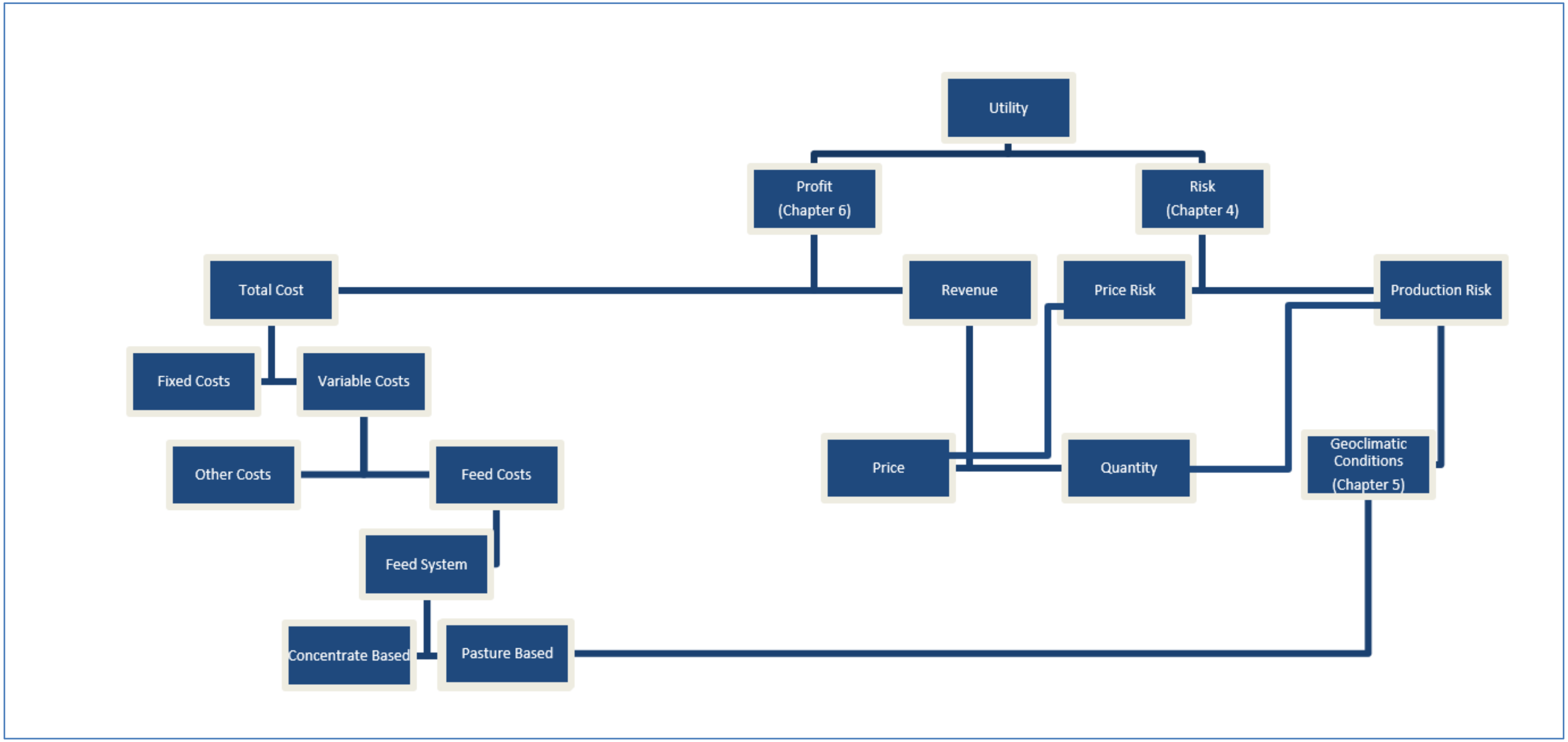
Chapter 2. Economic theoretical framework

2.1 Introduction

The purpose of this chapter is to frame this thesis in its economic theoretical context. This framework specifically highlights how economic theory can inform research into the Irish dairy farming as an economic system. While the previous chapter illustrated the role of the Irish dairy farming system as an embedded component of Ireland's macroeconomic, political, and ecological environment, Chapter 2 will reflect on this farm system through the lenses of production and risk theory as they pertain to the utility maximisation framework. This chapter will also discuss how these theoretical frameworks support the methodologies used in this thesis in the areas of agricultural production and risk.

Figure 2.1 below summarises how the analyses of this thesis fit into the dairy farmers utility maximisation framework. While utility maximisation is a complex and dynamic decision-making process for the farmer, this thesis analyses three key components of this framework in the three following analysis chapters (Chapters 4, 5 & 6). As stated above, utility is assumed to be as the risk adjusted profit of the farm operation. Farm profitability is addressed in Chapter 6 of this thesis which compares the profitability of farms of similar scales, but with differing feed systems. Chapter 4 analyses and compares the income risk of various agricultural systems in Ireland and finds that dairy farms are subject to high degrees of income volatility relative to other types of farms such as tillage or beef producing farms. This finding suggests that dairy farms, which are particularly feed intensive relative to other farm types, deserve special study of their risk profiles. This is particularly important since the results of this analysis suggest that current government policies exacerbate rather than reduce income volatility. While price risk and production risk are both important for farmers, this thesis also analyses the geoclimatic determinants of production risk in Chapter 5. In the context of a dairy farmer's utility maximisation, geoclimatic factors are key since they also impact the choice of feed system. As stated in Equation 2.3 below, feed system has direct implications on feed costs, which in turn can impact total costs and ultimately profitability and utility. By analysing profit, risk, and geoclimatic conditions, this thesis focuses on building understanding of three key nodes of the utility maximisation process in order to assist farmers and policy makers in their management decisions. It also sets groundwork for other research on the interdependent components of this framework.

Figure 2. 1 A dairy farmer's utility maximisation framework



Section 2.2 of this chapter will outline the key concepts of economic production theory including cost minimisation, production functions, and profit maximisation and how these concepts are applied in agro-economic research in general and in this study in particular. Section 2.3 addresses the issues of technical efficiency and input substitution. Section 2.4 will explore risk theory and the various risk factors that apply to farming and affect farmer decision making. Finally, Section 2.5 illustrates how economic theory informs the various analysis chapters of this thesis.

2.2 Economic production theory

Production theory is primarily concerned with explaining the choices firms make to determine their choice of output level and their use of factors of production to achieve this. Production theory involves the relationship between the prices of commodities and the prices of the factors used to produce them as well as the determination of the optimal quantities of both inputs and outputs. Under production theory, firms rationalise their production decisions in order to minimise costs and maximise profits. Firms make choices about the quantity, price, and type of inputs or factors of production as well as outputs or products. The production function, the relationship between factors of production and units of output, is of particular importance. Examples of such production functions include Cobb-Douglas and trans log functions (Cobb & Douglas, (1928). Business decisions, as represented in a production function are, in the first instance, concerned with minimising the cost of production in the short-run within the confines of a fixed capital stock and output level. The next level of decision-making focuses on maximising profits in the short run by determining the optimal level of production. In the long term, profit maximisation becomes more complex as markets and industries can change with firms entering or leaving the market and/or expanding their productive capital stock. Together, these three levels of firm decision making make up production theory.

Production theory models the short-run production choices of firms within a constrained decision-making space. Product type, input prices, and production capacity are taken as given and it is assumed that firms are price takers in input and output markets while the firm determines the lowest cost factor set for a given production level.

This decision-making process is modelled as a production function where output is a function of variable and fixed factors of production. Variable factors of production include labour and raw materials while fixed factors include machinery and land, the levels of which cannot be altered in the short-term. Product output is constrained by the production possibilities frontier (PPF) The PPF describes the range of production sets attainable with current technology and with optimal usage of inputs. Production sets within the PPF represent a suboptimal or inefficient usage of inputs, while production sets outside of the PPF are unattainable given the current technology set. In the long term, as new technologies are adopted into the production system, the PPF may shift outward allowing for more efficient usage of inputs. In the case of pasture-based feed production systems, a farmer is constrained by the PPF in terms of grass feed production given his available inputs of land and labour. However, new pasture management and feeding strategies may be adopted in the long-term and these new technologies can allow a farmer to utilise his land and labour more efficiently. These new technologies can lead to higher pasture-based feed production without increased costs. This additional grass feed can be utilised as a substitute for purchased feeds to lower feed costs and reduce purchased feed price risk. This technology adoption can therefore increase profitability and decrease risk which leads to higher farmer utility.

The cost of production is a function of variable costs and fixed costs. In order for businesses to reduce costs they must make decisions about modifying the set of variable factors in a process called factor substitution. By substituting lower cost inputs relative to their marginal productivities in place of more costly alternatives, variable costs can be reduced while production level is maintained within the required bounds. The sandwich/ squeeze theorem holds that the profit maximising input set of two inputs exhibiting complementarity must exist between the extremes of solely utilising one input or the other. Alternatively, firms may attempt to increase their output level for the lowest possible variable cost. As firms begin to think beyond merely minimising costs, the next step is to determine the most profitable level of production.

The process of maximising profits in the short-term requires businesses to consider the concepts of marginal cost and marginal product. Marginal cost describes the increase in variable costs associated with a one unit increase in output. As long as marginal cost is lower than the sale price of the firm's product, sales or revenue will increase as production level increases. Given that a firm's capital stock is fixed in the short-run, marginal cost tends to rise as the carrying capacity of productive capital such as land and machinery is reached. Variable inputs, such as labour and feed in an agricultural context, become more difficult or costly to acquire as the utilisation of these inputs increases. Diminishing returns to these factors eventually drive up the marginal cost as production increases. Once the marginal cost per unit of output is higher than what one unit of output can be sold for, the firm will lose revenue if it increases its output level. It follows that rational firms in a competitive market where they are price takers will maximise revenue and profits by setting their production level where marginal cost of a unit of output is equal to the price of that output.

Maximising profits in the long run adds an additional layer of complexity to firms' production decisions. In the long term, the capital stock of firms is subject to change through expansion or dismantling of capital within firms or through new firms entering or exiting the industry. If a firm is operating profitably where marginal costs exceed average costs then the profit incentive to increase capital levels may exist. Long run costs are minimised at each output level by optimising the capital level.

Technical efficiency and economic efficiency differ in the following ways. Technical efficiency fails to consider risk as a factor which impacts utility. Technical efficiency focuses on maximising production, but does not consider cost impacts or limitations to technology adoption and/or input substitution. Farmers are subject to limitations on capital such as limited land availability. As such, they also do not have perfect input mobility. In an agricultural context, the researcher must also account for uncertainty and risk (Moro and Sckokai, 2011) and risk theory is explored further in section 2.4.

2.3 Other management theories relevant to this thesis

Given that this thesis addresses the optimal usage of feed inputs for maximum production, efficiency plays an important role. While farmers strive to be both technically and economically efficient, this study focuses primarily on economic efficiency. Technical efficiency can be described as the optimal use of inputs as measured on a quantity basis, while economic efficiency measures the explicit or implicit economic prices of inputs as part of a given production technology (Cherchye et al., 2010). This thesis focuses on dairy feed systems as economic processes relying on two primary sets of inputs, pasture-based grass feed and indoor, cereal based feeding. By understanding that these two input sets are substitutable it becomes possible to evaluate the relative economic merits of these systems. The theory of input substitution holds that firms have a choice in the type and combination of inputs that may be utilised. This choice is largely based on the relative economic prices of these inputs. The rate at which businesses can substitute between production inputs is measured as the marginal rate of technical substitution (MRTS). The MRTS is calculated as the amount of inputs that would be required to be added to replace the reduction in the alternative input while keeping production constant. In the case of feed systems can be modeled according to equation 2.3 below. In this model the MRTS of a feeding system be it pasture based, F_p, or indoor system, F_i, is a function of the reduction of indoor, purchased feeding divided by the amount of pasture feed source necessary to replace it while maintaining dairy production.

$$MRTS(F_p F_i) = (-\Delta F_i)/F_p \qquad \text{Equation 2.1}$$

This analysis of alternative dairy farm feed systems, particularly the comparison of grass based with high input housed systems in Chapter 6, addresses the differing production possibility frontiers (PPF) and risk profiles which farmers may face if they adopt varying feed systems. Figure 2.3 below synthesises the comparison of these two systems.

Table 2.1 Comparing dairy feed systems

Feed System	Production	Cost	Risk
Housed, grain based	Output production can be increased by purchasing additional feeds	Higher feed cost	• Increased feed risk, • Reduced local climatic risk • Dependent on globalised feed markets
Pastoral, grass based	Pasture based feed production is subject to limited land inputs and climatic volatility	Higher land cost	• Higher local climatic risk • Can substitute between purchased feeds and pasture feeds to diversify input risk

Given that farmers have a choice between alternative feed systems, it is important to understand the theory of technology adoption which allows firms (in this case farm businesses) to expand their respective PPFs by changing their input systems such as feed. Straub (2009) finds that technology adoption is a complicated process of development unique to each individual and their perceptions. This theory is addressed in many works in the Irish agricultural context including Howley et al. (2012), McDonald et al. (2016), and Hennessy and Heanue (2012). which found that technology adoption has the potential to reduce costs, but can be risky and limited in scope by a range of personal, social, and economic farm characteristics including age and peer effects. Hennessy and Heanue (2012) measured how technology adoption leads to increased input efficiency or a shift in the production function, and thus to improved productivity. Still, technology adoption is rarely clear cut and often involves technology that is not easily adoptable in all settings due to complexity, risk, or requirements for system change (McDonald et al., 2016). Grassland management is an example of a technology which is challenging to implement due to its requirement for systematic change and new skillsets (McDonald et al., 2016). Technological improvements are further constrained by factors such as age, limited land area, and farm fragmentation (Lapple et al., 2015; Dillon et al., 2008). It is beyond the scope of this research to analyse how farm operators may transition (or be incentivised to transition) to alternative feed system technologies.

2.4 Risk theory

While the theory of risk can be framed and defined in several unique types of risk including climatic, statistical, management, and security risk, this study focuses on outlining the economic explanation of risk as it pertains to the utility of the farmer. The outsized impact of risk and risk management in the agricultural sector will also be discussed in Chapter 4. This section provides a framework for understanding risk theory that supports the analysis of agricultural income risk and volatility evaluation as conducted in Chapter 4.

While financial risk problems are typically defined in terms of the probability of investment returns being higher or lower than expected, problems of risk are dealt with differently from an economist's perspective. Under economic theory, decisions are made under uncertainty in such a way as to maximise the satisfaction of the decision maker (Gollier, 2001, p.3). Agricultural economic risk problems may, for example, concern unexpected or problematic volatility in market prices for inputs or outputs, while simultaneously consider the preferences of the farmer. It is different from an uncertainty in that the probability distribution of yield variations is known or at least can be estimated (Finger and Schmid, 2008). Increasing competition, the impacts of meteorological shocks, or unfavourable political changes can all fall under the broad umbrella of economic risk. This type of risk is calculated by combining the probability of an event with the assessment of its associated utility (be that utility positive or negative) into a single measure. The Von Neumann-Morgenstern expected utility function codifies this concept by combining the probability of each possible outcome with the utility of each possible outcome (Mas-Colell et al., 1995, p. 173) This study adapts this function as equation 2.4 below where R, risk, is equal to the sum, for all possible income levels, i, of the probability of a given income, $\mathbb{p}_i$, times the expected utility associated with such an income, U_i.

$$R = \sum \mathbb{p}_i * U_i \qquad \text{Equation 2.2}$$

The theory of expected utility is explored in further detail in the theory and hypothesis section of Chapter 4.

The agricultural sector as a whole (Di Falco et al. 2014; Moro and Sckokai, 2011), and Irish dairy farming in particular (McDonald et al. 2014; Bergmann et al. 2015; Loughrey et al. 2015) have become subject to increasing levels of economic and income risk due in part to increasingly competitive and integrated markets since the EU Common Agricultural Policy ended the use of price supports. Risk theory has been applied in multiple ways in the agricultural economics literature. Finger and Schmid (2008) highlight how risk aversion affects the expected utility function of farmers by decreasing production variation and increasing the optimal level of risk mitigating inputs. Farm decision makers who are risk averse may also reduce investment in an input whose return on investment is uncertain and be more likely to utilise off-farm rish management strategies (Meraner and Finger (2019). Moro and Sckokai (2011), Lehmann et al. (2013), and El Benni and Finger (2013) highlight market or price risk as well as technological or output risk as being particularly important in the context of agricultural production since they affect decision making and income variability. This is because risks influence output decisions which are not merely based on the choice of variable inputs. Production risks in an agricultural context mostly relate to climatic or meteorological shocks while price risk reflects the variation in market prices of agricultural inputs and outputs (Lehmann et al., 2013). El Benni and Finger (2013) find that price risk, rather than production risk is the main contributor to revenue risk in a study of dairy farms while yield risk was found to be significantly less important. Price volatility has the potential to lead to revenue risk and ultimately reduced competitiveness, particularly for risk averse dairy farmers (El Benni and Finger, 2013). Price risk is also perceived by farmers to be an important risk factor (El Benni and Finger, 2013). While risk perception is not addressed in depth in this thesis, it should be noted that it is influential in the production decision making process (Meraner and Finger, 2019). An important example of input price risk is the variability of concentrate feed prices faced by dairy farmers (El Benni and Finger, 2013). Climate change may increase the relative importance of production risks in the future by increasing such risks such as heat stress and fodder yield availability (El Benni and Finger, 2013). Finger and Calanca (2011) note that risk analyses in grassland production systems must account for climatic stress and new risk management strategies should be developed to mitigate such climatic shocks. Achieving these goals is hampered, however, by a dearth of farm-level yield data for grassland production (Finger and Calanca, 2011). While uncertainty can complicate production theory, it may still be addressed if certain assumptions are made. For example, a risk neutral, profit maximising farmer facing output price risk would also face choices based on expected prices (Moro and Sckokai, 2011). When technological risk is added, the farmer must also consider her expected output levels when making profit maximising production decisions. This study focuses on comparing grass-based versus concentrate-based feed systems due to the potential impact of feed system on risk and ultimately on the expected utility of the farmer.

Farm risk-management strategies are diverse and may be off-farm or on-farm, agricultural or non-agricultural, and the choice of these strategies may be influenced by farm and household characteristics, farmer risk perception and attitude (Meraner and Finger, 2019). While farmers have many methods of managing risk at their disposal, diversification is a primary risk mitigation strategy (Lehmann et al., 2013). It is important to note however, that risk management strategies such as diversification are subject to the constraints of limited farm resources (Lehmann et al., 2013).

By considering risk and uncertainty, agricultural production theory can more accurately describe the many complex production decisions which farmers face in reality. Chapter 4 of this thesis further considers the effects of policy instruments on the farmer’s production decisions. Taken together, these examples highlight the importance of quantitatively measuring risk and the economic impacts of the same in the agricultural sector.

2.5 Conclusion

While the general explanation of the production function can be found in section 2.2, this section develops a theoretical framework specific to the production decisions of farm operators as analysed in this thesis. In this framework farm operators maximise expected utility under conditions of risk as well as technology and capital constraints in the near term.

The short-term utility of the study farmer is assumed to be a function of risk adjusted profits, Y. Y is the object of maximisation for the study farmer and is equal to profits, π, multiplied by the risk preferences set of the farmer, V, which is jointly assessed upon exogenous risk conditions a, which summarises price risk and risk condition b, which includes production risk (Chavas et al., 2019). Given the risk preference set, V, the study farmer will seek to maximise, minimise, or be indifferent towards risk factors a and b. Taking the risk management decisions included in term V_{ab} as given, the farmer seeks to maximise profits, π, which are equal to total production revenue, R minus total costs C where both vary with $\underline{a}$ and b.

$$Y = \pi V_{ab} \qquad \text{Equation 2.3}$$

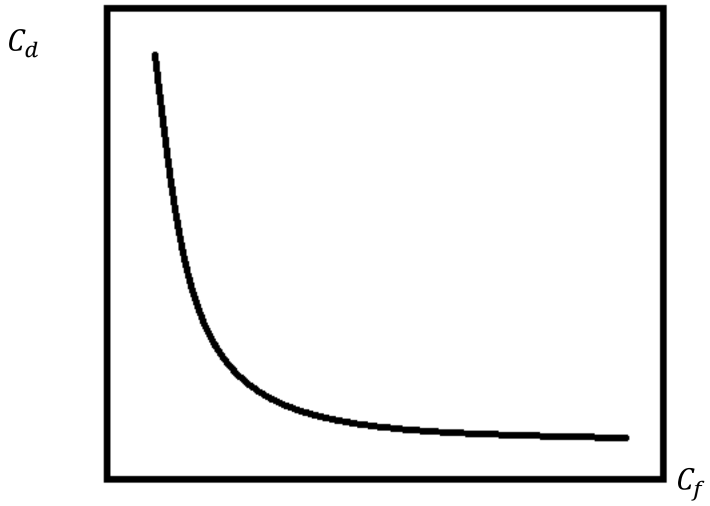
$$Max\, \pi = R_{ab} - C_{ab} \qquad \text{Equation 2.4}$$

Revenue, R, is a function of prices, P, and production, Q, which is fixed in the short term. Prices are subject to price risk, a, while production is subject to production risk, b. In the short term, production, Q, is also affected constrained by the existing technology set, t, and capital endowment, k. Although the adoption of novel technologies and investments in capital such as land, buildings, and machinery are possible in the longer term, technology adoption and farm investment decisions are beyond the scope of this thesis which is focused on short-term management decisions rather than long-term technology adoption.

$$R = P_a * Q_{btk} \qquad \text{Equation 2.5}$$

In Chapter 6 of this thesis total costs, C, are viewed as a function of variable feed costs including purchased concentrate feeds, C_f, other nonfeed in variable inputs such as labour, C_o, and fixed or capital costs, C_d, such as the cost of land and depreciation on buildings and machinery. Substitution between these costs and inputs is possible, but is limited by technological constraints, t, and capital restrictions, k. Figure 2.2 below describes the marginal rate of technical substitution between input costs exemplified by the substitutability of capital costs, C_d, such as pasture land area and feed costs, C_f, including concentrate feeds.

