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ClimAg: Multifactorial Causes of Fodder Crises in Ireland and Risks due to Climate Change

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

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1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

ClimAg: Multifactorial Causes of Fodder Crises in Ireland and Risks due to Climate Change

Authors: Nithiya Streethran, Kieran Hickey, Astrid Wingler and Paul Leahy
Lead organisation: University College Cork

Identifying pressures

The temperate climate of Ireland favours almost year-round grass growth, which has supported the development of a successful pasture-based farming system. However, this has been threatened by repeated severe shortfalls in fodder stocks, with resulting impacts on yields, revenues, and animal welfare. Grass growth may be influenced by a number of factors, including droughts, heat stress and other drivers, which can lead to the emergence of a fodder crisis.

This research identifies the key drivers of historic fodder crises, and investigates whether such events will become more or less frequent or severe under the climatic changes projected for Ireland by the mid-21st century.

Informing policy

By the middle of this century, total annual grass growth is projected to decrease throughout Ireland. However, the projected changes are spatially variable. Fodder production in the north-west of the country is likely to remain more resilient than elsewhere, with decreases in production most likely to occur in the south-east and, during summer months, in parts of the mid-west. This may result in gradual shifts in agricultural practices over time.

Growth limitation due to heat stress is unlikely to occur in any area of the country, even in the worst-case future climate scenario. However, interactions between drought and heat may lead to reduced growth in particular years.

Reductions in autumn growth and reduced cover at the end of the growing season are also projected, particularly in the south-east. This indicates increased risk in future to the resilience of pasture systems, especially as many of the highest-impact fodder crises develop over successive growing seasons. There may be potential short-term impacts on farm incomes, and mitigation measures are likely to impose additional long-term costs on farmers.

Developing solutions

This research has created a novel fodder crisis severity index which can be used to gauge the impacts of historic and future events. Past fodder crisis events have been multifactorial, and in many cases multi-annual. The research has also developed and validated an innovative modelling framework which combines climate change projection datasets with a computer model of grass growth. This can be used to determine pasture productivity under future climatic conditions.

Data is key to supporting better decision making at farm level and informing policy supports at government level. The modelling framework developed in this research can inform preparedness by being potentially coupled with long term weather forecasts to create an early warning system for adaptive pasture management.

Measures to increase the resilience of pasture systems against fodder crisis events are recommended. These include increases in stored fodder provision, and the development of early warning systems. Earlier closure in autumn may also allow for better growth recovery in spring in order to avoid the emergence of multi-annual events which have been observed several times since 2010.

EPA RESEARCH PROGRAMME 2021–2030

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Prepared for the Environmental Protection Agency

by

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DISCLAIMER

This report is based on research carried out/data from 2019 to 2023. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The temperate climate of Ireland favours almost year-round grass growth, which has supported the development of a successful pasture-based farming economy. This agricultural system is efficient, but the high dependence on fodder has led to the regular occurrence of fodder crises in Ireland, when available stocks run too low, with resulting impacts on yields, revenues and animal welfare.

Fodder crises may vary in spatial and temporal extent and occur due to a multitude of environmental and management factors, some of which may interact with each other. In particular, drought and heat stress may interact, resulting in reduced summer grass growth. To understand these events in greater detail, this report presents an integrated assessment of the occurrence of historical and future fodder crises, the latter under projected climate change conditions.

An impact-based five-level fodder crisis severity index has been developed and can be used to classify fodder crisis events. This severity index has been applied to fodder crises occurring between 1946 and 2022, the period for which accessible, high-quality data and records are available. Fodder crises occur two or three times per decade on average, and several significant events developed during this period. Some of the highest-impact events were driven by blocking anticyclones, which led to suppression of growth by drought and high temperatures.

An innovative modelling framework has been developed, evaluated and applied to project the future occurrence of fodder crises in Ireland. A mechanistic, dynamic grass growth model has been driven with high-resolution downscaled climate data from two different model families under historical (1976–2005) conditions and two future (2041–2070) climate change scenarios (examples of Representative Concentration Pathways (RCPs)), RCP4.5 and RCP8.5, corresponding to a 1.4°C and 2.0°C increase in global mean temperature by the mid-21st century, respectively.