Figure 2.2 The Marginal Rate of Technical Substitution between capital costs, C_d, and purchased feed costs, C_f.



$$C = \left(C_d + C_f + C_o\right)kt \qquad \text{Equation 2.6}$$

Feed costs, C_f, are a significant component of total costs and are an area of particular focus in this thesis. They are defined herein as a function of the farmer's choice of feed system, FS in equation 2.7 below. Feed systems for dairy enterprises can be generally divided into concentrate based or pasture-based systems. Concentrate based systems are represented in equation 2.8 by the term X_a where X represents the amount of purchased concentrate feeds, which is subject to price risk, a. Examples of price risk include policy, speculation, or other global market shocks which affect feed prices in an unpredictable way. Z_b represents pasture-based systems which primarily utilise grazed grass feeds, Z, and are subject to production risks, b, such as climatic shocks. As in Equation 2.5, the substitutability between feed systems is limited by capital constraints, k, such as limited grazing land or buildings for animal housing. Technology constraints, t, are also considered and can be exemplified by limited farmer training or knowledge of alternative feed systems.

$$C_f = f(FS) \qquad \text{Equation 2.7}$$

Dairy farm feed systems are shown as FS in equation 2.5.6 below. FS is a function of the amount of concentrate feeds used on a per animal basis, X, which is subject to price risk, a, as well as the per animal amount of pasture-based feeds, Z, which is subject to production risks, b. The farmer's feed system decision is further influence by the capital, k, and technology, t, at her disposal.

$$FS = f(X_a, Z_b, kt) \qquad \text{Equation 2.8}$$

Under these conditions farmers face a cost minimisation problem with respect to feed costs and must choose a feed system which minimises costs given the study farmer's aforementioned set of capital and technology constraints subject to producing the required level of output. Equation 2.9 illustrates this choice by setting feed costs equal to the specific function, $\emptyset$, of concentrate feeds, pasture feeds, and the individual farmer's capital and technology set.

$$C_f = \emptyset(X_a, Z_b, kt) \qquad \text{Equation 2.9}$$

Farmers seeking to control feed costs by utilising pasture-based feeds must clearly understand production risk, b, and this thesis addresses pasture feed production risk in Chapter 5 by analysing the impact of geoclimatic variability on grass growth. Increased utilisation of pasture-based feeds can also reduce the demand for substitute feed inputs such as concentrate-based feeds, X, which can lower costs while maintaining a given production level. The theories utilised in this study support the methods of analysis that are explained in chapters 4 through 6. Production theory is a key foundation of this thesis and supports the study of farm businesses as seeking to minimise costs and maximise output and profits. Theories around efficiency, input substitution, and technology adoption help to underscore the ability of farmers to optimise their production systems and adapt to more productive methods. Understanding the meaning of risk in an economic context promotes volatility as a component in the calculation of farm utility and ultimately having an impact on the production function. While this study does not directly address every theoretical topic included in this theoretical framework chapter, these concepts are important to develop a background of understanding for the chapters ahead. By establishing a basic theoretical underpinning, this study develops the process of data selection and methods which are appropriate to the subject area theory.

Chapter 3. Data

3.1 Introduction

The purpose of this chapter is to outline and describe the various data sources that this analysis of dairy farm feed system risk and reward draws on. The advantages and drawbacks of the data included and contextual background on why such data is used are also included herein. In a hypothetical ideal data setting, data would exist on every dairy farm in Europe from large to small, including their precise geographic location, agroclimatic conditions, detailed measurements of grass growth and feed consumption as well as financial and quantitative measures of output. In reality no such data set exists. The protection of farmers' personally identifiable data such as location, production capacity and financial returns are highly protected and rightly so. However, with the use of modern technologies such as satellite imagery and with econometric modelling to estimate weather conditions for example, it is possible to paint a detailed picture of the agronomic, environmental, and financial status of tens of thousands of individual farms. This allows the researcher to provide results which are representative of "real-world" farms rather than a hypothetical average farm or a nonrepresentative research farm.

The data included in this study is linked to each of the three component models of this thesis. The risk model which is included in Chapter 4 relies on the Teagasc National Farm Survey (NFS). The NFS encompasses Ireland's data submission to the European Union's Farm Accountancy Data Network. Chapter 5, which includes a grass growth model and cluster analysis uses a variety of data sources including spatially disaggregated satellite vegetation index data, microsimulated rainfall and temperature data and soil map data. Chapter 7 is an international comparison of the relative profitability of European dairy farm feed systems. This chapter employs data from multiple nations in the European Union's Farm Accountancy Data Network. Used together these data sources help to explain the risk and volatility of dairy farm incomes, how weather and growing conditions are related to grass feed production, and how different feed systems are associated with differing profitability outcomes across and within countries.

3.2 Data included in the Chapter 4. Risk factors for Irish farms

When conducting an analysis of farm income risk, it is important to measure and understand the wide variety of risk sources that farmers face. Climatic shocks, policy changes, and volatile markets for inputs and outputs are examples of these risk factors. The effects of risk are also a key part of any risk analysis. Risk has an effect on farm management, investment, and, ultimately on production outcomes. An ideal data source for risk analysis would include detailed data, not only on the financial situation of farms, but on management decisions and production patterns over time.

The data set used to analyse the determinants of risk for Irish farms is the 2005-2013 Teagasc National Farm Survey (NFS). This survey collects farm-level data which is nationally and spatially representative of Irish farms. While this survey collects data for the Irish component of the Farm Accountancy Data Network (FADN), it goes beyond farm finances to collect data on farm input and output quantities as well as demographic and agronomic characteristics of individual farms. NFS data is also utilised to develop a database for economic and rural development research and policy recommendation purposes in Ireland. The NFS is also a tool for the evaluation of farm management practices, farm performance and technology adoption. NFS surveys are collected by trained farm recorders who develop relationships with farmers over multiple visits per year. This reduces non-response and promotes trust between survey subjects and the collecting agency, Teagasc. The NFS is conducted as a rolling panel of farmers and so allows for farm income volatility within individual farms to be studied in addition to differences between farms. The NFS is the preferred data source for the analysis included in Chapter 4 for multiple reasons.

Given the nationally representative nature of the NFS, it provides a more detailed picture of farms across Ireland than representative farm models which employ a standard or average farm which are developed hypothetically using data from research farms. These models fail to capture the heterogeneity of farms across Ireland which vary widely in terms of size and agroclimatic endowment as examples. In the NFS key agroclimatic and farm management characteristics are measured across the full range of farms from the large and capital-intensive systems to small, limited farm operations. This allowed for a dynamic comparison of differences in farm volatility across a wide variety of farms. Within farm variation was also measured allowing exogenous stimuli such as market forces or weather to be controlled for on a temporal level. While the NFS includes a variety of management and farm input characteristics it does not collect data on the feed energy requirements of livestock farms, or the feed supplied from grazed grass on the farm. This data gap was highlighted by the association of income volatility with pasture intensive farm systems such as dairy farms. In order to address this gap in data coverage of pasture-based livestock feed inputs more data on growing conditions and grass production was assembled for use and evaluation in Chapter 5.

3.3 Data included in Chapter 5. Cluster analysis and grass growth model

In order to provide a clearer picture of grazed grass production in Ireland this study looked beyond existing survey data. This section will outline how grass growth data is collected and assembled in Ireland and will highlight the strengths and weaknesses of existing data sources. This section will also explain how the data used in the cluster analysis and grass growth model of Chapter 5 was selected and processed.

Modelling, measuring, and/or estimating the production and utilisation of grass growth on pasture-based livestock systems is an important, but difficult research task. Unlike other field crops, the yield of which is carefully measured every harvest at a granular spatial scale, pasture grass growth data is not recorded by the bovine, ovine, or equine harvesters. Even though grass is not measured in the same way as other crops it is an important feed crop which accounts for the vast majority of agricultural land in Ireland and other nations (many of them developing) which depend on grass growth as a primary agricultural input. Ideal grass growth data would be measured frequently at each grazing cycle throughout the growing season. It would indicate the spatial heterogeneity of grass growth at the field, farm, and regional levels. An ideal data set would also indicate the amount and energy value of grass utilised by grazing animals. While this hypothetical data source does not exist in whole, components of this data can be assembled from existing sources to provide a better understanding of grass growth patterns in Ireland.

Existing survey data on feeds for pasture animals focuses on purchased feeds. The FADN dataset includes detailed data on purchased feed costs and financial values, but does not include the quantities of feed purchased or utilized. The Teagasc NFS survey dataset in Ireland does measure feed quantities purchased and utilized, but does not include data on pasture feeds which are produced and consumed on the surveyed farm. Teagasc does however collect data on measured grass growth.

The Teagasc Pasture Base programme is a management tool for farmers which encourages and assists with the measurement of weekly grass growth levels at the field level for Irish farmers. Farmers use rising plate meters to measure grass growth across their various pastures in an effort to benchmark management improvements and to optimally rotate grazing animals onto fields with highest availability of pasture feeds. While the data collected by Teagasc in this programme is of high quality and detail it is primarily for the use of farmers and their agronomic advisors rather than researchers. This is due to the nonrepresentativity of the collected data. Only a small percentage of farms in Ireland take part in the Pasture Base system. These participants are almost entirely represented by larger, more capital-intensive operations in the most agroclimatically advantageous regions of the country. Farms who have not adopted rotational grazing practices are by definition not included in the pasture base system. It is for these reasons that Pasture Base data is not utilised in this study of national grass growth measurement.

Another methodology for estimating on farm grass feed utilisation starts with viewing a livestock farm as a net energy system. Jarrige (1989) developed a net energy system for cattle and sheep which estimates feed energy needs for animals based on their demographics as well as weight and production levels. O'Mara (1996) adapted the Jarrige system for Irish livestock systems and breeds based on the results of trials on research farms. In theory, farm level grass feed energy utilisation should be calculable as the difference between grazing livestock energy needs and the energy supplied by purchased feeds. The problems with this approach revolve around model development and data availability. Rather than being based on real world farm management practices, net energy system models were developed in the context of research farms using optimal management and technology. This means that variables such as animal weights and feed efficiencies are likely not reflective of actual farm situations or the heterogeneous nature of farms on a national level. In order to calculate feed energy supplied by grass growth it is necessary to have micro level data on animal demographics, breeds, and weights. While some of this data is available in the NFS, the researcher would still need to rely on standardised and/or imputed data for variables such as animal weights which are a key factor in feed consumption. This limits the heterogeneity in the model and makes it difficult to compare smaller, less intensive farm systems with larger and more capital-intensive systems. Finally, the grass utilisation results of a net energy system methodology are difficult to verify given the lack of measured grass production data.

Given the deficiencies of the aforementioned grass feed data sources, further data research is required to analyse the key determinants of grass growth. Agronomic grass growth models eliminate the problem of animal harvesting of grass by careful researcher measurements of grass growth on research plots specifically dedicated for this purpose. At first glance, such agronomic models seem like the ideal way to estimate grass growth. Detailed data is recorded on the inputs of grass production such as seed variety, fertilizer and mineral applications, management characteristics, and agroclimatic conditions. In terms of grass production, dry weight and feed energy and nutrition values are recorded in detail and at regular frequencies.

While this method of data collection produces a rich depth of agronomic detail, it is time and labour intensive to collect and is not possible to replicate on a representative heterogeneous sample of real-world farms. Thus, the scope of agronomic grass growth models is confined to the realm of research farms. Still, agronomic models such as those by (Shalloo et al., 2004) provide valuable data on the determinants of grass growth for which more localised and representative data may be sought out. Among these key determinants are agroclimatic variables such as temperature, rainfall, and soil type and texture. By developing a dataset which included these variables at a localised or farm level, the spatial heterogeneity of their effect on grass production can be thoroughly estimated and analysed.

In order to build a representative dataset of the determinants of grass growth in Ireland, this study begins by assembling a large and spatially heterogeneous set of agroclimatic variables including basic weather and soil variables. Weather data was provided by MetEireann, Ireland's national weather service. The original dataset provided included daily rainfall data for over 800 locations across Ireland from 1980 to 2013. Over the same time period, daily average temperature was provided for over seventy temperature stations across Ireland. Temperature stations were more limited due to the requirement for automatic digital thermometers, rather than simple rain gauges for rainfall measurement. In order to make this dataset more manageable and to control for the occasional non reporting of individual weather stations, daily values were aggregated to the monthly mean level. Stations that did not report for entire months during the target measurement period from 2003-2015 were eliminated from the sample leaving 702 rainfall stations and 79 temperature stations which were included in this analysis.

The next step in assembling a spatial database of agroclimatic variables was to collect the geographic locations of farms in Ireland. Data from the 2010 Census of Agriculture (CSO, 2012) conducted by Ireland's Central Statistics Office (CSO) was used to find the spatial locations of farms in Ireland. According to the CSO and its census results approximately 140,000 farms existed in Ireland during 2010. While detailed location data was not collected as part of the Census of Agriculture, farmers did report their addresses as a part of the survey programme. These text addresses were processed through the An Post Geodirectory which is a database of address locations maintained by An Post, Ireland's national postal service. Due to the incomplete coverage of the Geodirectory database and differences in address text between the database and how farmers reported their addresses 95,000 unique farm locations were established. After eliminating duplicate farms on the same location 91,000 unique farm locations were established. This provided a large and spatially representative sample of farm locations across the nation of Ireland. The next step in this data assembly process was to match the weather database to the farm location dataset.

A microsimulation methodology was employed to estimate monthly temperature and rainfall data to 91,000 unique farm locations. The first step of this method was to regress measured rainfall and temperature data on the data of the ten nearest weather stations while correcting for variables including straight-line distance and elevation and other weather conditions. Closer stations were granted a higher weight in this regression. The coefficients generated were then used to estimate weather variables for each of the 91,000 farm locations. By comparing predicted and actual weather data at the location of weather stations, the estimated rainfall data has a correlation of 0.98 with actual measured data. For temperature the correlation between predicted and measured data was 0.95. This slightly weaker correlation for temperature data is expected given the smaller dataset of temperature monitoring stations.

The other major component of agroclimatic data involved in this study is soils data. Soil type and texture are important indicators of growing conditions for grass production. Ireland has a wide variety of soil conditions across its land area, but thankfully also has a well-developed soil mapping programme. This study utilises the Soil Map of Ireland (Cramer, 2008) to add soil variables to each of the 91,000 farm location study cases. Farm locations are assigned a soil type based on the soil type polygon they lie in. The Soil Map of Ireland collected soil data on a spatially disaggregated scale across Ireland. Information on the 20 soil types was aggregated into 10 great soil groups. Soil texture was also collected and added to this study's database. Soil texture is important to measure due to the unique drainage characteristics of different soils. This is critical in Ireland which is a high rainfall temperate climate. While this soil data source provides valuable information on the heterogeneity of soil conditions their respective agronomic production possibilities, it is not a panacea of soil data. Farms can cover a large geographic area with a variety of soils existing side by side within farms and even within fields. While only a single map point and thus a single soil type and texture is assigned to each farm location, this issue can be addressed by aggregating farm locations into small districts with a variety of soils present in different proportions in each district. This aggregation is discussed in further detail in Chapter 5.

A final and key component of any spatial agronomic grass growth model data set is spatially disaggregated grass growth data itself. The limitations of survey, direct measurement, and net energy data collection as explained above mean that a novel grass production data source is required. In broad terms, remote sensing data can be divided into drone and satellite data. Drone data collection is still in its infancy, but has distinct potential in the context of small scale (farm or field level) data collection. Drone collection methods have also yet to develop standardised models for the interpretation and processing of the optical data which is gathered. For more information on the future potential uses of drone data collection for grass growth measurement please see the section 7.5 which outlines opportunities for future work in this area. In the case of the current study, which seeks to gather data across a national scale, satellite data is the preferred data source. Remote sensed satellite data has been used for decades to estimate the production of field crops where surveyed yield data is too slow or too difficult to collect. In the context of field crops, where yield data is collected with every harvest, it is possible to “ground-truth” remote sensed data by relating it to measured data on the ground. In the context of pasture grass growth, this “ground-truthing” becomes more difficult due to the dearth of measured data. Instead, this study develops the use of remote sensing data as a proxy for direct measurement of grass growth data on a nationally representative scale by relating remote sensed vegetation data with the known determinants of grass growth.

Before remote sensed data can be matched to ground level agroclimatic data, a satellite-based vegetation index must be selected. In order to do this, it is important to understand how vegetation data is generated from satellite imagery. The general method for measuring vegetation growth from satellite imagery is based around the concept of photosynthesis. Plants that are growing more rapidly and generating more biomass are absorbing more light energy on the photosynthetic spectrum and reflecting less light on this same spectrum. Humans can perceive this in a very simplistic way as more productive fields appearing “greener” than fields suffering from drought or nutrient deficiency for example. Satellites can measure this photosynthetic growth activity with more accuracy since they can measure the full spectrum of photosynthetic light, much of which is not visible to the human eye.

Over time, satellite technology and accompanying models have developed to provide more accurate and frequent vegetation data at a more granular spatial scale. One such satellite/model vegetation index system is known as the normalised difference vegetation index (NDVI). Under this system, satellites recorded vegetation growth data at a one-kilometre scale. The system was “normalised” in that it controlled for the difference in photosynthetic light reflectivity due to latitude and season. An improved version of NDVI known as the enhanced vegetation index (EVI) is able to measure vegetation growth at the 250-meter scale. This data is generally available at weekly frequency and first became available for Ireland in 2002. The EVI data used in this study was compiled by Stuart Green of Teagasc Ashtown and was aggregated to the monthly level. This aggregation allows missing data due to unfavourable atmospheric conditions to be controlled for. EVI data can be further aggregated to an annual cumulative measure which can be related to total grass production across a growing season. Individual farm location points were matched with EVI data based on the 250 square meter pixel that the farm location point was located in.

By establishing a large base dataset of 91,000 farm locations it is possible to use geographic datasets to add agroclimatic details not available from survey data. Weather data can be accurately simulated for each of these location points. Mapped soils data is also overlayed on the base map of farm locations and finally vegetation index data is applied to each farm point. It is important to note that in reality farm areas are not simple point locations and may include non-contiguous fields. For this reason, farm point data is aggregated to the electoral district level when regressed on vegetation growth. Once combined this dataset is used in Chapter 5 for analysing the relationship between vegetation growth and agroclimatic indicators across a larger sample than has been used heretofore in Ireland.

3.4 Data included in Chapter 6. International comparison of grass-based feed systems

Chapter 6 develops a comparison between the grass based dairy feed system most common in Ireland and the high input cereal-based feed systems which are more common in the dairy industries of peer nations in north-western Europe. To answer the research question of which system is associated with better profitability and farm viability specialised international data is required. A hypothetical ideal data set would collect comparable feed, management, and financial data at the farm level for a wide variety of farms across several countries. While not quite the perfect data source, the European Union’s Farm Accountancy Data Network (FADN) comes close to this ideal.

The FADN data collection programme was developed as a component of Europe’s Common Agricultural Policy (CAP) to provide a platform for the unbiased comparison of farm financial outcomes and farm incomes across each of the EU member states. It also allows for the assessment of CAP subsidy programmes and their financial impacts on farmers. Due to its financial and accounting focus, FADN does not collect a full battery of farm management variables or quantity measures of farm inputs such as feeds.

In order to find dairy feed systems which were broadly comparable with the Irish pasture system, this study utilises FADN survey data from farms across the primary dairy producing regions of north-western Europe. Specifically, these nations are France, Ireland, the United Kingdom, Denmark, the Netherlands and Belgium. By comparing Irish dairy farms with peers in north-western Europe, the analysis is not skewed by the many specialist dairy product producers that are present in Mediterranean Europe or by the less technologically advanced systems of Eastern Europe which are also governed under an alternative CAP payment schedule. Given this comparability, the nations in this study can and indeed do support both pasture-based and cereal-based dairy feed systems. FADN provides weights for each farm in order to scale the results of the survey to be representative of the nation as a whole. Based on these weights the data used in this analysis is representative of the commercial farms over the time period of 2003 to 2016 in each of the studied nations. All farms included in this analysis are categorized as specialist dairy farms meaning that while other livestock or crops may exist on the farm, the majority of the farm's production value comes from dairy production. The FADN dataset is specifically designed to produce comparable data across Europe, thus making it the preferred data source to compare dairy feed systems in this study.

3.5 Conclusion

The data in this study have been selected to provide both a depth of detail and a broad and representative spatial scope to this analysis of dairy feed systems. Through the use of nationally representative survey data such as the NFS in Chapter 4, it is possible to compare the risk profiles of disparate farm types to highlight the volatility of dairy farms and underscore the importance of feed and feed data in the dairy system. In order to fill a data gap in the area of pasture-based feeds, Chapter 5 employs geographically matched data on vegetation growth, weather and soils to develop a nationally representative and heterogeneous model of grass growth and its determinants. Chapter 6 compares dairy farm feed systems and their associated outcomes and uses an international FADN dataset to evaluate this. Together these data sets are the basis for an analysis at the national and international level, of the relationship between a pasture-based feed system and the risk, environment and financial outcomes of dairy farms.

Chapter 4. Risk factors for Irish farms

Agricultural income volatility has become a major hurdle for Irish farmers and policymakers to overcome in their drive to increase investment, production and ultimately income in the sector. The following chapter studies data from 927 farms in the Teagasc National Farm Survey between 2005 and 2013, the first nine years of the decoupled subsidy era. The primary income support for European farmers, the single farm payment (SFP), is analysed in the context of its relationship with market income risk, i.e. farm income excluding subsidies. Detrended measures of market income variability are regressed on a large set of control variables. These findings suggest that the amount of SFP received by farmers has a strong and statistically significant relationship with agricultural income volatility. The following sections 4.1 and 4.2 provide an EU and Irish context for agricultural income risk and the policies which seek to mitigate this risk respectively. Section 4.3 outlines economic risk theory while section 4.4 describes the NFS data and regression methods utilised in this study. Section 4.5 and 4.6 discuss the risk model results and conclusions respectively.

4.1 Introduction to agricultural income risk in Ireland and the European Union

The European Union has throughout its history, intervened in agricultural markets through the European Common Agricultural Policy (hereinafter “CAP”), which began in 1958 as one of the original core policies of the European Community (EC) (ECPA 2013). Much of this support is directed to farmers as Direct Payments (DP). These payments are an effort to stabilise and increase farm income while sustaining farm businesses and the agricultural goods and services that they provide. As farmers around the world face climate change and competitive global markets, farm incomes have become increasingly unstable (Di Falco et al. 2014). In this context, it is important to analyse the relationship between DP and the variability of market incomes (i.e. farm incomes excluding the DP) for the Irish case. A well-targeted DP policy can assist those farms which are inherently more vulnerable to high variability in market incomes. At the same time, the DP can incentivize farmers towards riskier behaviour than would otherwise be the case and these unintended consequences must be addressed in any economic analysis of the relationship between DP and farm income variability (Capitanio and Adinolfi 2009).

Volatility in Ireland's agricultural sector has become a key issue for stakeholders across the industry (O'Connor and Keane 2011; O'Donoghue and Hennessy 2015). The rise in farm income volatility is not confined to any one farming system (Hynes and Hennessy 2012). The increased volatility of milk output prices and dairy farm incomes has however, received the most attention (McDonald *et al*. 2014; Bergmann *et al*. 2015; Loughrey *et al*. 2015). European farmers, researchers, and policy makers are preparing for continued price and income volatility into the future (Assefa *et al*. 2015; El Benni and Finger 2013; European Commission, 2011; Finger et al., 2022). This raises a few interesting questions which must be answered if income variability is to be moderated for Irish farmers. Where does the increasing risk in Irish agriculture stem from? What are the implications of a persistently volatile farming environment? Which tools can we utilize to manage and adapt to risk while preserving the sustainability of Irish farms?

The purpose of this study is to build towards answers to these vital questions. In particular, we focus our attention on the potential relationship between decoupled farm payments[2] and the variability of market incomes. Decoupled farm payments can reduce the overall farm income variability as these payments provide a more stable income source relative to income gained through market activities (Severini *et al*., 2016b). This study adds to the body of literature which questions the extent to which the so-called "decoupled payments" are truly decoupled from production decisions (Capitanio and Adinolfi 2009; Femenia *et al.* 2010; Howley *et al.* 2012; Finger and Lehman 2012).[3]

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[2] Decoupled payments include Single Farm Payments and Disadvantaged Area Payments.

[3] While these studies found some relationship between decoupling and production decisions, a number of studies have found little or no significant relationship (Goodwin and Mishra 2005; Weber and Key 2012; O'Neill and Hanrahan 2011).

In the context of the potential relationship between decoupled payments and risk management decisions, Hennessy (1998) concluded in a U.S. study, that the term “decoupled” can be misleading as both the wealth effect and the presence of risk aversion can ensure that decoupled payments affect production decisions. Indeed, Finger and Lehmann (2012) found among Swiss farmers, that DP have a negative effect on the demand for hail insurance as a risk management strategy. Similarly, Koundouri *et al*. (2009) found that decoupled payments significantly altered the risk attitude of farmers in Finland after European Union accession. The literature has not always however, identified a significant relationship between decoupled payments and risk attitudes or risk management decisions (Serra *et al*. 2011). It is therefore an empirical matter as to whether or not a relationship exists between decoupled payments and farm income risk in a particular context.

In investigating the origins of the recent increase in commodity price risk exposure to farmers, there are some explanations including the role of macroeconomic forces (Karali and Power 2013) and monetary policy action and communication (Hayo *et al*. 2012). In microeconomic theory, the weakness of short-term production and consumption elasticities in responding to economic shocks are cited as contributory factors (Gilbert 2006; Gilbert and Morgan 2010). Food producers are particularly vulnerable to commodity price risk as they must commit resources for the duration of a production cycle whereas consumers may have the opportunity to switch their consumption patterns in the short run (Sandmo 1971; Bellemare 2015). In developed countries, the exposure of consumers to commodity price risk is therefore usually considered less problematic than the exposure of farmer producers. Barrett and Bellemare (2011) have concluded that from a consumer perspective, “the world does not necessarily face a price volatility problem. It faces a high food price problem”.

In the next section, we provide some detail on the policy background and in particular the efforts of European policymakers to address farm income variability. We follow this with a description of the theoretical relationship between DP, farm assets and farm income variability. This is followed by an empirical analysis of farm income risk in Ireland from decoupling in 2005 to

2013. The econometric analysis highlights the relationship between European single farm payment subsidies and the market income risk of farmers. While the single farm payment is seen "…as an important cushion against commodity price volatility" (DAFM 2015), the data suggests that high direct subsidy payments are actually associated with *higher* market income risk.

4.2 Agricultural income risk policy background

To avoid the negative impacts associated with high farm income variability, producers and policymakers internationally have developed a number of risk management strategies. Research has found that these strategies vary widely in terms of efficacy and may have actually served to increase income risk in the long term. Mishra and Sandretto (2002) examined the variability in net farm income in the United States since the development of farm price and income support programs in the 1930s and conclude that variability did not fall between the mid-1930s and the end of the twentieth century and that the increase in nonfarm income played an important role in reducing overall household income variability.

The European Union policy interventions have included a range of incentives including consumption subsidies, intervention prices, price floors, export refunds, import tariffs, quotas for food products, precautionary savings and crop insurance subsidies (Jongeneel *et al*. 2010; ECPA 2013). One of the objectives of the Common Agricultural Policy (CAP), as provided by Article Thirty-Nine in the 1957 Treaty of Rome, is "to ensure a fair standard of living for the agricultural community, in particular by increasing the individual earnings of persons engaged in agriculture". Food market stabilization has been identified as a key to reaching these goals CAP (ECPA 2013). The CAP expenditures now account for approximately 40 per cent of the European Union budget (European Commission, 2016).

The CAP policies dampened downside market risk, but were found to significantly boost the risk appetites of producers (Serra *et al*. 2009; Sckokai and Moro 2008). Matthews (2010) concludes that prior to 2005, the CAP successfully insulated EU domestic prices from the volatility of the world market but the price stability interventions became "increasingly intertwined with and dominated by" a motivation to simply transfer income to the EU farm sector. The associated "budget costs" and "environmental criticisms" motivated policymakers towards reforming agricultural policy supports and deciding to largely decouple farm subsidies from production in the 2003 reforms, which became enacted in 2005 (Capitanio and Adinolfi 2009).

These reforms essentially involved a replacement of price supports with direct subsidy payments based on historical production. Since DP do not directly affect farmers' price uncertainty as price supports do, these payments theoretically have a less distorting effect on production and risk decisions (Sckokai and Moro 2008). DP have the potential however, to increase farmers' wealth, which tends to slightly increase the risk appetite over the long term (Kazukauskas *et al*. 2013). Decoupled subsidies ought to reduce income variability as they are more predictable and not dependent on production (Fidrmuc *et al.* 2013) cited in (Kazukauskas *et al*. 2013). However, it is this very predictability that makes decoupled payments attractive as collateral to financial institutions (Rizov *et al*. 2013). This gives farmers the opportunity to increase debt levels and increase production which can ultimately lead to higher income risk. DP also act as a type of income insurance for farmers which crowds out other "natural" risk management strategies such as diversification and may induce less risk averse behaviour (El Benni *et al*. 2012; Falco *et al*. 2014)

The CAP has undergone numerous reforms and policy regimes since its inception. In a study of the relationship between the European Union policy regime and farm income variability among a subset of arable farms in Germany, Feil *et al*. (2014) found that farm income variability increased from the mid-1980s onwards and suggested that this could be attributed to "rising price volatility in markets for agricultural commodities" in addition to the relevant policy reforms. Mary (2013) found Single Farm Payments to be less investment distorting than counter-cyclical insurance payments among crop farms in France. In a study by Serra *et al*. (2009), decoupled payments were found to have negligible effects on risk preferences in the short run among a group of Kansas farmers. Severini *et al.* (2016a) investigated the farm income variability among Italian farms between 2003 and 2012 and found that income variability increased during this time but with significant differences among farm groups in the levels and evolution of income variability. Severini *et al.* (2016a) conclude that the increasing level of farm income variability supports the idea of introducing risk management tools within the CAP toolbox.

Research suggests that income variability is growing overall, but that each source of risk needs to be addressed individually. Farm type, size, and location are major factors in the risk burden that a farm carries and these elements also impact the farm's ability to manage risk (Severini *et al.* 2016b). High levels of income risk or improperly structured subsidy and risk management policies may cause farmers to reduce their provision of social, environmental, and economic goods (Capitanio and Adinolfi 2009). Farm families may restrict their consumption impacting negatively on their welfare. Investment may also be reduced, which can hurt productivity in the long term (O'Toole *et al.* 2014). Fortunately, farmers and policymakers have multiple methods at their disposal to mitigate income risk and the negative consequences associated with it. Although farmers have many ways of managing income risk independently, these strategies may be dependent on factors such as the production system, labor market, or financial situation of the individual farm. Government efforts to smooth farm incomes can often be costly and may induce riskier farmer behavior in the long run. As farm income volatility increases, policies must be structured to effectively manage short run and long run while efficiently utilizing limited government funds.

4.3 Economic risk theory and hypothesis

The theoretical framework for this paper is grounded on expected utility theory under a mean-standard deviation utility function. As in the case of (Boyle *et al*., 2005), we assume that farm incomes and farm assets follow a log-normal distribution $v(\mu^*, \sigma^*)$ where μ^* is the mean of the random variable and σ^* is its standard deviation. This research is not focused on delivering precise estimates of relative or absolute risk aversion. The focus is instead placed on the possible relationship between a particular public policy and farm income risk. Much of the research in relation to farmer risk aversion points to farmers being risk averse and therefore willing to make trade-offs between risk and expected farm profits (see, for example, Chavas and Holt 1996; Picazo-Tadeo and Wall 2011; Menapace *et al*. 2013).

The Single Farm Payment is a non-labour source of income thereby conferring a wealth advantage rising with the size of payment (Femenia *et al*. 2010). The Single Farm Payment is a liquid source of income and is therefore clearly distinct from other forms of wealth such as land and buildings. In the farm risk literature, it is sometimes assumed however, that income and wealth have equal weight in the argument of the utility function for risk decisions. For instance, Hardaker *et al.* (2004) assume that farmers make risk decisions under full asset integration. This appears to be a very strong assumption given that farm assets are typically of a much less liquid form relative to farm income. It therefore appears more reasonable to expect that farmers operate under partial asset integration where the farm assets are less influential than farm income in affecting risk appetite and therefore risk decisions.

Given the asset increasing nature of DP, we interpret our findings with reference to alternative degrees of asset integration including full asset integration withing expected utility theory (FAI-EUT) where money amounts relating to farm wealth and farm income have equal weight in the argument of the utility function. In particular, we consider the likelihood of partial asset integration (PAI-EUT) where farm wealth enters the utility function in a lower proportion to farm income. We also consider the possibility of no asset integration (NAI-EUT) where the farm wealth plays no part in the utility function and therefore no role in determining the decisions relating to farm income risk.

Given the illiquid nature of farm wealth in Ireland, we may therefore anticipate that farm income and farm wealth enter the utility function in different proportions to one another, i.e. partial integration.[4] In such

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[4] Irish farmers attach a non-economic value to the ownership of agricultural land and that market sales of agricultural land are relatively low as a proportion of agricultural area. It therefore seems reasonable to anticipate that the wealth attached to agricultural land is illiquid

circumstances, there is likely to be a relationship between wealth and the income risk of the farm but not in equal proportions. Cox and Sadiraj (2006) describe a model of expected utility of initial wealth and income under the following:

$$\int u(w,y)\,dG = E_G(u(w,y)) \qquad \text{(Equation 4.1)}$$

where G is an integrable probability distribution function and u can be considered as a utility function of initial farm wealth w and farm income y. Andersen *et al.* (2012) refer to this as the PAI-EUT model as it allows for partial asset integration. The model allows for the polar opposite cases of FAI-EUT and NAI-EUT. Under FAI-EUT, the utility is due simply to the sum of initial farm wealth and farm income where $u(w,y) = v(w+y)$. Under NAI-EUT, the utility is entirely due to the farm income flows and $u(w,y) = \varphi(y)$.

At present, the primary income protection policy for Irish farms is the wealth-inducing decoupled single farm payment. Enjolras *et al.* (2014) suggested that DP may have a slight positive association with income risk for crop farms in Italy, but this relationship was not statistically significant in France. French farms may have used the additional payment income as a way to shift down Blank's (2001) "farming food chain" to less risky production systems. Smaller Italian farms may have less flexibility in their production systems. Irish farms also tend to be small and have limited opportunities for expansion or transition to different production systems on the "farming food chain" given the climatic limitations of Ireland.

The relationship between risk and decoupled payments may be linked to the wealth effect of annual transfer payments (Kazukauskas *et al.* 2013).

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and cannot be readily accessed. In addition, farmers are reluctant to rent out land and therefore accrue the monetary benefits of rental agreements.

Rizov *et al*. (2013) also note that steady payments may increase farmers' access to, and preference for, financial goods, therefore increasing financial risk (Rude 2008). Others may use single farm payments to reduce their amount of buffer savings or time spent in off-farm work. The SFP may also result in lower risk for less entrepreneurial "entitlement farmers" who use subsidies to maintain their incomes with less business risk (Thorne and Hennessy 2007). These studies highlight the debate over the risk effects of decoupled payments, but their conclusions are not necessarily applicable to the largely livestock based agricultural system in Ireland. Consequently, hypothesis H1 needs to be empirically tested in the Irish context.

H1 *(income risk)*: Decoupled single farm payments as part of the Common Agricultural Policy are significantly associated with farm level market income risk in Ireland.

H2 *(farm assets)*: Farms assets are integrated into the decision-making of farmers in relation to farm income risk. This can be evidenced from a significantly positive econometric relationship between the size of the farm assets and the income risk of the farm.

4.4 Data and methodology employed in this study

To assess the income variability of individual Irish farms, the Teagasc National Farm Survey (NFS) dataset is used. Since 1972, the NFS has collected detailed financial and production data from farms as part of the EU Farm Accountancy Data Network. Between 1,000 and 1,200 farms are randomly sampled each year to represent 110,000 farms in Ireland. Due to attrition and to maintain representivity, about fifteen to twenty per cent of surveyed operations are cycled out of the NFS annually.

Variability is measured as the standard deviation of gross market income from the multi-year trend over the nine-year study period. Nine years was selected as the appropriate study period in order to limit attrition loss. This methodology is similar to that of Enjolras *et al*. (2014). Poon and Weersink (2011) note that the use of gross income eliminates the problems of negative incomes and avoids distortions caused by differences in overhead (fixed) costs. In many cases, farm overheads are difficult to differentiate from household fixed costs. For these reasons, the use of gross income has been used in a number of agricultural income risk studies such as Mishra and Goodwin, (1998) and Jetté-Nantel *et al*. (2011). Gross market income includes product sales less overhead costs. Market income does not include decoupled single farm payments or other subsidies such as environmental payments. The absolute value of decoupled subsidies was used as in Enjolras *et al*. (2014) rather than the ratio measure used by Severini *et al.* (2016b). Since many Irish farmers also have off-farm incomes, the absolute value of DP is of more interest than the proportion of farm income derived from subsidies. This study differs from the work of Enjolras *et al*. (2014) as it analyses a sample of primarily livestock farms which have a different risk profile than the field crop-based agriculture of France and Italy. This analysis also does not include crop insurance as Irish farmers do not have access to farm revenue insurance products.

Table 4.1 below displays summary statistics for the sample which includes farms observed during at least six of the nine years from 2005 to 2013. By utilising farms that were observed at least six times, linear time trends can be measured and controlled for. In all, 927 farms provided data on an average of 8.2 occasions. By controlling for linear income trends over the nine-year period, we can account for farms in deliberate expansion or decline. Risk management policies should not restrict the abilities of farms to expand or contract voluntarily, but should help farms to manage year to year income swings (Finger and El Benni 2014).

The independent variables in this analysis use the mean or initial values for each farm over the sample period such that each farm is represented by one observation. The key independent variable of interest is the initial value of decoupled payments and the farm-level change in payments over the sample period. As evidenced from Table 1, the decoupled subsidies contribute significantly to family farm income. Compared to other European countries, total per hectare payments to Irish farms are similar to those of Italian farms and are above French payment levels. Coupled subsidies include livestock and tillage subsidies which became increasingly rare over the 2005 to 2013 observation period. Gross output includes the market value of all agricultural production. At 1,251 euros per hectare, Irish gross farm output is below the mean levels of French and Italian farms analysed by Enjolras *et al*. (2014).

Farm level control variables include land farmed and rented as well as stocking rate, concentrates fed, and crop protection costs. Livestock density is significantly higher than the EU-27 average (Eurostat, 2015). Crop protection cost is very low compared to the sample of French and Italian farms used by Enjolras *et al*. (2014). This highlights the importance of livestock relative to tillage farming in Ireland. Mean farm size is small, but is similar to the mean size of the Italian farms in the sample used by Enjolras *et al*. (2014). Even though farm sizes are small in Ireland, land values are among the highest in Europe making the land wealth of Irish farmers significantly higher than that of Italian or French farmers (Keith, 2013). A significant number of farmers and their spouses were employed off the farm during the study period. In Table 4.1, the off-farm employment statistics refer to the initial condition when the farm first entered the sample. Table 1 shows that forty per cent of the sampled farms were primarily involved in beef production. Of these farms, just over half were suckler farms producing young beef animals while the remainder were primarily finishing farms. Specialist dairy farms are the single largest farm system, encompassing more than one quarter of the sample. This sample reflects the agricultural industry of Ireland which is predominantly livestock based. Like Enjolras *et al*. (2014), this data does not include information on farmers' use of forward contracting or spread selling, however these options are limited to tillage and dairy farmers and were not widely used during the study period. Unlike Enjolras *et al*. (2014), this data does not include savings or debt related information.

Table 4.1 Descriptive statistics

Variable	Mean	Standard Deviation
Detrended Standard Deviation of Gross Market Output (€)	11,842	12,287
Initial Decoupled Subsidies (€)	21,787	15,547
Change in Decoupled Subsidies (€)	-351	7,184
Mean Coupled Subsidies (€)	2,286	2,880
Mean Gross Output (€)	70,924	78,844
Farm Characteristics	**Mean**	**Standard Deviation**
Mean Livestock Units Per Hectare	1.34	0.60
Mean Daily Concentrates per L.U. (kg)	1.45	1.23
Mean Crop Protection Cost (€)	1,120	3,476
Mean Fertiliser Cost (€)	6,572	7,196
Mean Farmer Age	53.9	11.0
Mean Farmed Area (Hectares)	56.7	43.1
Off-Farm Work	**Percent**	**Observations**
Initial Off-Farm Job, Farmer	27.1	252
Initial Off-Farm Job, Spouse	36.8	341
Initial Farm System	**Percent**	**Observations**
Cattle Rearing	21.6	200
Cattle and Other	18.4	171
Dairy	26.9	249
Dairy and Other	13.3	123
Sheep	11.2	104
Tillage	8.6	80

To analyse the income variation among farms in this sample, this model adapts the methodology developed by Enjolras *et al*. (2014) and uses the standard deviation of farm market income as the key dependent variable. This model differs from Enjolras *et al*. (2014) by using the standard deviation from stationary, detrended market income rather than mean market income. This measure of variability accounts for the endogenous variability of farms that were purposefully expanding or shrinking during the 2005 to 2013 observation period. The natural log of standard deviation is used to normalize the distribution which is skewed by a few highly variable operations.

$$Ln(\sigma Y_i) = \beta Ln(Y_{di}) + \beta Ln(\bar{Y}_i) + \beta X_{it} + \alpha + \varepsilon_{it} \qquad \text{(Equation 4.2)}$$

where σY_i stands for the standard deviation of market income earned by farm i across all of farm i's observations, Y_{di} stands for the mean level of income from decoupled payments, d, for each farm over the sample period and X_{it} symbolises the set of additional covariates which control for coupled subsidy payments and farm characteristics. The term $\bar{Y}_i$ represents the mean market income or alternatively output of farm i during the period. We apply the mean market output in order to account for scale effects which may not be adequately captured by variability between farms in the mean market income or land area.

4.5 Risk model results

Table 4.2 below shows the results of the model for the full sample and for the four individual farm types. Income variation was significantly associated with initial decoupled subsidy payments for beef cattle and sheep farms, but this effect was insignificant for dairy and tillage farms. Dairy and tillage farmers in Ireland are far more profitable than cattle and sheep farmers and are thus less reliant on direct payments as an income source (Hennessy and Moran, 2015). Since Irish cattle and sheep farmers derive nearly all of their profit from direct payments, it makes sense that initial direct payments dictate the amount of income risk these farmers can take on (Hennessy and Moran 2015).

In all of the models, there is a strong positive relationship between increases in decoupled farm payments and market income variation. These results appear to be intuitive given that changes in decoupled payments can be accompanied by changes to the farm size thereby impacting on the farm income variability over the period. In terms of the initial size of the payments, the decoupled subsidy effect is found to be significantly positive for the full sample but is not found to be significant for dairy or tillage farms. This suggests that subsidies are less important in altering the risk profile of the more market-oriented, higher income dairy and tillage farms. Coupled subsidy payments are much smaller and have a much weaker effect on income risk overall. High gross output is also correlated with high income variability. This effect is particularly strong for tillage farms which may use their higher market revenue as a buffer against income variability.

The data suggests that certain farm inputs have a significant effect on market income risk. Farms with larger areas of owned and rented land tend to have higher income variability overall. Larger investments in land may be associated with a larger risk appetite which also translates into large year to year changes in income. Land owned is a source of wealth. In the case of dairy farms, this appears to be positively associated with farm income risk. This result may indicate some degree of partial asset integration into the risk decision-making process. Rented land is a very small proportion of farmland, but changes in rented land had a large effect on income risk for tillage farms. Stocking rate had a small negative effect on income variation overall which suggests that intensive grassland management may be associated with effective risk management.