The model was evaluated by driving it with reanalysis data and comparing the outputs with aggregated on-farm grass growth measurements. Then, simulations driven by climate model data from the historical period were compared with the contemporaneous values driven by the reanalysis data. Finally, simulations were carried out using future scenario outputs from the climate models. Two climate model datasets, Coordinated Downscaling Experiment – European Domain (EURO-CORDEX) and HiResIreland, were used.

Simulations driven by the HiResIreland dataset best matched observed historical grass growth patterns. Simulations driven by the EURO-CORDEX dataset had a poorer match to historical grass growth. The HiResIreland-driven simulations project a general decrease in future grass growth throughout Ireland, with the decrease being more pronounced in the more extreme RCP8.5 climate change scenario than in the more likely RCP4.5 scenario. Increases in growth are projected in spring while decreases are projected in summer and for most areas in autumn.

Autumn growth is particularly important for predicting the development of a fodder shortage, as farmers rely on late-season grass growth for the subsequent year, and heavy autumn grazing may delay and reduce spring growth. Simulations projected a decrease in autumn growth, except for the north-west of the country. Average closing farm cover, indicated by the stock of standing biomass at the end of the year, was predicted to decline in most of the country under future climatic conditions, and would in many areas fall below the current recommended cover of 500–600 kg DM ha^{-1}. This points towards a vulnerability of current pasture systems to multiannual fodder crises, particularly as the reduction in annual growth and summer growth is likely to result in reduced availability of stored fodder for the winter.

The modelling framework performed well in general with a linear relationship apparent between pooled model simulations and observations of daily grass growth for all locations. However, deviations between modelled and observed grass growth were identified particularly at the start of the growing season (which occurred later in the model than was observed in practice), and the model was found to be over-sensitive to extreme weather events.

Measures to increase the resilience of pasture systems against fodder crisis events are recommended, particularly in light of the projected reductions in autumn growth and closing grass cover. Potential measures include earlier closure in autumn and the development of early warning systems for conditions likely to lead to the emergence of fodder crises, in order to allow adequate stocks to be preserved from autumn to spring to avoid the emergence of multiannual events of the type observed several times since 2010.

1 Introduction

1.1 Background and Objectives

The focus of this report is the production of feed for ruminant animals from grass, or grass-dominated pastures, in Ireland. The term “fodder” is used to include all grass, primarily perennial ryegrass (*Lolium perenne* L.), produced for consumption, whether by grazing (forage) or preservation methods such as hay or silage. Prolonged or widespread shortages of animal feed may develop into “crisis” situations, leading to severe impacts on agricultural output, animal welfare and farm incomes.

The objectives of the ClimAg project were to:

- develop a definition and classification system for fodder crisis events;
- identify the key drivers of fodder crises;
- analyse the occurrence of fodder crisis events from the mid-20th century to the present date;
- develop a data and modelling framework that can be used to simulate fodder production in temperate pasture systems;
- estimate the future occurrence of fodder crises under projected climatic conditions in the mid-21st century;
- identify key vulnerabilities and make recommendations on actions to improve the resilience of pasture systems in Ireland.

1.2 Fodder Crisis Severity Index

Fodder crises have been widely reported in farming periodicals and the news media (e.g. see Dermody (2013) and Noone *et al.* (2017)), but, to date, there is no agreed definition of what constitutes a fodder crisis. Therefore, a severity index was developed to categorise such events by their duration, spatial extent, i.e. regional or national, and economic or social impacts.

The severity index is used to classify events into five categories (Table 1.1). The categories are defined primarily by the impacts of and responses to the event. Each category also has an associated characteristic spatial extent and temporal duration.

1.3 Meteorological Impacts on Grass Growth Leading to Fodder Crises

Fodder crises are multifactorial events by nature. A period of widespread below-average grass growth can be caused by a single meteorological driver or by a combination of multiple meteorological drivers. The main meteorological and environmental factors controlling the growth of perennial forage grasses, such as perennial ryegrass, are temperature, precipitation, water availability, solar radiation and light conditions, including photoperiod (Brereton *et al.*, 1996; Hurtado-Uria *et al.*, 2013a; Wingler, 2015). When variables such as temperature or moisture availability fall below certain threshold values, growth is restricted (Hopkins, 2000; Hurtado-Uria *et al.*, 2013a,b). In addition, developmental processes underlie the seasonality of growth, which results in a growth peak in late spring or early summer but lower growth under similar conditions later in the season (Hurtado-Uria *et al.*, 2013a; Wingler and Hennessy, 2016). Variation in precipitation and increases in daily temperatures and carbon dioxide concentration in the atmosphere influence pasture productivity and quality (Bell *et al.*, 2013; Rojas-Downing *et al.*, 2017). Cold winters may also affect long-term yield and result in a loss of biomass in spring (Wingler and Hennessy, 2016). Other precipitation events, such as heavy spring snowfall, can have impacts on grass growth by delaying the start of growth, and extreme summer rain or hailstorms may cause damage to grass, making it harder to harvest.