Although operator age is not significantly associated with income risk over the full sample, it is a significant factor for dairy and tillage farms. The quadratic effect suggests that the youngest and oldest farmers in the sample have the highest income risk. Younger farmers may be actively taking on new risks as they enter the market while older farmers may be less able to manage risk on their own. While the signs are somewhat expected, we find that off-farm work only has a significant impact on income risk for dairy farmers. The proceeds of an off-farm job could be used as a hedge against on-farm income risk and off-farm work may also mean less time for on-farm risk mitigation. Different production systems also have different levels of income variability. At the margin, dairy farms have significantly more income variation than all other farm types.

This comparative model suggests that farms most associated with volatile incomes tend to be high income dairies, with large and increasing single farm payments. It also shows us that the main sources of risk for dairy farms are not substantially different than those of other farm types. The r-squared for the individual farm type models are only slightly below the r-squared for the full sample model. This suggests that multi-year standard deviation is an appropriate variability measurement even when a single farm type with a smaller sample size is analysed.

These results remained robust when absolute deviation of income was used as the dependant variable and also when farms observed less than nine times were excluded from the sample.

Table 4.2 Standard deviation of market income on Irish farms

Variable	**Full Sample**	**Dairy Only**	**Cattle**	**Sheep**	**Tillage**
Initial Decoupled Subsidies (€10,000s)	0.10***	0.01	0.10***	0.19***	0.05
Change in Decoupled Subsidies (€10,000s)	0.13***	0.09**	0.10***	0.28***	0.15**
Log of Coupled Subsidies	0.02**	0.03	0.03**	0.07	0.03
Log of Gross Output	0.53***	0.63***	0.50***	0.31***	1.06***
Initial Land Owned (100 Ha)	0.13**	0.39***	0.18	0.03	0.12
Initial Land Let Out (100 Ha)	0.17	-0.15	0.45	-.09	-0.81
Initial Land Rented In (100 Ha)	0.24***	0.50***	0.18	0.50	0.38
Change in Land Owned (100 Ha)	0.06	-.09	0.04	0.01	1.69**
Change in Land Let Out (100 Ha)	-0.25	1.03	-0.72	-0.59	-1.19
Change In Land Rented In (100 Ha)	0.07	0.02	0.08	-0.05	0.07
Livestock Units Per Hectare (100 Ha)	-.07*	-.06	0.01	-0.13	-0.12
Daily Concentrates per L.U. (kg)	0.01	-.03	0.02	0.01	-0.04
Crop Protection Cost (10,000s €)	0.13*	0.24	0.29*	-0.03	0.26
Fertiliser Cost (10,000s €)	-0.03	-.07	-0.08	0.01	-0.44**
Mean Farmer Age	-0.01	-0.04**	0.01	-0.00	-0.03*
Mean Farmer Age Squared	0.00	<0.01**	-.00	0.00	<0.01**
Farmer Off-Farm Job	0.02	0.10*	0.01	-0.07	0.16
Spouse Off-Farm Job	0.01	0.03	-0.04	0.12	0.21*
Cattle	-0.23***				
Sheep	-0.18***				
Tillage	-0.33***				
Constant	-5.74***	-6.02**	-6.28***	-4.51***	11.00***
N	927	249	494	104	80
R^2	0.80	0.80	0.76	0.67	0.84

Note: ***, **, *Denotes that the corresponding coefficients are significant at 1%, 5% and 10% level respectively.

4.6 Conclusions drawn from this study

To test whether decoupled subsidy payments increase income risk on farms we model income variability over nine years for 927 farms in Ireland. This model supports the argument that decoupled payments and market income risk are closely and positively related. Even after correcting for individual level time trends and a variety of farm characteristics, these results remain robust. The positive relationship between decoupled payments and income risk in Irish farms is similar to the payments and risk relationship found by Enjolras *et al*. (2014) for Italian farms. The small farm sizes and relatively large payment levels in both Italy and Ireland contribute to their similar risk patterns. This model also paints a picture of Irish farms that are likely to have highly variable incomes. These farms are likely to be dairy farms with larger than average outputs in addition to large and increasing subsidy payments and lower stocking rates.

The findings of this study can be interpreted in a number of different ways. One may conclude that the positive association between decoupled payments and income risk is welcome as decoupled payments appear targeted towards farms with a higher risk profile. However, under an expected utility framework, the results are somewhat concerning. In this framework, the positive relationship suggests that decoupled payments induce farmers to take on greater risks in their market activities and that those farms with the largest payments are given an advantage in terms of their scope to manage market risks. The results suggest that some degree of asset integration is present and that the value of the decoupled payments influence risk management behaviour.

While large, decoupled subsidy payments insulate farmers against instances of low income, they utilise significant amounts of public wealth to accomplish this. Our results indicate that land ownership is positively associated with market income risk and therefore contributes to risky decision-making. Meanwhile, the private assets of farmers, which on average are more than five times greater than Irish households overall, are substantially underutilised (Thorne *et al*. 2015; *CSO* 2015). Ultimately, this system does not incentivise operators to manage risk. Indeed, the increased wealth and cash flow that the decoupled payments offer may be spurring farmers towards riskier business models. To use the example of the dairy industry, subsidies are unlikely to encourage the “better before bigger” policy which is seen as a key to dairy farm resilience (Boyle 2015). This project serves to provide further empirical evidence that single farm payments, under their current structure, are associated with increased risk over a multi-year period.

As the structure of the Common Agricultural Policy evolves, policymakers will need to take a hard look at decoupled payments. Irish farm income data from 2005-2013 suggests that subsidy payments are a very costly method of moderating farm income downturns. If supporting consistent farm incomes is truly a goal of the CAP, then the subsidy system may need to be overhauled. This is of particular concern given the increasing volatility pressures due to climate change and globalisation. Future risk management tools should do more than simply transfer wealth to farmers, but should incentivise farmers to take control of the many sources of risk that they face.

The body of literature on the risk impacts of decoupled payments has plenty of room for expansion. Part of the reason for this is that the decoupled era is currently less than two decades old. As this policy ages, more data will become available and should be thoroughly analysed to determine the long-term effects of decoupling on the risk behaviours of farmers. One of the limitations of this study is that it only includes the decoupled era which began in 2005. More detailed research in the area of agricultural income risk could look back to the DP era of the 1990s, or perhaps even earlier, to see what may have caused payments to start flowing to more volatile operations. This pattern continued as Ireland distributed payments based on the historical model, but more study is needed to determine the effects of payments distributed under regional or flat payment models. As farm income volatility increases and policies continue to evolve, analyses of other systemic risk factors not included in this chapter are likely to be highly valuable. Climate change, policy evolution, and changing farm asset values are just a few of these factors. A study of agroclimatic variability in Ireland is included in the following Chapter 5 and complements the purely financial risk analysis included in Chapter 4. While this financial study focuses solely on Irish farms, Chapter 6 of this thesis analyses the income conditions of dairy farms in six north-western European nations. Dairy farms are identified in the results of this chapter as the most exposed to income volatility and deserve special study. The results of this analysis raise questions which the following chapters 5 and 6 seek to answer. Namely, what are the agroclimatic conditions faced by Irish farmers and how may they impact income, particularly in relation to grass feed availability and overall feed costs? Once the agroclimatic conditions impacting grass feed growth are analysed in Chapter 5, Chapter 6 uses international data to analyse the heterogeneity of dairy feed systems and the relationship between feed system and profitability.

Chapter 5. Statistical cluster analysis and random effects model of grass growth in Ireland using remote-sensed data

Farm level differences in the volume of grass production per hectare may partially explain differences in the economic performance of farms in Ireland. The extent to which such differences in grass production are due to geoclimatic, agronomic, or other factors remains unclear. The absence of farm level grass measurement data presents a challenge in exploring this research question. A spatial model that can explain the dynamic effects of location on grass growth would offer valuable insight to farmers and agricultural policy makers. Remote sensed enhanced vegetation index (EVI) data from 2002 to 2015 was used as a proxy measure for grass growth along with a wide range of pedologic and climatic data for over 90,000 farm locations in Ireland, representing nearly two-thirds of all farms in Ireland. Annual EVI was regressed on a range of spatially disaggregated geoclimatic variables using random effects models. These models explain up to seventy-three per cent of the overall variation in vegetation growth and are robust at the national and regional levels. This underscores the value of remote sensed data when modelling agronomic conditions for farm performance. These results remained robust even when the sample size was reduced to distinct geoclimatic clusters. This analysis highlights the wide variations in growing conditions across time and space in Ireland and introduces a method to quantify these variations. Policy makers can use this information to tailor economic farm supports to specific local needs and farmers can compare their performance and grass feed growth potential against peers with similar geoclimatic conditions. The following section, 5.1, contextualises the importance of grass growth in the Irish agricultural context and highlights the data gap that exists with respect to large-scale grass measurement. Section 5.2 of this chapter introduces the large datasets employed in this analysis including remote-sensed vegetation growth data, farm locations, weather observations, and soils data. The statistical and econometric methodologies used in this analysis are explained in section 5.3 below. Section 5.4 shows the results of the random effects grass growth model for each of the clustered pedoclimatic zones in Ireland, as determined by the cluster analysis outlined in section 5.3. Finally, section 5.5 describes the implications and applications of this methodology which combines both statistical and econometric techniques to bridge the data gap of grass growth observations.

5.1 Introduction

Grass growth is central to Irish agriculture. More than eighty percent of Ireland's farmland and more than two fifths of Ireland's land area are made up of grassland (CSO 2012; Eurostat 2012). The efficiency of Ireland's grass-based system, thanks to favourable temperate climatic conditions, have made Irish dairy and cattle production systems some of the most efficient in Europe in terms of feeding costs (Finneran et al. 2010). In Ireland, grass can supply more than seventy per cent of the dietary requirements of Irish dairy cows (Dillon et al. 2005).

Despite the importance of grass production to Irish farming, only limited quantitative data on yields exists at a nationally representative scale. Grass growth models, such as those evaluated by Hurtado-Uria et al. (2013), are typically developed in the context of research farms and under ideal conditions. Thus, their accuracy is reduced when they are applied to areas with different agroclimatic conditions. This is an important drawback given that Irish grazing systems vary dramatically from intensively managed farms with high stocking rates to part-time extensive farming. Irish farmers also face a diverse set of weather and soil conditions even within similar geographic areas. Failure to consider the heterogeneity of farming systems may cause generalised recommendations to be disregarded by farmers and/or policy makers. Given this situation, the idealistic yet unrealistic solution would be to develop ad hoc technological and management improvements for each farm. Another more practical process would be to develop typologies of farms with similar natural and management characteristics. This process can also help us to describe the important linkages that exist between pedoclimatic patterns and agronomic disparities (Shulzke & Kaule, 2001).

Irish agronomic models have developed in tandem with detailed soil and weather datasets for Ireland. Irish data on agricultural soil and weather conditions has become increasingly precise over time, but agronomic typologies still lack empirical grass yield data. (Collins and Cummins, 1996; Crowley et al., 2008, Fealy & Green, 2009). The importance of spatial data on geoclimatic conditions was highlighted during the fodder crisis of 2012 and 2013 in which poor weather conditions severely reduced grass feed production. This event also underscored the need for empirical study of the effect of weather and agronomic patterns on the inter-annual variability in grass growth.

Typological studies allow policymakers to identify similar agricultural areas where policies are likely to be successful (Kostrowicki, 1977) Developing clusters of similar farms also lays the foundation for econometric models which require typical or representative samples in order to estimate significant relationships and effects. Agriculture is more than a simple set of hedonic components, but is rather a system of numerous interrelated and dynamic factors (Kostrowicki, 1977). To better understand these relationships and dynamics, individual farming systems can be organized into groups based on characteristic similarities. Spatial typology methods have been utilised to establish a framework for agronomic research (Carmona et al., 2010) and land use research (Martinez Fonseca et al., 2006). In Ireland, Holden and Brereton (2003) developed a crop yield typology with implications for agri-environmental study while Crowley et al. (2008) constructed an agronomic atlas of Ireland. In the Irish case, agricultural typology can be used to draw distinctions between geoclimatic zones.

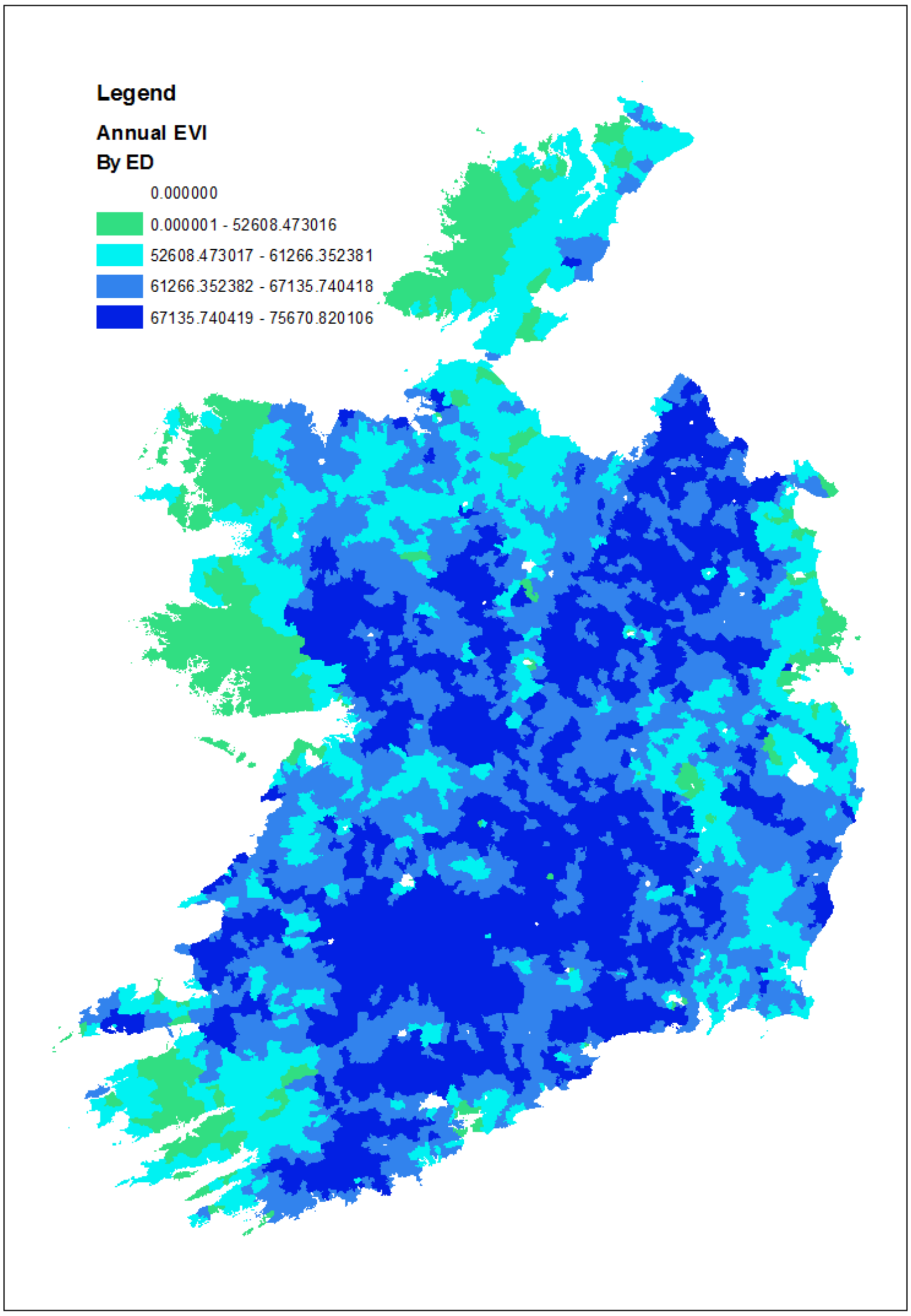
While the importance of grass growth is widely acknowledged, the accurate measurement of grass production across Ireland is difficult. One possible solution to this problem lies in the use of remote sensed vegetation data as a proxy for grass growth. This paper relates farm level weather, soil, and topographic data, as well as electoral district level farm size and stocking rate data to the enhanced vegetation index (EVI). The strong relationship between positive growth conditions and high EVI indicates that EVI is a valuable tool to estimate grass growth in Ireland.

5.2 Data collection and processing

Multiple national data sources were linked spatially to build a large dataset which matches a proxy for grass growth, the enhanced vegetation index (EVI) with weather and soil data as well as information on animal stocking rate and farm size.

The enhanced vegetation index (EVI) measures the proportion of light in the photosynthetic spectrum which is being reflected from the ground relative to the amount of light energy being absorbed by plants. Data is collected in pixels which measure 250 square metres. While satellite over-flights occur daily, atmospheric conditions sometimes distort measurements. Cumulative monthly EVI was compiled by Stuart Greene of the Spatial Analysis Department at Teagasc Ashtown. Monthly data was summed to produce a cumulative annual EVI, which can be used as a proxy for grass production during the target year. Farm locations where a non-positive annual EVI was observed were dropped from the sample as these locations are highly unlikely to be agricultural. This accounts for cases where a farmer’s mailing address may be located away from the farm itself. Map 1 describes the spatial variation in average annual cumulative EVI across Ireland.

Figure 5.1: Annual EVI by Electoral District



Weather data comprised of daily rainfall totals and daily mean temperature data were provided by Met Eireann. Rainfall data was collected at 702 rainfall stations and temperature was measured at 79 stations. For each weather station, weather was modelled using the observed weather at the ten nearest weather stations. Differences in altitude and distance were corrected for. These coefficients were used to simulate observed weather for all 90,994 unique farm locations based on the three nearest weather stations.

The An Post Geodirectory and the 2010 Irish Census of Agriculture were used in tandem to identify and locate farms**.** The An Post Geodirectory database includes all business and residential postal addresses in Ireland. For this analysis all locations which met the Irish Central Statistics Office's broad definition of a farm used for the 2010 Census of Agriculture were included. This definition specifically includes, "…every agricultural holding in the State where the area used for farming is at least one hectare. In addition, farms with less than one hectare will also be included in the Census if they are engaged in intensive production e.g. of pigs or poultry" (CSO, 2023). Stocking rate and farm size data were also extracted at the electoral district level from the 2010 Census of Agriculture. Since this analysis is primarily spatial, duplicate farms with the exact same address were dropped from the sample. This sample includes about 65 percent of all farms in Ireland.

Soil type and texture data was drawn from the Irish Soil Information System (Creamer, 2008). The Irish Environmental Protection Agency and Teagasc jointly conducted soil surveys to build a detailed soil map at the 1:250,000 scale. This study used the ten major soil groups of Ireland as established by the Soil Information System.

In order to control for individual farm level error, data was aggregated by electoral district. Farms were assigned an electoral district based on the farm address location coordinates from the An Post Geodirectory. This also allows for mean district farm size and stocking rate to be included in the analysis since electoral district is the smallest area for which these variables are published. Variable selection was based on the available, high quality spatially disaggregated geoclimatic and management variables which were relevant to grass growth (Köbrich et al., 2003). The large sample size of this analysis follows the recommendation of Escobar and Berdegue (1990).

Table 5.1 displays the summary statistics for the 90,994 farm locations in 2,919 electoral districts in Ireland. EVI, rainfall, and mean temperature data for each farm location was measured on a monthly basis from 2002 through 2015. Data from the 2010 Census of Agriculture (CSO, 2012) was used to calculate an average stocking rate and average farm size for each electoral district.

Annual cumulative EVI was calculated by summing the monthly values for each calendar year. Rainfall peaked in January on average while April was the driest month for the observed farm locations. Mean temperature was highest in July and August while January and February tended to be the coldest months. The most common soil type for the sample was grey-brown podzolic, while the most common soil texture was mixed, followed by sandy. Irish farms in this sample tended to be on relatively flat ground not far from the sea at relatively low altitudes. The livestock units per hectare variable is low since agricultural land includes commonage and tillage lands as well as grazing lands. Average hectares per farm were calculated by dividing the number of agricultural hectares in each CSO electoral district by the number of farms in each district.

Table 5.1 Weather Summary Statistics

Variable	Observations	Mean	Standard Deviation
Annual Cumulative EVI	1,275,470	64,039	8,845
Monthly EVI	15,819,216	5,339	1,201
Monthly Rainfall January	1,275,360	132	54
Mean Temperature January	1,275,360	4	2
Monthly Rainfall February	1,275,360	88	58
Mean Temperature February	1,275,360	4	2
Monthly Rainfall March	1,273,305	81	33
Mean Temperature March	1,273,305	6	2
Monthly Rainfall April	1,273,305	72	29
Mean Temperature April	1,273,305	8	3
Monthly Rainfall May	1,273,305	90	37
Mean Temperature May	1,273,305	9	2
Monthly Rainfall June	1,273,305	85	44
Mean Temperature June	1,273,305	12	2
Monthly Rainfall July	1,273,305	94	39
Mean Temperature July	1,273,305	13	3
Monthly Rainfall August	1,273,305	94	48
Mean Temperature August	1,273,305	13	3
Monthly Rainfall September	1,273,305	86	49
Mean Temperature September	1,273,305	11	2
Monthly Rainfall October	1,273,305	127	48
Mean Temperature October	1,273,305	9	3
Monthly Rainfall November	1,270,995	130	60
Mean Temperature November	1,267,151	6	2
Monthly Rainfall December	1,271,644	126	52
Mean Temperature December	1,267,800	5	2

Note:.Mean temperatures are reported in degrees Celsius; mean rainfall amounts are reported in millimetres.

Table 5.2 Soil Summary Statistics

Soil Characteristics	Observations	Percent	Standard Deviation
Brown Earth	90,994	16	0.37
Brown Podzolic	90,994	13	0.34
Grey-Brown Podzolic	90,994	28	0.45
Podzol	90,994	1	0.11
Peaty Podzol	90,994	4	0.20
Gley	90,994	26	0.44
Peaty Gley	90,994	0	0.04
Rendzina	90,994	6	0.23
Lithosol	90,994	2	0.14
Peat	90,994	8	0.27
Other Type/Not Surveyed	90,994	0	0.03
Blocky	90,994	0	0.01
Clayey	90,994	24	0.43
Clayey/Silty	90,994	0	0.00
Gravelly	90,994	4	0.21
Marshy	90,994	0	0.00
Peaty	90,994	2	0.15
Sandy	90,994	26	0.44
Sandy/Clayey	90,994	1	0.07
Sandy/Silty	90,994	0	0.04
Silty	90,994	0	0.00
Stony	90,994	0	0.07
Mixed	90,994	33	0.47
Other Texture/Not Surveyed	90,994	10	0.03
Topographical Characteristics	**Observations**	**Mean**	**Standard Deviation**
Altitude (Metres)	90,994	86	52.40
Slope (Percent)	90,994	3	2.60
Distance to Sea (Kilometres)	90,994	29	22.82
Kilometres North	90,994	214	96.25
Electoral District Farm Characteristics	**Observations**	**Mean**	**Standard Deviation**
Livestock Units per Ha.	2,919	1	0.38
Average Ha. Per farm	2,919	33	11.43

5.3 Statistical cluster analysis and random effects model

A multivariate statistical analysis was used to indicate the most appropriate method to describe and typify the electoral districts in the sample. This analysis adapted the multi-step procedure of Galasakis et al. (2012) and (Köbrich et al. (2003).

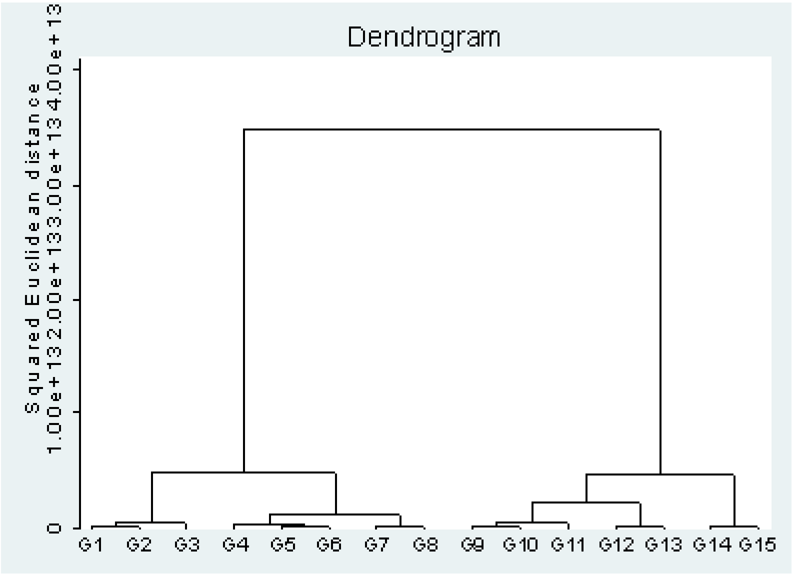
The Ward's linkage method of hierarchical clustering was first used to determine the optimal number of clusters for the dataset. This method was selected because the solutions generated by the Ward's linkage method are clearer than those of other hierarchical agglomerative methods (Aldendorfer and Blashfield, 1984; Köbrich et al., 2003). Cluster solutions are generated by minimizing within cluster variance while maximizing between cluster variation (Galasakis et al., 2012; Köbrich et al., 2003; Ward, 1963). This is achieved by joining cases or clusters that result in the minimum increase in the within-clusters sum of squares or error sum of squares where $ESS = x_i^2 - \frac{1}{n(\Sigma x_i)^2}$ (Ward, 1963). Squared Euclidean distance, which is the sum of squared differences in values for each variable, was used as the distance measure between observations (Köbrich et al., 2003).

Table 5.3 below shows the agglomeration schedule from which the number of clusters was decided using the elbow rule. This rule assesses the optimal number of clusters by plotting the number of clusters against the change in squared Euclidean distance for each stage of clustering. Each stage represents a combination of two clusters which reduces the total number of clusters by one. As fewer and fewer clusters remain, the within cluster dissimilarity, as measured by squared Euclidean distance, will increase. Large changes in distance are indicative of ideal cluster solutions which separate the most different cases while keeping similar cases together. The largest change in distance (after the initial separation of the data into two clusters) occurs when four clusters are used. This result indicates that four clusters is the optimal number of clusters to use for the successive k-means cluster analysis. This result can also be represented graphically as a dendrogram (Figure 5.1) and a scree diagram (Figure 5.2). The vertical axis of the dendrogram shows the level of within cluster dissimilarity at each of the various clustering stages. A flat or smooth curve in the scree diagram suggests that no new information is portrayed by additional clusters that follow (Halpin, 2016). Alternatively, the slope of the Euclidean distance measure is steeper when two dissimilar clusters are merged (Halpin, 2016). Both figures illustrate that within cluster dissimilarity does not decrease substantially when more than four clusters are used.

Table 5.3: Cluster analysis of 2,919 electoral districts, using Ward's linkage and squared Euclidean distances

Number of Clusters	**Clusters Combined**		**Squared Euclidean distance**	**Change in distance**
	Cluster 1	**Cluster 2**		
1	1617	514	3.47E+13	-
2	722	2840	4.93E+12	2.98E+13
3	2775	2918	4.56E+12	3.70E+11
4	2286	1836	2.09E+12	2.47E+12
5	1407	2581	1.19E+12	8.98E+11
6	422	2746	4.30E+11	7.58E+11
7	2065	1495	3.81E+11	4.90E+10
8	1026	2763	3.30E+11	5.06E+10
9	1925	1806	1.57E+11	1.73E+11
10	2611	2905	1.32E+11	2.51E+10
11	2865	746	1.08E+11	2.39E+10
12	224	2444	8.92E+10	1.91E+10
13	1147	2536	7.65E+10	1.27E+10
14	1488	599	5.82E+10	1.83E+10
15	2552	2671	4.50E+10	1.32E+10

Figure 5.2 Hierarchical clustering of electoral districts using Ward's linkage, n=2,919



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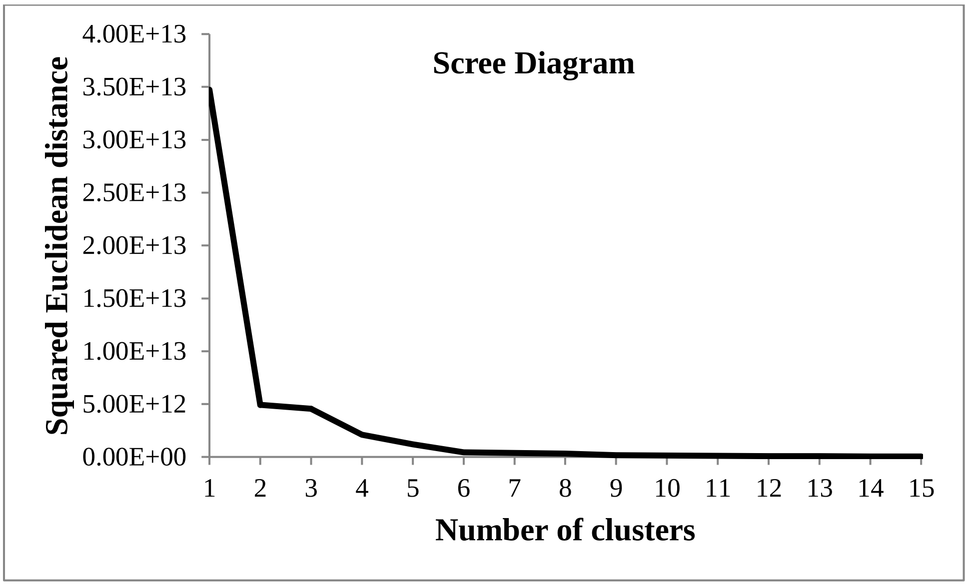
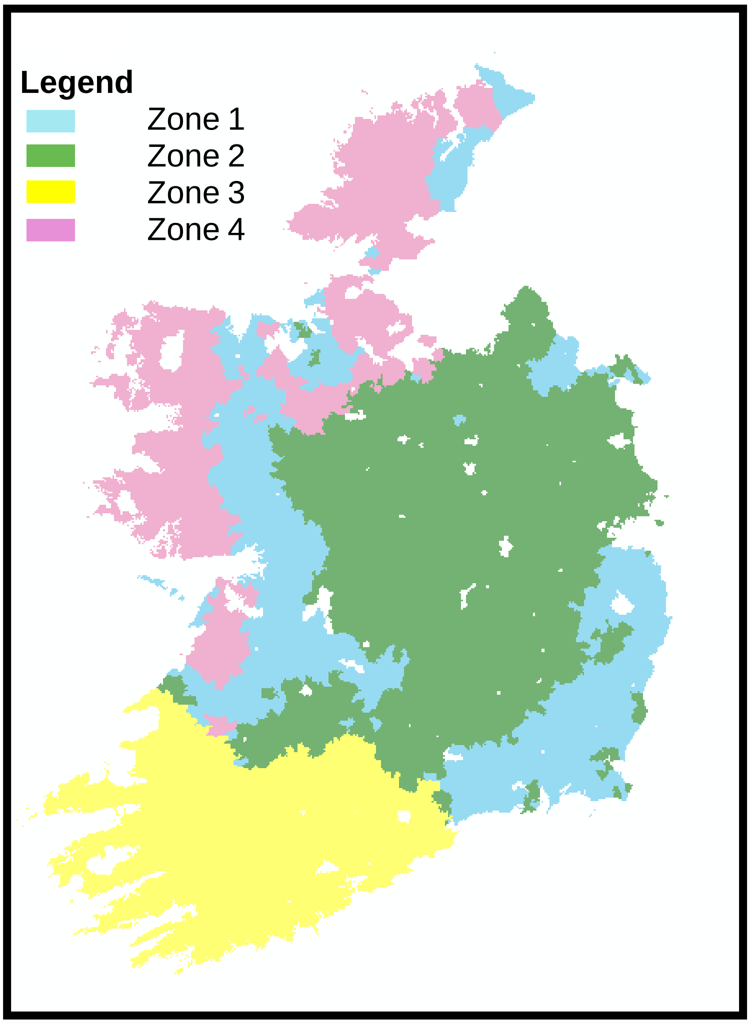


After determining the optimal number of clusters, k-means cluster analysis was used to allocate districts into four clusters. Map 2 illustrates the spatial extent of the four clusters which each have unique conditions for grass growth. White spaces represent developed, non-agricultural districts or districts with few farms for which the CSO does not publish statistics on confidentiality grounds. To compare the characteristics of each cluster, the between group differences were evaluated by means of a one-way analysis of variance (ANOVA) analysis. A Bonferroni comparison was used to test the significance of the difference in means between each individual cluster.

Zone 1, in blue, occupies generally productive agricultural lands on the south-east coast and in the west. Zone 1 had slightly above average EVI and temperature and below average rainfall. Good quality soils in this region allowed for average stocking rates even though this region incorporates some hilly areas in the north of the country. Average farm size in Zone 1 is significantly smaller than in Zones 2 and 3, but is larger than that of Zone 4. Zone 2, in green, is the most central growth condition zone and had the highest EVI and the lowest rainfall. Temperatures were above average in Zone 2 as were stocking rates and farm sizes. Zone 3, in yellow, is located in the south-west of Ireland. It had the second highest EVI score and the second highest rainfall of the growth condition zones. Temperatures at farm locations in Zone 3 were lower than average. This was likely due to the fact that Zone 3 farms have the highest altitudes and are, on average, located farther inland than farms in Zones 1 or 4. Zone 3 has high quality soils and the highest mean stocking rate of any growth condition zone. Zone 4 in pink is located primarily along Ireland’s rugged western coastline. This zone has the lowest vegetation growth as measured by EVI and the highest rainfall rates. Zone 4 has the highest mean temperature likely due to its coastal location. It is characterised by smaller farms with lower stocking rates and poorer soils.

Figure 5.4 Irish Grass Growth Condition Zones



A random effects model assumes that variation in the error term is exogenous to the model and is randomly distributed across the data set. In this model, the residual is primarily composed of differences in farm level management techniques. There is no evidence in this dataset to suggest that farmers in more favourable geoclimatic zones exhibit better land management skills. In fact, grass growth performance, as measured by EVI, is often high in favourable microclimates within seemingly unfavourable regions such as the Burren and Connemara.

5.4 Results

Establishing spatially disaggregated measures of grass growth and understanding the location specific relationships between grass and agronomic conditions are critical to improving grass production on Irish farms. This study tests the use of EVI as a proxy for grass production by modelling its dependence on known geoclimatic indicators of growth in 2,919 electoral districts across Ireland. These indicators include monthly temperature and rainfall, soil type and texture, altitude, slope, distance to sea, latitude, stocking rate, and mean farm size. Table 5.4 below shows the results of the annual EVI random effects model at the national and regional levels. As expected, rainfall and temperature throughout the year have a significant impact on vegetation growth. High March temperatures were positively related with grass growth at the national level, but are insignificant for each of the individual geoclimatic zones. The effects June rainfall also exemplify the disparity between national and regional effects. While higher rainfall in June had a strong negative effect on vegetation growth nationally, effects were less pronounced in the individual zone models. Together these results highlight the significant differences that exist across the unique agronomic regions of Ireland. Peaty gley soils were associated with the lowest EVI while rendzina soils performed the best nationally and in the geoclimatic zones where they were present. Soil effects, like weather effects were largely as expected and confirm a statistically significant link between EVI and known pedoclimatic indicators of grass growth. Annual binary variables were also included to control for discrete annual weather patterns and pedoclimatic reactions.

The optimal altitude for vegetation growth was estimated at between 145 and 170 metres across all models. Slope is particularly important in Zone 4 in the topographically rugged west coast of Ireland. Farms further south and further from the sea tended to have higher EVI measurements. Optimal stocking rates were near two livestock units per hectare in all four models. Optimal stocking rates were near two livestock units per hectare, but the effect was insignificant in Zone 4 where stocking rate varies widely. Average farm size effects suggest that regions with larger farms have higher vegetation growth. This may be due to better resourced farms or to historical location effects.

While these effects are unsurprising when compared with existing Irish grass growth models, they underscore the agronomic diversity of Ireland and prove that grass growth can be effectively modelled on a broad spatial scale. The relationship between EVI and agronomic conditions is robust at the national level and across the diverse growing regions of Ireland. This suggests that EVI is a valuable proxy measure for grass growth nationally and locally.

Table 5.4 Selected national and zonal coefficients of agroclimatic conditions on annual cumulative EVI per electoral district

Variable	**National**	**Zone 1 -Blue**	**Zone 2 - Green**	**Zone 3 - Yellow**	**Zone 4 - Pink**
Monthly Rainfall January	-2.35***	-5.34***	-3.74***	0.89	-3.65***
Mean Temperature January	53.97***	146.02**	190.86	374.29***	167.72***
Monthly Rainfall February	-1.67***	-1.32	-0.38	-5.43***	2.09*
Mean Temperature February	-15.61	708.68***	342.32	-278.98	762.12***
Monthly Rainfall March	1.60***	6.17***	6.01	3.69***	-3.08*
Mean Temperature March	670.20***	-205.2	-65.87	-565.21	-182.32
Monthly Rainfall April	-8.26***	-4.19***	-9.28***	-14.09***	-7.4***
Mean Temperature April	-235.77***	-469.18***	-208.14***	-279.38	-1056.85***
Monthly Rainfall May	-5.75***	-6.55***	-5.5***	-5.65***	-3.52**
Mean Temperature May	-338.91***	-107.34	94.34	-772.23***	-587.17***
Monthly Rainfall June	-12.27***	-5.63***	-9.82***	-0.89	-5.08***
Mean Temperature June	-118.87**	361.53**	229.56	640.23**	914.66***
Monthly Rainfall July	4.34***	10.93***	9.7	-14.61***	7.98***
Mean Temperature July	218.21***	1,193.96***	1208.8	-2,340.91***	-36.57
Monthly Rainfall August	7.88***	6.43***	0.47	2.77*	3.63**
Mean Temperature August	-333.77***	-481.18***	-1115.69***	264.44	-16.9
Monthly Rainfall September	-2.15***	6.08***	0.41	-5.07***	-1.93*
Mean Temperature September	420.10***	-1,542.55***	79.26	1,488.62***	438.98**
Monthly Rainfall October	-0.41	-5.34***	-1.23	3***	0.74
Mean Temperature October	-103.90***	269.33**	-299.7***	760.06***	-65.54

Monthly Rainfall November	4.58***	6.85***	3.27	6.12***	-0.74
Mean Temperature November	-245.99***	385.22***	-304.71***	707.37***	449.53***
Monthly Rainfall December	7.03***	7.79***	12.79	2.73***	5.85***
Mean Temperature December	199.98***	-480.74***	509.7	-294.7**	136.79
Brown Earth	-1,026.95***	-2,684.59***	870.27	-3005.71***	-60.35
Brown Podzolic	-2,579.16***	-4,190.63***	-804.54	-3,415.63***	-4601.32***
Podzol	-261.63	-1,388.77	40,607.87	-65,494.58	-3,120.27*
Peaty Podzol	-3,878.38***	-6,577.42***	-5001.64	-4,794.77***	-6,743.22***
Gley	436.88*	-103.22	1,043.67	508.75	-2,620.19**
Peaty Gley	-6,867.28***	omitted	-4,623.28***	Omitted	-11,389.11
Rendzina	3,554.07***	2817.23***	5,397.61	Omitted	-1,029.78
Lithosol	-5,795.42***	-5,291.33*	- 47031.85***	-1,765.62	-5,682.35***
Peat	-3,227.16***	-1,027.37	-5,553.79***	-2,751.56*	-7,477.23***
Other/Not Surveyed	-3,791.99**	-11,032.82	-8,419.27***	-37,905.42**	-3,124.63
Blocky	-3,028.23	12,3779.9	Omitted	Omitted	-45,917.49*
Clayey	-649.16**	-100.15	-922.76***	-1895.28***	1010.62
Clayey/Silty	10,4490.50	omitted	11,3629.4	omitted	Omitted
Gravelly	-3,158.84***	-430.2	-2,926.43***	4,100.65*	-1,399.13
Marshy	-14,0556.10	Omitted	Omitted	omitted	71,809.76
Peaty	-6,180.33***	9,053.13	-8,481.71***	-366.23	-4,399.88**
Sandy/Clayey	265.81	-14,339.89	342.44	Omitted	1,407.08
Sandy/Silty	-2,203.58	-6,735.57	Omitted	Omitted	-697.47
Silty	-52,914.62	Omitted	Omitted	Omitted	11,8390.4
Stony	-1,674.72*	-721.7	-242.75	Omitted	1,019.12
Mixed	-913.91***	643.06	-246.79	-8837.23***	602.63
Other/Not Surveyed	-1,196.72**	1,495.2*	2,110.9	-382.58	-4,633.1***
Altitude (Metres)	70.47***	67.88***	55.46	50.74***	131.57***
Altitude Squared	-0.21***	-0.23***	-0.19***	-0.12***	-0.42***
Slope (Percent)	-202.86***	-164.65	-154.9	-266.54*	-728.09***
Distance to Sea (Kilometres)	3.66	55.72***	11.53	36.56**	-0.48
Kilometres North†	-0.74	-0.98	-2.20	15.30**	-4.36
Livestock Units per Ha.	26,210.17***	22,741.55***	31,798.62	19,280.82***	14,251.69***
Livestock Units per Ha. Squared	-6,866.07***	-5,632.41***	-9,223.14***	-3,879.22***	-1,147.28
Log of Average Ha. Per Farm	1,189.45***	2,214.7***	-148.38	1,038.29**	2,078.74***
Constant	40,694.26***	40,271.36***	37,950.92	4,8614***	34,498.18***
NT	40,680	9,741	17,816	7,734	5,389
N	2,919	697	1,273	564	385
Overall R^2	0.70	0.55	0.65	0.76	0.73
Within R^2	0.64	0.65	0.74	0.64	0.46
BetweenR^2	0.71	0.52	0.62	0.72	0.75

Note: ***, **, * Denotes that the corresponding coefficients are significant at 1%, 5% and 10% level respectively. †Kilometres north is a function of relative latitude expressed in one-kilometre units.

5.5 Conclusions

This study finds that there is a strong significant relationship between EVI and known indicators of grass growth. Although the geoclimatic relationships at work are complex, econometric and statistical techniques can be used to organize and better understand this data. By identifying clusters of similar agroclimatic conditions, “one size fits all” management solutions can be avoided. Policymakers can utilise this information to establish economic programmes which support environmentally disadvantaged farms while farmers can compare their own performance against peer farms with similar growing conditions and environmental challenges.

Although on-farm grass growth is difficult to measure, EVI can be a useful proxy when establishing links between grass growth and soil and weather conditions. This work establishes that grass growth varies widely from year to year and month to month. This model allows us to compare growing periods quantitatively at a national scale for the first time. This model also allows for comparisons of growing conditions between regions and demonstrates that the effects of growing conditions differ between regions.

This method lays the framework for future research into the management or “nurture” component of the “nature versus nurture” relationship. Additional study in this area should focus on the management and feeding practices of farmers. By establishing a supply and demand of feed on individual farms, the true nutritional and economic value of grazed grass can be computed. This information, when matched with EVI data can allow farmers and policy makers to see the value of grassland on an individual and national level.

Chapter 6. An international profitability comparison of dairy feed systems: grass-based feed systems versus concentrate-based housed systems

Chapter 6 is an international profitability comparison of dairy feed systems which employs data from the EU Farm Accountancy Data Network survey years 2003-2018 to isolate and quantify the relationship between dairy feed practices and profitability while controlling for differences in other farm management practices. This chapter complements the previous analysis chapters which have focused on the Irish context by comparing results from Ireland with geoclimatically similar dairy producing nations in north-western Europe. The results of this analysis demonstrate that dairy feed system has a large and significant association with profitability *ceteris paribus*.