In Ireland, growth is co-limited by solar radiation and temperature from September to December, while temperature is the main driver of growth from January to March (Hurtado-Uria *et al.*, 2013a). Growth limitation early in the year is consistent with inhibition of cellular growth in the growing points (meristems) by low temperatures (Wingler, 2015). Little or no grass growth occurs at temperatures below 5°C, despite continued photosynthetic activity. This results in an accumulation of the carbohydrate fructan, which protects the cells against cold damage (Wingler, 2015). Low winter temperatures are also required for vernalisation of

Table 1.1. Definition of the categories in the fodder crisis severity index

Index value	Duration	Spatial extent	Impacts and responses
0	N/A	N/A	None
1	Seasonal to annual	Regional	Transfer of fodder from unaffected areas within Ireland A price rise for fodder is likely because of high demand Possible above-normal amounts of commercial feed purchased
2	Seasonal to annual	National	Movement of fodder from unaffected farms within Ireland A significant price rise for fodder is likely because of high demand Above-normal amounts of commercial feed purchased
3	Annual to multiannual	National	Heavy reliance on the purchase of commercial feed Animals malnourished in some cases
4	Annual to multiannual	National	Some farmers no longer have the money to purchase commercial feed Government intervention Import of emergency fodder and donation of cut grass, e.g. from airports Increasing numbers of malnourished animals Early culling leading to a loss of farmer income
5	Annual to multiannual	National	Starvation and death of significant numbers of animals on farms Large-scale early culling, leading to a significant price drop for meat and significant loss of farmer income Large-scale government intervention and, where possible, import of large amounts of emergency fodder Long-term damage to the national herd, national flock and farm incomes

N/A, not applicable.

perennial ryegrass, enabling flowering later in the year as the days get longer and temperatures rise (Wang and Forster, 2017). However, flowering can have negative impacts on overall production by restricting late-season growth (Hurtado-Uria *et al.*, 2013b) and reducing forage quality.

Heat stress inhibits perennial ryegrass growth rates through the accumulation of reactive oxygen species, inhibition of photosynthesis and membrane peroxidation (Jiang and Huang, 2001; Loka *et al.*, 2019; Soliman *et al.*, 2012). However, persistent damage occurs only under severe heat stress (35°C day/30°C night, according to Perera *et al.*, 2019; 40°C day/35°C night, according to Yang *et al.*, 2014), whereas mild climatic conditions, i.e. heating of swards up to 7°C above ambient temperature, were observed to have only minor effects on perennial ryegrass growth (Langworthy *et al.*, 2020). Under the mild Irish climate, heat stress on its own is therefore not very likely to have a major impact on perennial ryegrass yield.

In waterlogged soils, the oxygen supply to roots is reduced, resulting in impaired root development, lower leaf chlorophyll content and reduced rates of photosynthesis in perennial ryegrass (Frisk *et al.*, 2022; McFarlane *et al.*, 2003). Submergence (i.e. shoots at least partially under water) further exacerbates these effects and reduces shoot water-soluble carbohydrate content (Liu and Jiang, 2015). The combination of impaired photosynthesis and increased carbohydrate demand for fermentation in the absence of oxygen reduces the availability of carbohydrate for growth (Loka *et al.*, 2019).

Dry summers, for example as experienced in 2018, can limit perennial ryegrass growth in Ireland. Although heat stress mainly impairs photosynthesis and results in lower levels of carbohydrate formation (Loka *et al.*, 2019), drought, similar to cold stress, affects growth more strongly than rates of photosynthesis (Muller *et al.*, 2011). This results in carbohydrate accumulation in perennial ryegrass under severe water deficit (Hofer *et al.*, 2017). Water deficit restricts hydraulic growth within the plant, and also leads to reduced soil nitrogen availability and lower plant nitrogen content (Hofer *et al.*, 2017); however, the nitrogen status of perennial ryegrass can recover once water becomes available again (Hofer *et al.*, 2016).