Section 6.1 places this analysis component in the thesis as a whole, while also locating this analysis in the body of existing literature on dairy farm profitability, international comparisons of dairy systems, and the usage of the Oaxaca-Blinder decomposition method. Section 6.2 of this chapter explains the analysed dataset from the Farm Accountancy Data Network which is the basis of this analysis. This section will also explain the Blinder-Oaxaca decomposition method and how it is employed to decompose profitability differences between feed systems. Section 6.3 outlines the methodological framework employed in this study. This section will explain the Blinder-Oaxaca decomposition method and how it is employed to decompose profitability differences between feed systems. Section 6.4 of this international comparison highlights the variables utilised and illustrates the results of this decomposition analysis. Section 6.5 concludes this chapter and underscores the key contributions of this work to the existing literature on dairy feed systems and profitability. Also included in the conclusion is a discussion of the implications of this work in terms of policies and practices for the dairy sector.

6.1 Introduction and literature review

This chapter compares the economic costs of feed for specialist grazing versus specialist granivore dairy systems. As stated in section 1.4, a key objective of this thesis is to compare the profitability outcomes of pasture-based dairy feeding systems with concentrate-based feeding systems. This serves to address the concerns of farm managers who, while encouraged by agronomic advisors to increase grass growth and reduce the use of purchased feeds, may seek improved profitability simply by increasing farm scale. As the dairy sector becomes increasingly globalised and competitive, farmers and policy makers seek to lower the economic cost per output, while maintaining product quality. Simultaneously, the abolition of milk quotas has allowed farmers to increase the milk output and scale of their enterprises. Increasing the input of grain based concentrates is one method to boost milk production under land constraints, but also comes with significantly higher feed costs. While dairy operations in Ireland are still largely pasture based relative to their European peers, it is useful to compare farms on different ends of the grain-grass feed system spectrum while controlling for size and asset covariates, in order to isolate the ceteris paribus profit differences. These results will better inform the decisions of farmers as they seek the most cost effective feed system. It will also allow policy makers to identify pathways to improved cost competitiveness.

In order to place this profitability comparison in its economic and academic context it is valuable to survey the existing literature which addresses the recent economic changes in the European dairy sector as well as previous studies which have compared agricultural profitability at the international level. This literature review will also address the general and agricultural usage of the Blinder-Oaxaca decomposition method.

Authors such as Nehring et al. (2016) and Gillespie et al. (2015) have addressed the changes that have occurred in the dairy sector at the international level and in the Irish context. Among the changes noted by Nehring et al. (2016) are increases in milk productivity, the consolidation of dairy operations into fewer and larger farms, and changing governement policies which facilitate globalisation and competition. While Nehring et al. (2016) finds a significant association between larger farm scale and profitability, this study does not specifically address the impact of feed system on this profitability difference. Gillespie et al. (2015) noted that Irish farms were expanding their scale even before the milk quota system was offically abolished although land and labor limitations constricted the ability farms to upscale and intensify. Irish farms that did expand production were however associated with reduced total factor productivity (Gillespie et al., 2015). Studies that have focused more specifically on the association between feed system and profitabiliity in the dairy sector include Winsten et al. (2000). This study uses a highly detailed, but localised, Northeastern United States data set to compare the profitability of intensively managed concentrate-based systems, intensively manged grass-based systems, and mixed systems. Winsten et al. (2000) found that management effort was the key to return on investment in both concentrate-based and grass-based sytems, and that intensively managed grass-based systems were the most economically viable production system in the studied area. More recently, Notte et al. (2020) compared the economic sustainability of feeding systems on Urugauyan dary farms and found that low stocking rate systems with limited supplementary feeding were associated with higher productivity and gross margins than more concentrate intensive systems.

In order to effectively compare the profitability of alternative feeding systems, a methodology which separates the profitability difference associated with farm scale from the profitability difference attributable to feed system. The Blinder-Oaxaca decomposition methodology achieves this separation of profitability differences and is the selected methodology for this study. In order to introduce the Blinder-Oaxaca decomposition method, the original literature as well as more current and agricultural applications of this method will be described in this literature review.

The Blinder-Oaxaca decomposition method was first developed and applied in the works of Blinder (1973) and Oaxaca (1973). Blinder (1973) decomposed the gender and racial wage gaps in order to isolate the impact of discrimination. Oaxaca (1973) developed a novel method to quantify the impact of discrimination in the gender wage gap. Most current studies which employ the Blinder-Oaxaca method also explore the discrimination component of wage gaps such as Chen and Zheng (2018) and Takacs and Vincze (2020). Takacs and Vincze (2020) also expanded the Blinder-Oaxaca method to machine learning. The version of Blinder-Oaxaca method employed in this study however follows the method of Jann (2008) which specifically identifies the categorical predictors. For a further discussion of the application of the Blinder-Oaxaca method in this study, please see the following section 6.2

Alternative applications of the Blinder-Oaxaca include Etezady et al. (2021) which decomposes the generational difference in attitudes towards transportation. While the application of the Blinder-Oaxaca method in the field of agricultural economics field is relatively rare, Shita et al. (2020) did employ this method to analyse the relationship between agricultural technologies and the implementation of best practices and profitability.

Previous studies comparing the profitability of dairy feed systems have relied on small and localised samples. The body of literature which uses the Blinder-Oaxaca method is large, but the application of this method to analyse farm profitability gaps has not yet appeared in the literature. The objective of this study is to use a novel methodology to quantify the profitability gap between feed systems using a large and international dataset which includes a wide spectrum of feed systems.

This introductory section has highlighted the key knowledge gap which this analysis seeks to fill. Namely to empirically identify, on a ceteris paribus basis, the relationship between dairy feed system and profitability. The following sections will discuss in further detail the data and methodology utilised as well as the results of this decomposition analysis and the key conclusions to be drawn. Given that the overall theoretical framework of this thesis is grounded in the farmer's expected utility framework, profitability is key component. As shown in Chapter 2, section 5 of this thesis, utility is a function of profit and risk. While risk is analysed in Chapter 4 of this thesis, the current chapter focuses on profitability. In the case of the dairy production sector, feed cost is a key variable cost which significantly impacts profitability

6.2 Selection and use of the Farm Accountancy Data Network dataset

In order to make profitability comparisons between dairy farms in different countries, a source of internationally comparable microeconomic farm accounting data is required. In Europe, the only source of microeconomic data with harmonised bookkeeping and consistent variable definitions is the European Union's Farm Accountancy Database (EC, 2021). This section will introduce the Farm Accountancy Data Network database which is employed in the present analysis. The determination of sample selection will be explained as well as the usage of microeconomic data as opposed to aggregate data. The Oaxaca-Blinder decomposition method will be employed to quantify the association between dairy feeding practices and farm profitability at the individual farm level and across countries.

The Farm Accountancy Data Network (FADN) was established in 1965 by the European Council as a public database which aggregates farm income and business data collected from European Union member states (Markou, 2004). The primary purpose of FADN is to provide data to policymakers on the impact of the European Union Common Agricultural Policy. EU member states collect FADN data at the national level by surveying commercial agricultural enterprises. This survey data is weighted to be representative of the region, economic size, and agricultural sector of all the commercial farms in each country.

Individual farm-level micro data was used in this analysis. A request for access to micro-level FADN data was made to the European Commission Directorate General of Agriculture in October of 2018 and the requested data was received in April of 2019. The use of micro-level FADN data allows for the individual heterogeneity of farm financial characteristics and feed practices to be controlled for in this analysis. FADN provides variable consistent definitions, contains detailed panel data, and utilises high collection and data management standards. However, the use of FADN data is not without challenges. This data is only representative of commercial farm operations and focuses on farm costs and revenues, but does not include complete management or agronomic indicators.

The specific component of the FADN dataset employed in this decomposition analysis covers the collection years 2004 to 2016. This period includes the final years of the dairy quota system in Europe as well as the immediate post-quota years. Pooled-cross sectional data during this time period is used and the observed farms are confined to specialist dairy producers in order to avoid observing biased profitability measures in mixed farming systems. The selected profitability measure in the FADN dataset which is decomposed in this analysis is Farm Net Income (SE420). This variable represents the accounting profit or loss accruing to the farm operation’s land labour and capital in the accounting year. The income from farm subsidies as well as the costs of labour, rent, interest, and taxes are included in this profitability measure.

The countries selected include the major dairy producing nations of north-western Europe. These specifically include Belgium, Denmark, France, Ireland, the Netherlands, and the United Kingdom. While broadly similar climatically, these countries exhibit a large degree of heterogeneity with respect to dairy feeding systems. Countries like Ireland employ a largely grass-based feeding system, whereas in Denmark, for example, concentrate-based indoor feeding systems are much more prevalent. For a more detailed illustration of the sample heterogeneity please refer to the summary statistics in Table 6.1 as well as the graphed feed system variability in the Appendix.

The use of the FADN data allows for an equitable comparison of heterogenous farm systems across six nations due to the detailed and comparable observations collected. While the above section 6.2 has discussed the data utilised in this study. Further information on the selection and use of the methodological framework employed in this study is provided in the following section 6.3.

6.3 Methodological framework and employment of the Blinder-Oaxaca decomposition method

This section introduces the Blinder-Oaxaca methodology which is used to analyse the FADN data explained in section 6.2 above. Also included in this section is a brief overview of the FADN data variables selected for this analysis.

This study adapts a counterfactual decomposition technique first implemented by Blinder (1973) and Oaxaca (1973) and as applied by Jann (2008) to analyse the difference in farm net income between farms with grass-based and grain-based feed systems for each of the six countries studied. This method is typically utilised to break down the outcome differences across groups into explained characteristics versus unexplained or residual effects. For example a gap in wages between male and female emplyees may be attributed to differences in observed education or experience as opposed to unobserved discrimination. For a further explanation of the alternative applications of the Oaxaca-Blinder decomposition, please see the literature review in section 6.1. In its application in this study, the Oaxaca-Blinder technique is employed to decompose the differences in farm profits across groups of farms with different feeding systems. This method will measure how much of the group differences in profit is attributable to observed management characteristics such as feed savings versus unobserved predictors such as feed efficiency.

The following equations construct, first, the methodological framework of this study and, second, the application of the Oaxaca-Blinder decomposition technique to the analysed variables. Equation 6.1 below defines the farm net income (Y) of individual farm i in period t and country c is a function of subsidy income (S_{itc}) plus farm operational revenues (R_{itc}) minus costs (C_{itc}).

$$Y_{itc} = S_{itc} + R_{itc} - C_{itc} \qquad \text{Equation 6.1}$$

Where subsidies are a function of historical production levels, revenue is a function of time variant market output prices times farm level production quantities.

$$R_{itc} = P_{ct} * Q_{it} \qquad \text{Equation 6.2}$$

Costs are a function of farm level production levels and country specific operational expenses. Expenses themselves are influenced by farm level management decisions and country level input prices (N_{ct}).

$$C_{itc} = Q_{it} * E_{itc}(M_i, N_{ct}) \qquad \text{Equation 6.3}$$

This study divides farms by management style on a spectrum from grass based to concentrate based farms utilising the concentrate feed cost per ruminant livestock unit as the primary variable of interest. The decomposition analysis is then used to determine whether differences in income and costs can be attributed to management differences beyond simple feed cost savings.

Adapting the formulae of Jann (2008), unobserved feed system predictors are symbolised by R which is a function of the expected value of the profit of farms, $E(Y)$, in the study groups, i, subtracted from that of the base group, b.

$$R = E(Y_i) - E(Y_b) \qquad \text{Equation 6.4}$$

In order to further decompose this outcome difference, R can be broken down into the component of the differential caused by group level differences in predictors,E, individual coefficient contributions, C, as well as I which represents the interaction effect of simultaneous differences in group level endowments and individual coefficients.

$$R = E + C + I \qquad \text{Equation 6.5}$$

The specific variables used in this analysis are shown in the summary statistics Table 6.1 below. The Farm net income variable, as explained in the data section 6.2 above, represents the overall profit of farm activities and as well as the impact on profitability of subsidies, taxes, land rents, and interest. While the mean farm net income of the high concentrate use comparison group is higher than that of the low concentrate group, the national samples exhibit wide heterogeneity. The Denmark dairy sample is an outlier for its low mean net income this is due to the dramatically higher debt levels and interest costs which Danish dairies face. Danish dairy farms also have significantly higher concentrate feed costs per ruminant livestock unit due to the very intensive concentrate-based feeding system which predominates in Denmark. The use of paid labour units on dairy systems also varied across the international dataset. Whereas the Belgian dairy sector employed less that one paid labour unit per thousand livestock units, the United Kingdom and Danish dairy sectors employed more that four and five times that amount of paid labour per livestock unit respectively. In terms of farm scale, farms in the high concentrate use sample are larger in dimensions including land, livestock units, and asset values. This variation in farm scale and endowments underscores the importance of including such variables as covariates in any analysis of profitability differences. Fertiliser expenditure serves as a proxy for the intensity of grassland management on farms in each studied group and country and was highest in the United Kingdom, Denmark, and Ireland. Farm subsidies have a large impact on profitability and favour the high concentrate use study group which receives significantly more subsidies, but also pays more in taxes. The land values per hectare of each country correlate with the more intensive systems of the Netherlands and Denmark which also exhibit the highest land values. The sample size of 37,646 individual farm year observations is evenly divided between the high and low concentrate use groups and each sampled country has several thousand observations.

Table 6.1 Mean summary statistics

Variable	**Full Sample**	**Low conc. group**	**High conc. group**	**BEL**	**DAN**	**FRA**	**IRE**	**NED**	**UKI**
Farm net income (€)	45,423	42931	47910	57,827	7,870	34,771	56,929	66,731	68,318
Concentrate expenditure per ruminant livestock unit (€)	494	331	657	359	1,015	342	330	511	588
Unpaid labour input (Full time equivalents) per livestock unit	0.015	0.016	0.015	0.019	0.006	0.020	0.016	0.014	0.011
Paid labour input (Full time equivalents) per livestock unit	0.002	0.002	0.003	<0.001	0.005	0.002	0.002	0.001	0.004

Table 6.1 Mean summary statistics (continued)

Variable	**Full Sample**	**Low conc. group**	**High conc. group**	**BEL**	**DAN**	**FRA**	**IRE**	**NED**	**UKI**
Total utilised agricultural area (ha)	96	88	105	56	166	95	59	60	114
Total livestock units (lu)	152	137	167	110	281	100.6	116	151	210
Fertiliser expenditure (€)	11,069	8947	13186	6,894	12,883	9,582	11,889	7,808	16,518
Total subsidies received (€)	37,706	33534	41868	24,835	78,353	33,321	22,396	31,646	36,624
Farm taxes paid (€)	2,727	2257	3196	1,561	8,835	1,766	264	5,215	686
Land assets per ha (€)	13,333	10,664	16,003	5,931	31,373	515	17,516	40,127	10,337
Building assets per lu (€)	1363	1283	1443	1202	3167	1087	1030	2028	457
Machinery assets per lu (€)	812	726	899	750	1200	841	477	989	589
n	37,646	18823	18867	3,282	4,936	14,094	4,187	4,425	6,722

The methodology section above offers an explanation of how the Oaxaca-Blinder decomposition method can be applied in a novel way to an individual level farm dataset. The included variables in the summary statistics table 6.1 above serve to control for the differences in farm scale between the two feed system study groups in order to fairly compare their respective profitability potential. The results of this analysis in section 6.4 below represent the output of this methodology which describes the difference in profitability between farm systems in a detailed breakdown of explained and unexplained differences.

6.4 Decomposition results

To analyse difference in profitability gap between low and high-concentrate dairy farms a threefold Oaxaca-Blinder decomposition method is applied. This method first breaks down the difference in profits between groups into an explained an unexplained term and then associates these terms with individual variables. The results of this decomposition are shown in tables 6.2 and 6.3 below. Table 6.2 shows the overall breakdown of the profitability differences by each of the six analysed countries into an explained and unexplained component. Table 6.3 below shows a more detailed breakdown of the explained and unexplained components into the proportion of each associated with the control variables. On the whole, the results of this analysis demonstrate the significant profitability potential of grass-based feeding systems when compared to concentrate-based feeding systems when compared on a *ceteris paribus* basis. The unexplained component in this analysis represents the unexplained differences in the covariates between the two comparison groups

The results shown in table 6.2 demonstrate that low concentrate farms would be significantly more profitable if they had the same endowments as high concentrate farms in all country cases except Denmark where high concentrate farms have high debt service costs and consequently low profitability. Low concentrate farms have a higher profitability in Ireland where pasture-based dairy farming is more common. Low concentrate farms would be more profitable, after controlling for differences in endowments, in France and the Netherlands. In the United Kingdom, the profitability difference between low concentrate and high concentrate use farms becomes insignificant when farm endowments are controlled for. The unexplained portion of the profitability gap in this analysis, as shown in Table 6.2 below, indicates the effects of unobserved farm endowments such as farmer management skills and land access. This unexplained term was strongly negative in the case of Belgium and Denmark. This may indicate that lower-concentrate use farms in these generally high-concentrate use countries are subject to limitations in farm management practices, i.e. the low-concentrate group in these countries should perhaps be viewed as a poorer farm performance group rather than a radically different feeding system.

Table 6.3 shows further details of the decomposition analysis in a per-variable breakdown. While the effects pattern varies by country, the overall story of profitability in grass-based farms being handicapped by lower farm endowments is present in each country. The constant in Table 6.3 represents the effect of omitted variables on the profitability difference and, as such, is not present in the explained variable column for each country.

Low-concentrate farms in Belgium have significantly less animal, subsidy, and land endowments which negatively impact the profitability of these farms. While the building and machinery assets variables directly contribute to higher profitability for the lower-concentrate use farms, they may indicate a less efficient utilisation of such assets per animal overall. In the Belgian case, lower concentrate farms with higher numbers of livestock units enjoyed a significant, but unexplained profitability advantage. This may be attributable to some large dairy farms with highly efficient feed usage and other good management practices falling into the lower-concentrate usage group.

In Denmark, both the low concentrate and high concentrate groups had relatively low profitability. While Danish dairy farms have high farm returns (€231,487), their low profits can be substantially attributed to the high total debt levels (€3,149,966) and thus high interest expenses (€107,371) in Denmark. The other high production costs faced by Danish farmers are costs for wages (€68,550) and land rent (€31,149). While the difference in profitability between the two groups was insignificant, Denmark was unique in having results suggesting that lower-concentrate farms actually had a significant profitability advantage from their farm endowments included in this analysis. This suggests that these farms may be larger operations since they have a profitability advantage from larger endowments of such inputs as labour, livestock units, fertiliser buildings, and machinery. Like Belgium, the unexplained component of the profitability decomposition was strongly negative for lower-concentrate usage farms. This suggests that these farms are at a disadvantage in unobserved farm attributes such as farm management skills or animal breeding quality.

In France, low-concentrate usage farms were slightly, but significantly less profitable than the high-concentrate usage group of farms. Lower-concentrate farms suffered a significant profitability disadvantage from lower levels of observed farm attributes, and if they had been operating on an even playing field in terms of observed farm endowments, these low concentrate farms would actually be more profitable than high concentrate usage farms. The unexplained component of the profitability decomposition was positive and significant for French farms. This can be interpreted as an unexplained profitability advantage for the lower-concentrate usage group. This advantage may be attributable to such unobserved characteristics as farm management ability.

Interestingly, the number of livestock units in low-concentrate farms in Ireland is associated with a significant negative explained effect and positive unexplained effect on profitability. Lower concentrate farms tend to have fewer livestock units and thus logically generate less profit from that farm endowment. However, the large unexplained effect from having fewer animals may be attributable to increased care and attention per animal and/or improved genetic merit in a smaller herd.

Serious land limitations in the Netherlands are associated with large and significant negative explained and unexplained impacts on profitability for low-concentrate usage farms.

The results of the decomposition analysis in the United Kingdom suggest that unpaid labour units may be utilised less efficiently which negatively impacts the profitability of low-concentrate usage dairy farms as shown in the unexplained term. The unexplained component of the decomposition associated with building assets is strongly positive however for low-concentrate farms in the United Kingdom.