Furthermore, the interacting effects of drought and heat can impair growth. During periods of water deficit, stomatal closure results in reduced cooling through transpiration, which can increase the leaf temperature; in turn, higher leaf temperatures can increase transpiratory water loss (Jiang and Huang, 2001). Drought can therefore exacerbate the effects of heat and vice versa. Unexpectedly, however, warming by 3°C above ambient temperature did not increase soil water depletion in perennial ryegrass and ribwort plantain (*Plantago lanceolata* L.) mixtures (Naudts *et al.*, 2013).

1.4 Non-meteorological Drivers Contributing to the Emergence of Fodder Crises

Apart from meteorological conditions, non-meteorological factors may contribute to the emergence of a fodder crisis from a period of below-average growth. Factors such as the physical properties of soil, including the drainage characteristics, intensity of grazing, nutrient availability, make-up of the sward and the choice and timing of management actions, such as cutting, grazing and fertiliser or slurry applications by farmers (Falzoi *et al.*, 2019; Grace *et al.*, 2019; Jordon *et al.*, 2022; O’Donovan *et al.*, 2011, 2022), may exacerbate the impacts of a low-growth period. Prior management decisions such as the provision of preserved fodder stocks or supplements and management actions taken in response to low growth may also exert an influence on the development of a fodder crisis.

1.5 Overview of Pasture Systems in Ireland

The island of Ireland has a temperate oceanic climate that favours grass growth throughout the year (Brereton *et al.*, 1996; Hurtado-Uria *et al.*, 2013a). The most widely grown grassland species in intensively managed grasslands in Ireland, and globally, is perennial ryegrass (Grogan and Gilliland, 2011; Hennessy *et al.*, 2020), a C_3 grass species belonging to the subfamily Pooideae, the cool season grasses (Bell *et al.*, 2013; Yang *et al.*, 2014).

The typical growing season in Ireland is over 300 days, with an increasing trend (O’Donovan *et al.*, 2011). Due to the long growing season and relatively mild conditions, animals are grazed much of the year. The long growing season allows the Irish dairy industry to rely primarily on grazing as a cheap source of animal feed (van den Pol-van Dasselaar *et al.*, 2020). Fodder production in Ireland is therefore dependent on grassland productivity, and grassland accounts for almost 60% of the total Irish land area and over 80% of agricultural land (Central Statistics Office, 2022a). By providing grass, silage and hay (i.e. fodder), Irish grassland forms the basis of ruminant livestock production, and a high proportion of fodder is produced and stored on the farm for on-farm consumption. Irish agriculture is dominated by specialist beef (44% of farmed area), specialist dairy (22%) and specialist sheep (11%) farming (Central Statistics Office, 2022b). In 2022, 1.9 million cattle and 3.2 million sheep were slaughtered in Ireland and 8.8 million litres of domestically produced cow’s milk were processed in creameries (Central Statistics Office, 2023a,b).

In the Irish grass-based dairy production system, grazed pasture typically makes up over 60% of the dry matter consumed by cows, and grass-derived sources such as silage make up 20% (O’Brien *et al.*, 2018). Concentrate feeds (mostly derived from beet, maize, barley and soybean) are used in Irish agricultural systems to supplement pasture grass, hay or grass silage in the event of grass-based feed shortages (Hennessy *et al.*, 2021). Concentrates and other non-grass feeds make only a minor contribution (less than 20%) to a cow’s diet (French *et al.*, 2006; Hennessy *et al.*, 2021; O’Brien *et al.*, 2018). Stored fodder is used to feed cattle during the winter while they are housed indoors and when grass growth rates are low or zero. Therefore, the amount of stored fodder at the end of the grazing season and the timing of the start of growth the following spring are two key factors that determine the adequacy of fodder supplies. This pasture-based ruminant production system is used by the majority of livestock farmers in Ireland and is reliant on benign climatic conditions to produce sufficient levels of fodder over the long growing season with low levels of inputs (Dillon *et al.*, 2005; Hennessy *et al.*, 2020; O'Donovan *et al.*, 2011).

The environmental sustainability of Irish ruminant production systems was recently reviewed by O'Mara *et al.* (2021), discussing options to reduce emissions of the greenhouse gases methane and nitrous oxide and to improve water quality through reduced fertiliser use. The increase in nitrogen fertiliser costs in 2021 and 2022 highlighted the importance of reducing fertiliser applications. This can be achieved by the inclusion of legumes in the sward, which form microbial associations (root nodules) with rhizobia, bacteria that can fix molecular nitrogen from the atmosphere. Inclusion of the legume white clover (*Trifolium repens* L.) in perennial ryegrass swards increases dry matter production (Guy *et al.*, 2018). Importantly, fertiliser use can be reduced from 250 to 150 kg ha^{-1} without negative impacts on herbage yield or milk production (Egan *et al.*, 2018). Plot trials have shown benefits of adding more species (grasses, legumes and herbs) in perennial ryegrass swards, thus creating multispecies swards. The benefits include increased biomass yield with less nitrogen fertiliser and the potential to mitigate drought effects (Finn *et al.*, 2018; Grange *et al.*, 2021; Hofer *et al.*, 2016). However, grassland management (grazing and cutting) can affect the species proportions, e.g. grazing can reduce herbage yield of multispecies swards (Grace *et al.*, 2019). How these species mixtures perform under grazing should be evaluated further (O'Donovan *et al.*, 2022).

2 Previous Occurrence and Multifactorial Drivers of Fodder Crises

In all, 15 fodder crises were recorded for Ireland over the period from late 1946 to 2022, some of which were multiannual events. They vary in cause, duration, severity and impact (Figure 2.1). This chapter will give an overview of their chronology, including causes, duration and impacts.

2.1 Chronology of Fodder Crises, 1946–2009: Drivers and Impacts

The first fodder crisis was in 1947 and was a result of an extended very cold spell that started in late 1946 and carried on until early May 1947. Heavy and persistent snowfalls significantly delayed the start of spring grass growth, and animals were kept inside for much longer than usual whenever possible, which led to fodder shortages for many farmers. There were mass mortalities of animals in the fields, including both domestic and wild animals, due to the snow and the lack of food. There were also difficulties in securing alternative feed because of blocked roads and railways and the high cost of fodder. This resulted in many farmers having no option but to allow their animals to starve or, in some cases, to sell their animals for slaughter, often at reduced prices because of their poor condition (Kearns, 2011).

A series of less severe fodder crises occurred in the 1950s, including in 1950, 1955–1956 and 1958, with the first and last being regional in scale and the other having island-wide effects. None was associated with mass starvation or mass early slaughter of animals. Only one fodder crisis was recorded for the 1960s, and this was associated with an extended winter cold spell that lasted from December 1962 into late March 1963, leading to a delay in the start of grass growth and fodder problems for many farmers, who had to continue feeding their animals on fodder stocks later than usual. There were incidents of starvation and increased mortality of animals as a result.

A more complex event, associated with an exceptionally long dry period, developed from October 1974 to September 1976 (Stead, 2014). This generated a fodder crisis spanning 1975 and 1976, albeit with some intermediate recovery in fodder growth and stocks.

In the 1980s, there was only one fodder crisis recorded, a multiannual event occurring between