Table 6.2 Overall Oaxaca-Blinder profitability gap decomposition coefficient results

Variable	**BEL**	**DEN**	**FRA**	**IRL**	**NED**	**UKI**
Low-concentrate group	51,160***	7,151**	33,922***	57,856***	61,835***	6,2337***
High-concentrate group	64,493***	8,338***	35,627***	56,002***	71,630***	74,298***
Difference in profitability	-13,333***	-1,187	-1,705***	1,854	-9,794***	-1,1961***
Explained difference	-8,553***	10,558***	-4,635***	-3,350***	-10,798***	-11,259***
Unexplained difference	-4,780***	-11,745**	2,930***	5,204***	1,003	-703

*** Indicates p-value <0.01, **indicates p-value <0.05, *indicates p-value <0.1

Table 6.3 Decomposition of profitability gap between explained and unexplained effects

Country	**BEL**		**DEN**		**FRA**		**IRL**		**NED**		**UKI**	
Variable	**Explained**	**Un-explained**	**Explained**	**Un-explained**	**Explained**	**Un-explained**	**Explained**	**Un-explained**	**Explained**	**Un-explained**	**Explained**	**Un-explained**
Unpaid labour units per livestock unit	535*	-5,429	630	-28,350***	-62	188	-115	8,333***	3,572***	-11,591*	958**	-9,042***
Paid labour units per livestock unit	99	133	3,072***	11,461	492***	450*	81	1,026	-40	127	3,764***	-2,111
Total utilised agricultural area (ha)	-237	-5,053	-3,834	8,611	851***	1,310	344	-3,020	-3,215***	-44,444***	5,434***	-1,377
Total livestock units	-4,931***	25,776***	5,685*	-31,231	-1,891***	1,106	-2,070***	18,440***	-10,407***	38,260***	-13,273***	-14,951*
Fertiliser expenditure (€)	-707	-7,178**	6,115**	-46,173***	2,507***	1,032	-2,781***	4,450	2,187	-2,090	558	-2,458
Total subsidies received (€)	-6,159***	-6,643	-345	11,095	-6,946***	4,041	-1,930***	474	-4,424***	3,595	-7,671***	7,905
Total taxes paid	-715	497	-7,538***	-9,375	-503	-2,235**	296	1,588	-976	-10,054***	-29	1,391
Land assets per ha	-866**	4,523**	308	-199	-78***	1,240***	82	-208	-3,481***	-4,484	-902***	-3,275
Buildings assets per livestock unit	3,584***	3,689*	2,198**	24,904***	459***	696	2,116***	-813	1,249	-4,530	1,185***	6,722***
Machinery assets per livestock unit	844***	9,124***	4,267***	-12,039	534***	-1,344*	628***	3,369**	4,737***	20,944***	-1,281***	1,731
Constant		-24,218***		59,550**		-3,555		-28,436***		15,271		14,764

*** Indicates p-value <0.01, **indicates p-value <0.05, *indicates p-value <0.1

The results shown above in Table 6.2 and 6.3 demonstrate that while grass-based feed systems have significant profit potential, this potential varies with country specific differences and is sometimes masked by the lower farm endowments that are typical of grass-based farm. Given the results of this analysis, a one-size fits all approach to dairy feed systems is not indicated. The results from the detailed decomposition of profitability differences into explained and unexplained effects by each analysed variable were highly heterogeneous across the six studied nations. A key point raised by these results are the significant profitability potential of farms with low-concentrate usage and higher levels of grass-based feeding. While this effect can be masked by the fact that grass-based dairy operations tend to be smaller and have fewer farm endowments, the use of the Oaxaca-Blinder decomposition method aids in assessing profitability between systems on a level, ceteris paribus, playing field.

6.5 Discussion and conclusions

This analysis of international feed systems has empirically measured the profitability impacts low and high-concentrate feed systems across six European countries using comparable Farm Accountancy Data Network data. As a component of the larger thesis, this comparison focuses on the profit term of the expected utility function, whereas Chapter 4 analysed the risk term and Chapter 5 studied grass feed production in terms of geoclimatic risks and the potential to reduce purchased feed costs.

In an era of increasing globalised competition in the dairy sector farmers are seeking all possible avenues to improve profitability. The agronomic literature mentioned in section 6.1 encourages farmers to be better before bigger, that is to implement best practices to reduce costs, most notably feed costs by improving the utilisation of grass feeds. While in the Irish case, pasture-based feeding is widely used, neighbouring dairy producing nations in Europe, most notably Denmark and the Netherlands have adopted more intensive feeding systems, which rely heavily on purchased feeds. Through the use of international comparable data, new insights can be gained into the profit and profit potential of different feeding systems within and between countries.

This analysis has made multiple contributions to the body of agricultural economics literature. The employment of Oaxaca-Blinder decomposition into agricultural economic analysis is novel and allows for a fair comparison of heterogeneous farm feeding systems without forcing alternate systems to fit into the same regression. This study also offers economic empirical support to the existing agronomic studies which encourage higher grass utilisation. The results shown in section 6.4 above suggest that unexplained differences in profitability offer new insight into international heterogeneity of farm management skills and other unobserved characteristics beyond the financial and accountancy data collected by the Farm Accountancy Data Network. This bolsters the case for the collection of internationally comparable data on farm management skills on genetic merit of herds in addition to financial farm data. Such expanded data collection could further the case for grass-based dairy systems which, in the cases of profitability in France and Ireland, are bolstered by unexplained variation not measured in the FADN data.

In addition to its academic contributions, the current study and the results produced are of value to policymakers, farmers, and farm advisors. The results of this analysis offer a unique perspective to low-concentrate usage nations like Ireland as to what their dairy sector could look like if milk output expansion via increased purchased feeds is fully realised. Increased concentrate purchases without large expansions in land, labour, buildings, and other farm endowments would, according to the results of this study, increase output, but not necessarily profitability.

The limitations of this study primarily concern the limitations of the Farm Accountancy Data Network data set. The Farm Accountancy Data Network programme focuses on financial data such as farm income, costs, and assets, but does not collect data on farmer knowledge, skills, training, or ability. Detailed information on discrete individual farm level attributes such as animal genetic merit and localised soil and geoclimatic conditions is also unobserved. The benefit of utilising the Oaxaca-Blinder decomposition technique with such data is that the explained and unexplained components of the profitability gap between farms are clearly delineated. This allows for clear conclusions to be drawn with respect to the explained difference, while highlighting that much of the profit gap cannot be explained solely by analysing financial data. The FADN dataset also did not include data on the differing feed prices paid by individual farmers or the specific nutritional content of utilised feeds. An agronomic net energy system model of feeding could ameliorate this data gap in the future.

The results of this study prompt several potential opportunities for future work in this research area. Firstly, the analysis of this study demonstrates the importance of micro-scale data on farmer skills and abilities. Future studies in this area of feed system analysis could incorporate survey and administrative data on farmer training and use information on the farm-level implementation of best practices as a proxy for farmer skill level. This could illuminate a clearer pathway to improved profitability through grass-based feeds via farmer training and a focus on best practices implementation.

While a strict one-size-fits-all approach to dairy feed systems is not indicated by these results, which demonstrate the heterogeneity of feed systems across countries, the overall message of this analysis shows that low-concentrate dairy farms, after controlling for differences in farm size and endowments have significant profitability potential across many of the dairy producing nations of Europe. The findings of this study offer novel empirical economic backing to the connection between low concentrate usage and higher profitability, even in such countries which have relatively more intensive concentrate-based feeding systems. Overall, this study highlights pasture-based feeding as a significant profitability opportunity, not just for Irish farms, but for farms in several countries across Europe.

Chapter 7. Conclusions and contributions

This concluding chapter underscores the important findings of this thesis. The primary findings of this study are outlined in section 9.1 as they pertain to the three main objectives of this work outlined in Chapter 1. Specific attention is given to the economic and environmental importance of grass based dairy farming in sections 7.2 and 7.3 respectively. This chapter will also offer remarks on the opportunities, and risks for the grass based dairy system in the future at the Irish, European, and international levels in section 7.4. Section 7.5 of this chapter will cover the potential policy implications of this work, while alternative applications of the methodologies explored herein will be explored in section 7.6. Section 7.7 reinforces the contributions of this research to the state of the art of dairy farm feed economics. Section 7.8 outlines the opportunities for future research in the area of dairy feed systems. The limitations of this thesis are addressed in section 7.8 and concluding comments are offered in section 7.9

7.1 Primary findings of this thesis

Prior to this study, research into dairy feed systems has been largely sequestered into two disparate silos of (i) economic and (ii) agronomic research. Economic research uses price and survey data to compare feed systems on the basis of volatility, profitability, efficiency, or sustainability. These studies employ a wide breadth of representative farm data, but often lack the depth of environmental or management data given the limitations of survey instruments. On the other hand, agronomic research collects minutely detailed data on research or model farms, but for its part typically fails to address the wide variability of farm systems due to geoclimatic, management, and capital differences. In order to fully understand the economic implications of dairy feed systems, data must be employed which is both broad, heterogeneous, and representative, but also deep and agronomically detailed. Together the three applied economic studies included in this thesis blend the data and methods of these two research silos with the objective of analysing, measuring, and decomposing the income volatility of dairy farms, the environmental effects on dairy grassland feed, and the profit differential along the continuum of dairy feed systems from pasture based to concentrate based.

In completing the first objective of this thesis which was to evaluate farm system income risk, detailed farm survey data was utilised to quantify the income volatility faced by tillage, sheep, beef, and dairy farms in the Republic of Ireland from 2005 to 2013. This study component found that dairy farms, even after controlling for their larger than average size, had significantly higher levels of income volatility when compared to other farm types. Feed expense variation was a primary contributor to this volatility. This finding prompted questions such as why dairy is particularly exposed to feed risk and where along the value chain does this feed risk originate. While chapter three considered farm survey data such as concentrate feed expense, this component of the thesis identified a data gap with respect to the environmental effects on grass feed production and flagged dairy farms and their feed systems as an area deserving of special study given that income risk directly impacts farm viability.

Objective two of this thesis directly follows from the findings of objective one. In order to measure the environmental impacts on grassland feed production a new dataset and model was required which went beyond both the survey data commonly utilised by economists as well as the single farm, spatially homogeneous agronomic models employed by agronomists. In order to bridge this data gap, more than 90,000 individual farm locations in the Republic of Ireland were identified and matched with spatially disaggregated data on weather, soils, topography and remote sensed vegetation growth. The relationship between agroclimatic characteristics and vegetation growth was then modelled. The results of this model found that spatial and temporal variation in grass growth can be quantitatively evaluated even when spatially representative ground level grass growth data does not exist. This model also allowed the relative effect of nature versus nurture to be empirically evaluated at the farm level and at the local area level. Finally, this component of the thesis lays the groundwork for future research using remote-sensed data to analyse grassland agriculture much as remote sensed data has been used to great extent regarding field crop and tillage agriculture.

While objectives one and two of this thesis focused on data from the Republic of Ireland, objective three uses international data to compare dairy feed systems across a set six of dairy producing north-western European nations. This analysis allows the grass-based feed systems which are predominant in nations like Ireland to be quantitatively compared to the concentrate intensive feed systems more commonly employed in nations such as Denmark and the Netherlands. Specifically, farm profit is compared between with high and low levels of purchased concentrate feed intensity, the difference in profitability is decomposed by way of the Blinder-Oaxaca decomposition method into an explained term associated with the observed control variables and an unexplained term which can be associated with farm level discrete heterogeneity in such unobserved variables as farmer management skills, herd genetic merit, localised geoclimatic conditions. Finally, the profitability gap is further broken down into its association with control variables measuring farm size and profit potential. While high-concentrate farms were found to have higher profit levels overall, this difference was diminished or reversed when differences in farm size and endowments such as land, livestock, labour, and assets were controlled for. While the profit potential of pasture-based feeding systems can be masked by the larger scale of intensive concentrate feeding operations, the results of this international comparison highlight the fact that the important relationship between grass-based feeding and profitability is not an Ireland-only phenomenon.

The introductory Chapter 1 established the economic, environmental and policy contexts of the three research objectives above. As an important component of the Irish agro-economy, the dairy sector’s farm level viability is a critical area of interest, particularly in light of ever increasing international competition and market volatility. Also important are the outsized and growing environmental impacts of dairy farming on the quality of water, soils, and air at the national and international levels given rising global demand for dairy products. The policy environment for dairy farmers in Ireland has been in flux over the past two decades with the advent of decoupled subsidy payments in 2005 followed by the abolition of dairy quotas in 2015. This has given dairy farmers the opportunity to expand their operations and increase output. Given the considerable land constraints which Irish farmers face, output increases will primarily be a function of increased feed inputs either from additional purchased concentrate feeds or from improved growth and utilisation of grazed grass.

Chapter 2 contributes to the findings of this thesis by laying out the theoretical basis for this study. Production theory highlights the importance of inputs and input substitution in the farmer's profit maximising production function. Risk theory helps to explain risk aversion and why a feed system's risk profile is also important to farmers along with profitability. Chapter 3 explains the diverse data sources employed across the following three analysis chapters. Chapter 4 continues the discussion of risk and volatility from the theoretical framework by modelling volatility as a function of farm characteristics and empirically measuring the volatility of different farm types. By finding that dairy farms have significantly higher income volatility, Chapter 4 accomplishes the first primary objective of this thesis. Chapter 5 is concerned with outlining the geoclimatic data employed in objective two, the grass growth model. Establishing a set of spatially disaggregated data on weather, soil, and grass growth conditions at specific farm locations allows the association between geoclimatic conditions and grass growth to be accurately assessed in Chapter 5. Chapter 6 completes the final objective of this thesis by quantitatively explaining the relationship between farm feed system and profitability and finding that grass-based systems are in many international cases significantly more profitable than their concentrate-based counterparts after controlling for disparities in farm endowments.

7.2 Economic and environmental value of grass feed in Ireland

Grass is Ireland's most important crop. Ireland has highly favourable conditions for grass growth and the majority of Ireland's land area is covered by grasslands. Irish farmers rely on pasture as a key feed source for their livestock. Despite the importance of grass production to the Irish agro-economy, existing representative data is limited with respect to the volatility and determinants of grass growth as well as the relative profitability of grassland agriculture versus indoor feed systems. By quantifying the central role of grassland agriculture to dairy farm stability and profitability, this study improves understanding of the connection between feed system and economic farm viability. This thesis also uses environmental variables to lay a quantitative foundation for measuring annual grass production in a similar way to how other agricultural commodities such as milk, wheat, or meat production are measured.

Environmental sustainability is another crucial component of the long-term viability of dairy farms. As the impacts of climate change become felt more acutely, it is vital to understand the complex mechanism by which weather events interact with topographical and pedological conditions to affect the production of crops like grass. The completion of a spatially disaggregated agronomic grass growth model in Chapter 5 begins the process of understanding how climate change will impact farms in different agronomic regions in diverse ways. Measuring farm risk in Chapter 4, particularly with respect to pasture feed inputs, also becomes essential as climate change makes extreme weather events more frequent and less predictable.

Still, environmental upsides and positive externalities exist for grassland farming. Pasture and grassland have the potential to be significant carbon sinks if managed properly. This can help to offset agricultural emissions such as methane from ruminant livestock. Grassland also contributes to the vast amenity value of the Irish countryside which attracts millions of tourists per year. Finally, grassland agriculture’s social component cannot be ignored. By measuring, understanding, and preserving the economic viability of pasture based dairy farms, rural population, employment, agricultural heritage and overall social cohesion can also be strengthened in the face of rural depopulation and urbanisation in developed nations like Ireland.

7.3 Strengths, weaknesses, opportunities, and risks for the grass based dairy system in the future

The overall objectives of this thesis seek to establish baseline measurements and comparisons of the grass-based feed system at the present time. However, establishing an empirical starting point also provides an improved vantage from which to highlight the key strengths, weaknesses, opportunities, and risks faced by grassland dairy farmers in the coming years.

As pastoral dairy farmers look to the future certain strengths of this agricultural system stand out. Grassland farmers are likely to continue to enjoy lower feed costs and higher profitability relative to concentrate intensive operations which will be exposed to volatile international feed prices. Another strength of pasture-based systems is the ability to weather coming agricultural policy storms including limitations on nitrates emissions which may limit livestock numbers in the future. As common agricultural policy funding diminishes, and as environmental quality standards become more stringent, economically viable and environmentally sustainable grassland farms are more likely to stay in business. Still, grassland agriculture is not without its drawbacks. Farmers that rely on favourable grass growing conditions as a primary feed source may suffer acutely from the weather volatility that accompanies climate change.

The potential for changes to carbon accounting are a major opportunity for dairy farmers to burnish their environmental image. Dairy and other forms of ruminant agriculture have long suffered an environmental image problem due to their emissions of methane which is currently accounted for having as 13 times the heat trapping potential of carbon dioxide. In fact, Ireland’s ruminant heavy agricultural sector accounts for nearly forty percent of Ireland’s total carbon dioxide equivalent emissions. Research by Lynch et al. (2020) argues for a reduction in the greenhouse gas penalty for methane due to its much faster dissipation rate (forty years) versus that of carbon dioxide (500 years). Further opportunities exist to sequester the carbon emissions of the grassland agriculture sector. While currently only forestry is accepted as a carbon sequestering land use according to European

Union regulations, an increasing body of evidence supports the sequestration potential of grassland and pasture areas. Other potential policy changes offer more risks than opportunities for Irish dairy farmers. New environmental regulations as well as the transition from historical to equalised subsidy payments have the potential to reduce farm profitability through reduced stocking rates, increased regulatory compliance cost, and reduced subsidy income.

7.4 Implications and contributions of this study for farmers, policymakers, and researchers

The following section outlines the implications and contributions of the three main components of this thesis. The results of this study's analysis of dairy farm income risk, the use of satellite data to measure grass growth, and the effects of feed system on dairy farm profitability fill gaps in understanding and knowledge of how the environment, feed systems, and farm viability are inextricably linked. Farmers will be interested to know how their production system compares to others nationally and internationally on the basis of income volatility and profitability. This study adds empirical support for the use of remote sensed data on grassland farms by farmers, policy makers, and researchers alike. Policymakers may use the findings of this thesis to improve the structure of agricultural income supports to ameliorate income volatility and target subsidy aid to the most environmentally deficient farms. For researchers this work expands the body of knowledge on farm income volatility, agronomic modelling, and farm profitability by feed system.

While farming has always been a risky undertaking, quantitative measurements and comparisons of agricultural risk have been limited heretofore. The results of the risk model of this thesis allow farmers and their knowledge transfer advisors to better understand the sources of income risk with a view towards managing farm income volatility and promoting business stability. Environmental growing conditions are factors that lie largely outside of the farmer's control, but are not necessarily impossible to measure and adapt to. With the advent of "smart" farming bringing an array of new technologies and data into the agricultural sector, farmers are better able to gather detailed, localised data on weather and grass crop growth. Still, it is critical that farmers understand and trust the new information they collect. In the collection and utilisation of remote sensing data, grassland farmers have so far lagged behind crop farmers. The results of this study's grass growth model provide new impetus for the usability of remote sensed vegetation data given the significant relationship between the enhanced vegetation index and existing agronomic indicators. Ultimately profit drives many of the decisions made by farmers. This means that farmers require accurate information on the profitability impacts of any management changes they are considering. In the case of dairy feed systems, the international profitability comparison included in this thesis suggests that grass-based systems are associated with higher profit levels *ceteris paribus*.

Policy makers can also make use of the findings of this thesis as they craft programmes and regulations that support farm viability and rural development as well as environmental conservation. By analysing the income volatility of dairy farms, this research makes clear that the focus of existing agricultural subsidy programmes on income supports has failed to address income volatility, particularly for dairy farms. In fact, higher subsidy payments are associated with increased levels of income volatility thereby incurring a perverse effect on farm viability. The results of this study also support the use of remote sensing data by policymakers over the long term and near term. In the long term this data can be utilised to identify areas of natural constraint which require special subsidy supports if farm viability is to be maintained. In the short term, this data provides opportunities to assess the impacts of extreme weather events on grass production, predict feed shortages, and ultimately to accurately direct emergency farm aid to those regions where farmers are most in need. The third objective of this thesis reinforces the value of internationally comparable data for policy makers. By comparing the profitability outcomes of heterogeneous dairy feed systems across Europe, policy makers in countries like Ireland can better understand the implications of major changes to feed systems in a dynamic political and economic environment. With this new understanding, policies can be crafted to guide farmers towards feed systems that are both environmentally sustainable and economically viable in the long term.

This study contributes to the economic knowledge of farm feed systems and provides a foundation for future research into the complex interplay between agricultural risk, environmental agronomics, and farm profit. By quantifying and comparing farm income risk, this study confirms the volatile nature of dairy farming and shows that this volatility stems not only from market forces. The development of an agronomic model on a broad spatial scale informs researchers in agronomics and agricultural economics that their respective methodologies can work together to provide a more accurate and representative model of grass growth. This study also bolsters empirical support to extend the use of remote sensing technologies from field crops into grassland agriculture where it can provide useful information on grass growing conditions and production. While comparing farms systems across national borders is difficult, the research of this thesis into the relationship between feed system and profitability employs a novel methodology which can be applied by researchers to analyse the profitability impacts of other farm management decisions beyond feed.

The analysis conducted in this thesis has implications for farm management decisions and policy frameworks. It also provides signposts for future avenues of academic research in agricultural economics. In particular, the use of remote sensing data such as the enhanced vegetation index offers a new method of data collection for the analysis of grassland agriculture.

7.5 Alternative applications of this work and future research opportunities in this area

Due to the inevitable limitations of time and data as well as the interesting findings of this thesis, additional research opportunities exist in the area of feed system economics. A selection of these potential new lines of inquiry, which stem from the three primary objectives of this thesis, is outlined below.

While the risk model of this thesis provided important findings about farm income volatility, this type of model still has room to grow. Due to the limited temporal scope of comparable survey data, the panel utilised for this thesis component was limited to 2005 to 2013. An expanded time series could be used to assess the income volatility impacts of CAP reform which occurred in 2005 relative to the period before the introduction of decoupled subsidy payments. In a similar way the extension of this panel beyond 2013 could further understanding into the income risk impacts of precipitated by the abolition of dairy quotas which occurred in 2015.

Alternative applications as well as potential new research avenues stem from the results of the spatial grass growth model developed in Chapter 5 of this thesis. The potential applications of spatial grass growth data are enormous, but this data could be of particular use for developing nations. In the general context of developing nations, agricultural survey data is limited due to the expense of collection, environmental stresses such as droughts are common, and local agriculture represents a large and important part of the food supply and economy. Given this situation, remote sensed data has the opportunity to play a major role. The costs of collecting remote data are considerably lower than generating a comparable amount of survey data. At the same time, this data can provide real time feedback to policy makers about the magnitude and spatial extent of environmental shocks. Finally, remote sensed data can be used to accurately target aid resources to farmers in areas hardest hit by unfavourable climatic changes.