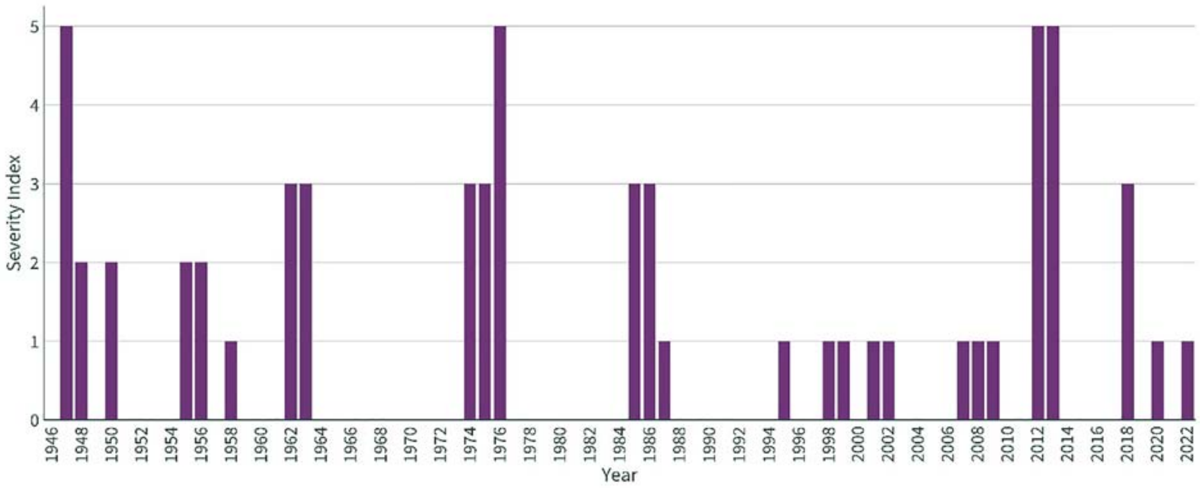

Figure 2.1. Annual occurrence of fodder crises, 1946–2022, with associated scores on the fodder crisis severity index. Multiannual events are represented by separate bars for each year of their duration.

1985 and 1987. This consisted of two main components. First, a series of major thunderstorms and downpours across Ireland in July 1985 caused large-scale damage and destruction of fodder and led to shortages in the following winter. Second, a very wet summer in 1986, when combined with low fodder stocks carried forward from the previous year, led to a further fodder crisis during the winter of 1986 that continued into 1987. In the latter case, this was associated with the death from starvation of some animals.

Two events of note occurred in the 1990s. The 1995 event was associated with heat and drought from June to October limiting grass growth and fodder production, leading to problems with fodder for some farmers and some shortages but not extending into the winter (Mac Cárthaigh, 1996). This was not the case with the event occurring from 1998 to 1999, when an exceptionally wet summer resulted in low grass growth rates and reduced fodder production, leading to a fodder crisis in the winter that was relieved only by spring grass growth in 1999. Again, this was limited in terms of its impacts, with some farmers struggling to feed animals through the winter.

There were two significant events in the 2000s. The event of 2001–2002 began to develop in the summer. The summer of 2001 was dominated by high temperatures that continued into November but did not affect grass growth. The crisis arose because of the highly variable nature of precipitation, ranging from very low in June, September and November to very high in July, August and October, creating the conditions for a period of poor grass growth and fodder production (Ryan, 2002). This led to a fodder crisis in the winter of 2001–2002, which was relieved only by spring grass growth in 2002. This was another relatively low-impact event, with issues on only some farms in relation to fodder but no evidence of mass starvation and mortalities. A similar, limited-impact, fodder crisis took place between 2007 and 2009. This event was associated with two exceptionally wet summers reducing fodder production and stocks and leading to a fodder crisis in the winter of 2008–2009. The exceptionally wet summer and November of 2009 (Hickey, 2010) did not seem to cause any significant fodder issues, although many farms in the west and south suffered extensive flooding, resulting in the movement of animals off flooded land and the loss of some stored fodder.

2.1.1 Recent fodder crises: 2012–2013, 2018, 2020 and 2022

Extreme weather events, such as those experienced in 2012–2013 and 2018, led to reduced grass growth in Ireland (Green *et al.*, 2018; White *et al.*, 2020) and thereby shortages of fodder. The major fodder crisis of 2012–2013 had the highest impact of any event since that of 1946–1947. This event was a result of another very wet summer, which led to low grass growth and fodder production. This caused stocks to run low in the winter of 2012–2013. In other years, such a crisis would be ended by spring grass growth, but that did not happen in this case. As a result of very low spring temperatures, grass growth did not start to any great extent until May 2013, and by this time many farmers had run out of fodder and money to buy feed. This led to government intervention and the import of fodder from France to alleviate the situation. There was widespread hunger among animals and some deaths, as well as the premature slaughter of an estimated 30,000 cattle below their target weights. This event put renewed focus on Ireland’s dependency on fodder production and storage, and the possible role of climate change in exacerbating the crisis and concerns about the increasing vulnerability of grass growth and fodder production to these types of meteorological extremes (Hennessy, 2013).

The 2012–2013 fodder crisis in Ireland occurred after a series of meteorological events: a summer of below-average temperatures and sunshine hours combined with above-average rainfall, a cool and dry autumn, a cold and wet winter, and a very cold spring with variable rainfall (Hickey *et al.*, 2018). These events led to delays in the start of grass growth in the spring of 2013 (Hickey *et al.*, 2018), followed by ground conditions that were too wet for grazing (Dermody, 2013). As a result of the 2012–2013 fodder crisis, input expenditure, especially on animal feed, was very high in 2013 (Hennessy and Moran, 2015), as fodder had to be imported and greater amounts of concentrate feed had to be used (Dermody, 2013; Hickey *et al.*, 2018). Other economic consequences of this fodder crisis included a reduction in milk production, early culling of cattle and livestock deaths (Hickey *et al.*, 2018). This fodder crisis is estimated to have cost the Irish agricultural sector around €500 million. Feed costs in the livestock sector were 50–70% higher than average. The impacts were felt most strongly in the south and west, where the grazing season is usually longer, as farmers in these regions typically rely less on purchased feeds than those in other areas, which increased their vulnerability to the weather conditions (Hennessy, 2013).

The 2018 event was associated with a summer heatwave and drought, which was preceded by heavy snowfalls in February. However, the fodder crisis was limited in scope thanks to a strong recovery of grass growth and fodder production in autumn. A similar outcome occurred in two crises in the early 2020s, albeit with different causes. In 2020, very dry conditions in March, April and May led to a widespread drought being declared, which was followed by a wet June and July (Met Éireann, 2021). In 2022, there was another heatwave and drought, with numerous temperature records being set in July and August.

Three drought events of note, which resulted in fodder crises, occurred in 1976, 2018 and 2022, and all were associated with a blocking anticyclone. In this scenario, a large high-pressure system remains over Ireland for several weeks. This blocks the usual pathway of Atlantic depressions associated with high rainfall, leading to high temperatures and low precipitation and, as a result, a significant drop in grass growth (Falzoi *et al.*, 2019; Swindles *et al.*, 2010). The 2020 event was also associated with a blocking anticyclone (Met Éireann, 2021).

2.2 Prehistoric and Historical Droughts and Fodder Crises

There has been significant research on droughts in Ireland covering the last 4500 years and using a variety of techniques at different timescales. Swindles *et al.* (2010) were able to identify summer droughts in Ireland over the last 4500 years through the analysis of testate amoeba-derived water table reconstructions from raised peat bogs. Four coherent dry phases are identified in the records at *c.*1150–800 BC, 320 BC–AD 150, AD 250–470 and AD 1850–2000; however, at this scale, it is not possible to infer the likelihood of fodder shortages. Hickey (2023) infers some losses due to fodder shortages by looking at historical cattle losses from epizootics and extreme weather, e.g. in AD 1139, but most non-disease-related cattle losses were associated with winter cold spells.

Extensive work has been carried out on droughts in Ireland going back to 1765, and Murphy *et al.* (2020) note that there were significant fodder issues for Ireland during the extreme droughts of 1765–1768 and 1834–1836. Work on Irish drought and precipitation indices by Murphy *et al.* (2017), Noone *et al.* (2017) and O'Connor *et al.* (2022) clearly identifies several drought-rich periods, defined by Noone *et al.* (2017) as periods in which at least 40% of the 25-station study sample experienced events of at least 18 months' duration. These include 1803–1806, 1854–1859, 1933–1935, 1944–1945, 1953–1954 and 1975–1977. Droughts in 1887–1888, 1891–1894 and 1971–1974 were also identified and categorised by O'Connor *et al.* (2022) as "moderate" by the contemporaneous values of standardised precipitation index and standardised streamflow index, according to the classification of McKee *et al.* (1993). Although there is summary mention of agricultural impacts in these drought studies, any detailed assessment of these impacts is outside the remit of the articles. O'Connor *et al.* (2023) examined the impacts at a summary level using 11,000 reports from newspaper archives and 15 drought impact categories, which were then further grouped into two simple categories: land-based impact reports and water-based impact reports. However, no direct mention of fodder is made.

3 Data Sources and Modelling Approach

3.1 Overview of Approach

The study area is the island of Ireland (hereafter referred to as “Ireland”), which spans approximately 5.4–10.7°W and 51.4–55.5°N. Grass growth was modelled using hindcasts of climate model datasets for a 30-year historical reference period, 1976–2005. Similarly, projections of climate model datasets under climate change scenarios for a 30-year future reference period, 2041–2070, were used to model climate change risks to grass growth in the mid-21st century.