While this thesis empirically demonstrates the value of using remote sensing data to analyse grass growth, more work is necessary to fully exploit this new data source. When used to measure the growth of field crops, satellite imagery is “ground-truthed” by comparing remote sensed data with harvested yield information. This allows farmers and policy makers to accurately predict yields by equating remote sending model results with historical yield data such as tons of production per hectare. However, in the realm of grassland agriculture where cattle themselves are the crop harvesters, ground level harvest and yield data is more difficult to come by. One method of gathering grass growth and grass utilization data is by directly measuring sward height on a regular basis. Unfortunately, this method is time consuming for busy farmers and existing datasets which employ this data collection method fail to represent the full spectrum of grassland farmers. Given this situation, actual grass yield estimates in tonnes of dry matter per hectare (DM/ha) vary widely. There is considerable debate in the literature as to the actual and potential grass feed production of Irish farms. Production estimates range from 6.4 tonnes of grass DM/ha (McCarthy et al., 2011) to 7.1 tonnes for average dairy farms (Creighton et al, 2011) to 12-15 tonnes for more efficient farms with higher stocking rates or dairy farms (Shalloo et al, 2011; Hanrahan et al, 2017; Kavanagh, 2016) to 13 tonnes under experimental conditions (Shalloo et al, 2004). Still other research has attempted to measure grassland feed indirectly by analysing profitability and milk production along with weather conditions, but does not directly estimate feed energy yields (Perez-Mendez et al., 2018). Despite this body of research, a knowledge gap exists around the accurate estimation of feed value from grass yields whether by remote sensing or other methods.

In light of this gap in the literature, another method of collecting yield data is called for. The use of a net energy system to model the feed demands of livestock at the farm level based on surveyed animal demographics and production and comparing this demand with the supply of non-grazed feeds, the nutritional value of grazed grass can be estimated as the remainder. This value, calculated from survey data can then be used to ground-truth satellite based or other remote sensed vegetation models and express data like the enhanced vegetation index as tonnes of dry matter or calories of feed energy. This would make the results of remote sensing models much more transparent and actionable for farmers and policymakers. From a research standpoint, feed energy calories provided by grass can be directly related to calories from concentrates or other purchased feeds. This allows the economic contribution of grass production to be measured at the national level. It would also allow pasture-based feed to be compared on a cost per calorie basis at the farm level. Unfortunately, this level of data collection poses problems for farmer confidentiality as survey respondents. This issue of confidentiality is one of the limitations of this study which will be further explained in the following section 7.6.

The utilisation of the Oaxaca-Blinder methodology in this thesis, which has heretofore primarily been employed in discrimination studies, is novel in the agro-economic realm. Future studies may exploit the descriptive and analytical power of this method to compare farm systems within countries or on an international basis. The Oaxaca-Blinder decomposition method has advantages over regression methods for comparative analyses since highly heterogenous systems, such as farms, are not forced to fit into one model which may be suboptimal for specific groups in the comparison.

7.6 Limitations of this study

Whilst this thesis provides multiple novel insights into the importance and analysis of dairy farm feed systems limitations still exist. Like all microeconomic research projects, this study was conducted within the limitations of data availability and data quality.

As stated in section 7.5, the income risk component of this thesis was limited in its temporal scale by the availability of comparable data in the Teagasc National Farm Survey (NFS). Under this circumstance it did not consider environmental variables or grazed grass production which could be a factor in feed volatility given that Irish dairy farms are highly dependent on pasture grass production to meet their animal feed requirements. Future studies in this area will be able to conduct more thorough analyses and may arrive at additional interesting findings as the NFS panel of comparable data expands over time.

Given the large and varied datasets employed by the grass growth model component of this study, data quality rather than quantity became an issue in certain respects of the analysis. Although more than 90,000 unique farm locations were identified, the weather and soil data utilised did not reach the same level of spatial detail.

Monthly weather data was available from some eight hundred rainfall stations, but only seventy temperature stations across Ireland. This was particularly acute in the south-west of Ireland where temperature data was sparse. Still the estimated coefficients of effect were as expected, even after a regional clustering of the data was conducted. This suggests that limited weather data did not materially distort the results of the disaggregated agronomic model.

The spatial resolution of the soil maps used in this analysis was also below that of the farm location map that was developed. In an effort to overcome this shortcoming, the combined dataset was aggregated to the electoral district level which reduced the number of spatial study cases from over 90,000 farms to less than 3,000 districts. This improved model performance and more accurately reflected the fact that grassland farms are not located at a single pinpoint on the map. In fact, pasture-based farms are often composed of discontiguous fields and contain varied soil types within a single farm.

The aggregation of the dataset away from specific farm locations also alleviated data protection concerns and better allows the results of this study to be presented as maps. Although Teagasc currently does collect accurate location data along with the, NFS which is Ireland’s component of the EU Farm Accountancy Data Network, this data is not available for research purposes at present. In this situation it was not possible to spatially match economic survey data with environmental data. As remote sensing technologies and imagery become more advanced, the use of this data represents an area of concern for farmers who wish to maintain confidentiality about their production systems. It is also within the realm of possibility that policy makers may restrict the use of such data or set guidelines around the ownership structure of remote sensed imagery of a farm operation.

The international profitability comparison of this thesis made use of EU Farm Accountancy Data Network (FADN) data. This data is generated from farm surveys collected at the national level. Some member nations such as Ireland collect highly detailed farm system data in addition to the basic accounting centred data which is the focus of the FADN programme. However, when international data is used, only the more limited accounting-based variables are available. Under this constraint, purchased feed expenses was utilised as a proxy for specific feed types and amounts in an effort to categorise farms by their concentrate feed intensity. Also lacking from the FADN dataset were variables observing farmer management skills, geoclimatic conditions, and herd genetic merit. Still, the FADN data provides high quality data which is highly comparable on an international level.

7.7 Concluding comments

This thesis examined the relationship between dairy farm feed systems and farm viability using an economic approach. In order for grassland farms to keep operating and providing the jobs, environmental amenity, and the traditional way of life that is central to rural society, three conditions must be met. Grassland farms must provide a stable source of income, be able to face environmental changes and shocks, as well as being profitable and competitive. The three objectives of this thesis address these conditions by analysing the determinants of income risk (Chapter 4), by modelling the relationship between pasture growth and the environment (Chapter 5), and by comparing the profitability of farms with different feed systems in different countries (Chapter 6). Ultimately the findings of this thesis offer empirical support to what farmers have been telling researchers and advisors all along about the instability of farm income, the wide variation in environmental endowments across farms, and the harsh competition to maintain profitability.

Appendices

Appendix I. Detrending coupled gross income

In Chapter 4 above, coupled gross income is used as the explanatory variable in a model of Irish agricultural income risk. The following appendix I explains the methodology employed to correct for linear time trends in coupled gross income.

Correcting for the linear time trend allows us to focus on income as a stationary variable and ignore variability caused by long term trends in income. Ordinary least squares regressions of individual farm income from 2005-2013 adapted from Richardson *et al*. (2000) are used to test for significant time trends. Equation 1 below expresses the market income, Y, of an individual farm *i* in year *t*. Here income is a function of the observation year times a trend coefficient plus a constant and error term. If the trend coefficient is determined to be statistically significant (p-value less than 0.05), then $\hat{Y}_{it}$ is used as the predicted farm income for each year.

$$\hat{Y}_{it} = \hat{a} + \hat{b}(\text{Trend}_{it},) + \hat{e} \qquad \text{(Equation I.1)}$$

If the trend coefficient is insignificant, then the mean income level, $\bar{Y}_{it}$, is used as the predicted farm income for each year as expressed in Equation 2.

$$\hat{Y}_{it} = \bar{Y}_{it} \qquad \text{(Equation I.2)}$$

Farm incomes were only detrended if their linear time trend was significant at less than the p=.05 significance level. About twenty per cent of the 927 sampled farms met this criterion. This group was approximately equally distributed between positive and negative income trends, but specialist dairy farms were more likely to have a significant positive trend. Although using a benchmark significance level is an imperfect method of detecting time trends, failing to correct for farm level time trends has its own costs. Non-detrended data would be more likely to exaggerate the endogenous variability of farms which are steadily shrinking or expanding over time.

Calculating Historic Model Decoupled Payments

Decoupled DP in Ireland were calculated using the historic model with minimal coupled payments (DAF 2004). Other nations, such as Germany, moved towards a regional per hectare payment while France opted to retain many of its coupled payments (EC, 2010). The historic model averaged the number of subsidy eligible animals and hectares for each farm in the years 2000, 2001, and 2002. Those averages were then multiplied by the 2002 payment rate in the form given by Equation 3 below (O’Neill and Hanrahan, 2011).

$$SFP = \sum_{i=1} \overline{H}_i \times P_i + \sum_{j=1} \overline{N}_j \times P_j$$

(Equation I.3)

Here, the Single Farm Payment, SFP, is a function of acreage and livestock payments. The sum of average hectares, $\overline{H}$, eligible under scheme i, multiplied by the 2002 payment rate, P_i, is added to the sum of average animals, $\overline{N}$, eligible under scheme j, multiplied by the 2002 payment rate P_j.

The level of single farm payment received by farms each year is not normally distributed. While no farm receives negative payments, outlier farms exist which receive extremely high payments and these skew the distribution to the right.

Results Using Farm Assets

Table I.1 includes the results of the model when farm assets are used to control for scale effects instead of land area. The farm assets variable is the sum of farmer-reported values for land, buildings, machinery, and livestock. These results are broadly aligned with the results of the land area model. Once again, we see that decoupled payments are significantly associated with income variability. Farm assets appear to be associated with increased income risk, at least for cattle farms where there is wide variation in asset levels between operations. This likely speaks to the illiquid nature of farm assets in Ireland. Due to this illiquidity decoupled subsidies and farm revenue are more likely to be used as buffers against income volatility than assets.

Table I.1 Standard deviation of market income on Irish farms (farm wealth model)

Variable	**Full Sample**	**Dairy Only**	**Cattle**	**Sheep**	**Tillage**
Initial Decoupled Subsidies (€10,000)	0.11***	0.02	0.11***	0.25***	0.06
Change in Decoupled Subsidies (€10,000)	0.14***	0.09***	0.11***	0.29***	0.15**
Log of Coupled Subsidies	0.02**	0.02	0.03**	0.06	0.03
Log of Gross Output	0.51***	0.66***	0.45***	0.34***	1.00***
Log of Total Farm Assets	0.07**	0.08	0.14***	-0.04	-0.00
Livestock Units Per Hectare (100 Ha)	-0.09***	-.16***	-0.02	-0.13	-0.00
Daily Concentrates per L.U. (kg)	0.01	-.02	0.03	-0.01	-0.04
Crop Protection Cost (10,000s €)	0.19***	0.06	0.30**	-0.28	0.34*
Fertiliser Cost (10,000s €)	-0.01	-0.00	-0.05	0.08	-0.37**
Mean Farmer Age	-0.01	-0.04**	0.01	-0.01	-0.02
Mean Farmer Age Squared	0.00	0.00**	-0.00	0.00	0.00
Farmer Off-Farm Job	0.02	0.10*	0.02	-0.04	0.21
Spouse Off-Farm Job	0.01	0.03	-0.05	0.14	0.21*
Cattle	-0.24***				
Sheep	-0.16***				
Tillage	-0.40***				
Constant	-5.75***	-6.58***	-6.28***	-4.55***	-10.60***
N	927	249	494	104	80
R^2	0.80	0.79	0.76	0.66	0.81

Note: ***, **, *Denotes that the corresponding coefficients are significant at 1%, 5% and 10% level respectively.

Appendix II. Histograms of concentrate expenditure per ruminant livestock unit in specialist dairy farms in six FADN countries.

The following histograms in figures II.1 and II.2 describe the spectrum of concentrate expenditure per livestock unit in the sample of FADN data used in the international comparison of feed system profitability in Chapter 6 of this thesis. Specifically, Figure II.1 shows the full sample, while Figure II.2 shows the range of concentrate expenditure for specialist dairy farms in each of the analysed nations. Annual concentrate expenditure per ruminant livestock unit is used as a proxy for concentrate feed usage and as a means of delineating feed system groups in the Chapter 6 decomposition analysis.

Figure II.1 below shows that concentrate expenditure per ruminant livestock unit is widely dispersed and exhibits a rightward skew with a long left tail. This indicates that the balance of sampled farms spend less than 1,000 euros per year, per livestock unit on concentrate feeds. However, a small number of highly intensive operations spend 2,000 euros or more per livestock unit on concentrate feeds. Based on this highly skewed and widely dispersed international data sample, the use of individual country data for the profitability decomposition analysis is indicated as it provides a more realistic, like-to-like comparison of feed system spectrum.

Figure II.1 Concentrate expenditure per ruminant livestock unit for all six countries from FADN sample

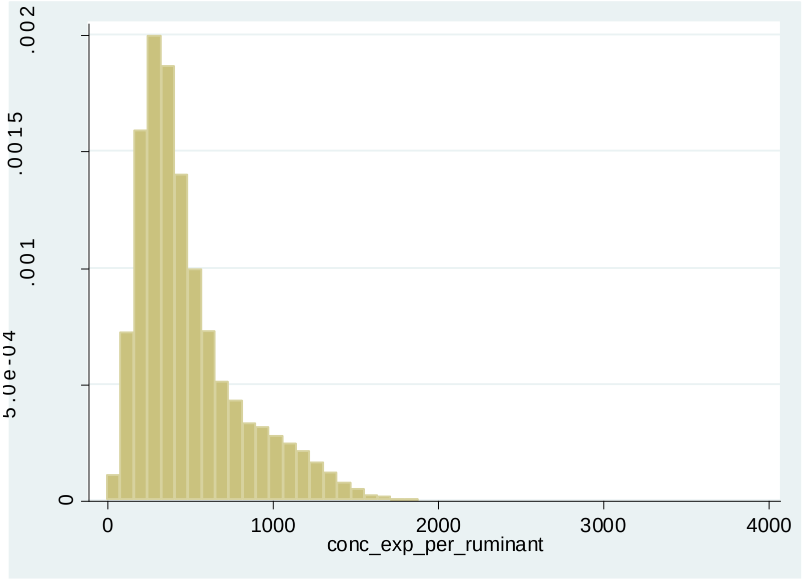
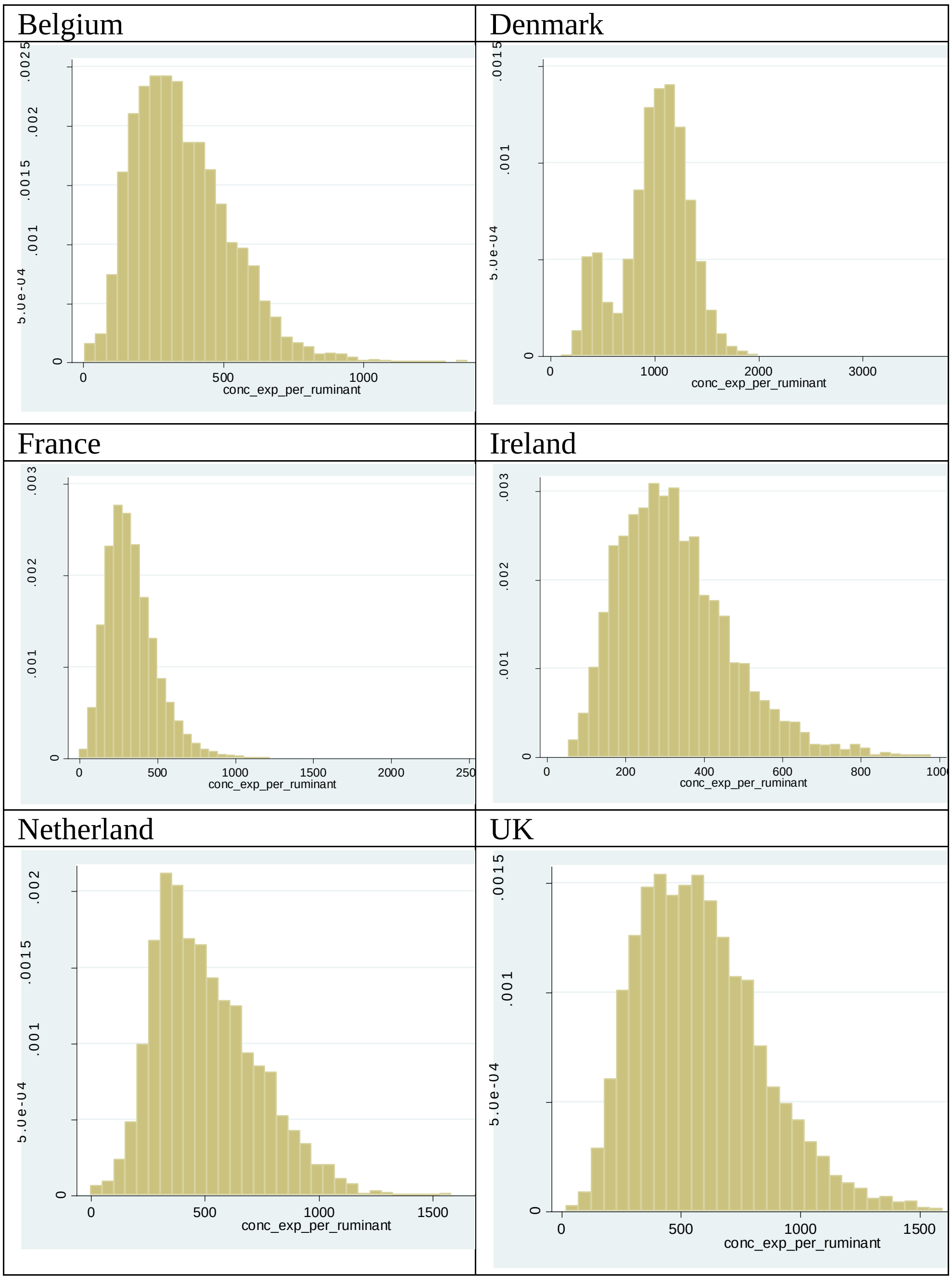


Figure II.2 below shows the range of concentrate expenditure per ruminant livestock unit for each of the north-western European nations included in the FADN sample of specialist dairy farms. In Chapter 6, the farms in each of these nations were divided into an above-median and a below-median concentrate use group for the purposes of comparing the profitability of high and low concentrate usage dairy farms. As shown in the diagrams below in Figure II.2, concentrate expenditures vary widely between nations, but each exhibits a long right tail representing a small number of high concentrate usage farms. In Belgium the majority of farms in the FADN sample spend less than 500 euros per livestock unit on concentrate feeds. Danish farms had the highest concentrate expenditure at over 1,000 euros per LU, but a significant number of Danish dairies were clustered around 500 euros per LU suggesting a dichotomy between pasture focused and indoor concentrate feed systems in Denmark. The French sample was similar to the Belgian pattern of concentrate feed expenditure, but with a longer right tail of high-concentrate farms with expenditures exceeding 2,000 euros per livestock unit. Irish dairy farms were the most dependent on pasture with most sampled farms spending less than 400 euros per LU. Still, intensive, high-concentrate feed systems do exist in Ireland with some farms spending 1,000 euros or more on concentrate feeds. The data from the Netherlands and the United Kingdom exhibit more intensive use of concentrate feeds than in Ireland, but less than in Denmark. In both the Netherlands and the UK, concentrate expenditure per livestock unit is clustered around 500 euros per year with the highest concentrate users spending roughly three times that amount.

Figure II.2 National sample histograms of concentrate expenditure per ruminant livestock unit

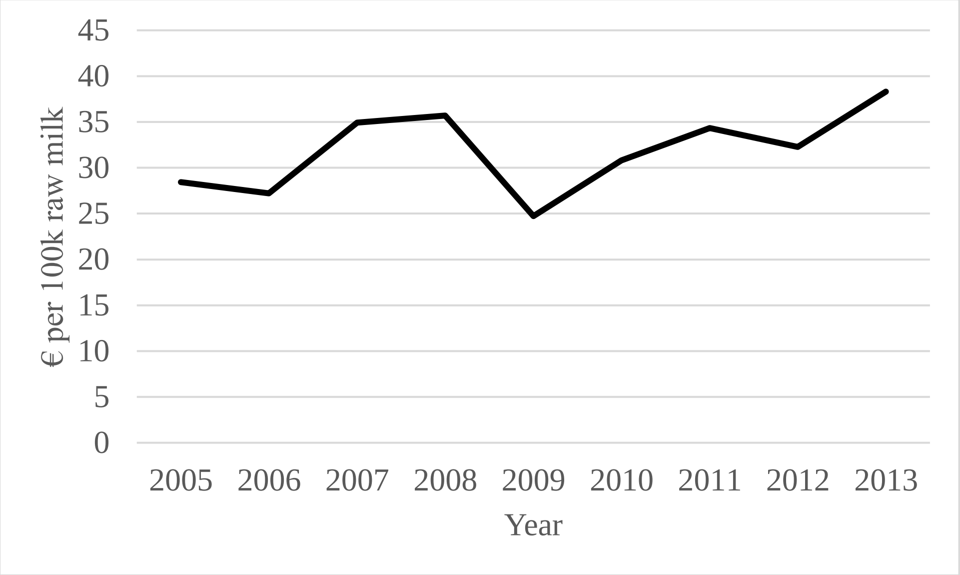


The histograms above in figures II.1 and II.2 provide further background information on the key independent variable used in the Chapter 6 analysis as a proxy for feed system. These figures also provide a visual justification for the use of nationally separate feed system comparisons given the wide range of between-country feed system heterogeneity. For example, the hypothetical comparison of a low-concentrate usage Irish farm with an intensive, high-concentrate Danish farm is likely an unrealistic comparison. For a further explanation of the variables and methods in the international profitability comparison of feed systems, please see Chapter 6 above.

Appendix III. Mean annual Irish milk prices during the 2005-2013 study period

Figure III.1 below describes the annual mean prices for raw milk paid to farmers over the study period (2005-2013) of the income risk analysis conducted in Chapter 4 above. This data is derived from the monthly market prices collected by the European Commission's Directorate General for Agriculture and Rural Development and published in the Agri-food Data Portal. Given that income from milk sales is the primary income source for Irish specialist dairy farmers and that farmer income is the primary dependent variable of the income risk analysis conducted in Chapter 4 above, annual milk prices are relevant to farmer income. Figure III.1 below demonstrates a slight upward trend in milk prices over the 2005 to 2013 study period. It is important to note that while monthly and seasonal prices may vary substantially, on an annual basis, which is the temporal unit of analysis employed in Chapter 4, price variation is not extreme. This supports the conclusion of the risk analysis in Chapter 4.

Figure III.1 Irish annual mean raw milk price 2005-2013



(EC, 2023)

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