The overall modelling framework is represented in Figure 3.1. To evaluate the grass growth model’s performance, grass growth, modelled using Met Éireann Re-Analysis (MÉRA) weather data as input, was compared with contemporaneous observations of grass growth for the period of overlap, 2013–2018. The suitability of the climate model data was assessed by using the data to drive the grass growth model for the historical period, and then comparing the simulated grass growth against that driven by the MÉRA data for the period of overlap. Lastly, the model was run with future climate model data for the period 2041–2070, which was compared with the historical climate model data runs to project changes under future climatic conditions.

3.2 Model Description

The ModVege[1] grass growth model, developed by Jouven *et al.* (2006a,b) at the French National Research Institute for Agriculture, Food and Environment (INRAE), was used in this study to simulate grass growth. ModVege is a mechanistic, dynamic model for managed permanent grasslands that has been parameterised for the temperate mountainous Auvergne region in central France (Jouven *et al.*, 2006a).

ModVege has been adapted in a number of studies to model grasslands in China (Zhang *et al.*, 2022), France (Lardy *et al.*, 2011, 2012; Ruelle *et al.*, 2018), Ireland (Hurtado-Uria *et al.*, 2013b; Ruelle *et al.*, 2018) and Switzerland (Bittar *et al.*, 2018; Calanca *et al.*, 2016). Hurtado-Uria *et al.* (2013b) performed an evaluation of three models, including ModVege, for predicting grass growth in Ireland over a period of 5 years using data from Teagasc’s Animal and Grassland Research and Innovation Centre in Moorepark, County Cork. The authors concluded that the ModVege model is likely to be suitable for modelling grass growth in Ireland because it is not empirical and requires universal input parameters, which are likely to make it more effective under meteorological conditions affected by climate change

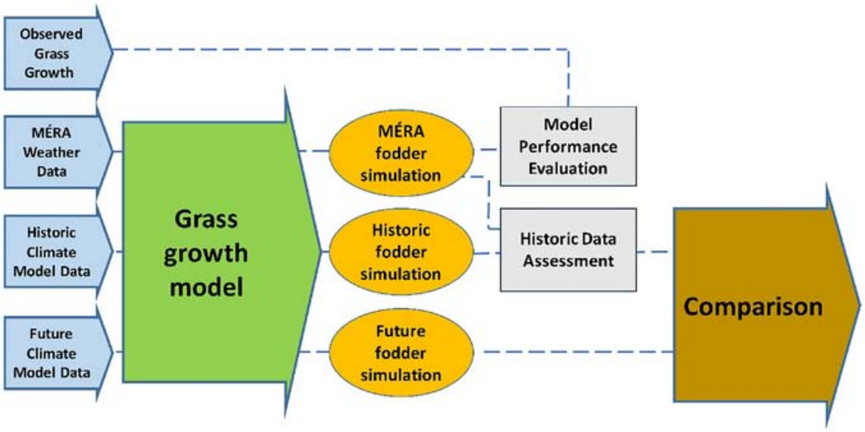

Figure 3.1. Overall modelling framework for ClimAg.

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[1] The grass growth model developed by Jouven *et al.* (2006a) has been referred to as “ModVege” in subsequent publications.

(Hurtado-Uria *et al.*, 2013b). The Moorepark St Gilles grass growth model, developed jointly by Teagasc in Moorepark and INRAE in Saint-Gilles, France, uses the ModVege model as its basis (Ruelle *et al.*, 2018).

ModVege runs at a daily frequency for one calendar year and requires four meteorological time series inputs: mean temperature (°C), incident photosynthetically active radiation ($\mathrm{MJ\,m^{-2}\,day^{-1}}$), precipitation ($\mathrm{mm\,day^{-1}}$) and potential evapotranspiration ($\mathrm{mm\,day^{-1}}$) (Jouven *et al.*, 2006a). A cutting height is specified to simulate biomass harvests, and the model assumes that there will be no reproductive growth after a cutting event (Jouven *et al.*, 2006a).

3.3 Climate Data

3.3.1 Climate model datasets – EURO-CORDEX and HiResIreland

Two downscaled climate model datasets were used as the source of meteorological inputs to model future grass growth. These were HiResIreland, developed by the Irish Centre for High-End Computing (Nolan and Flanagan, 2020), and EURO-CORDEX (Coordinated Downscaling Experiment – European Domain), developed as part of the World Climate Research Programme's coordinated downscaling experiment (Jacob *et al.*, 2014). These datasets are regional climate model (RCM) outputs driven by global climate models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al.*, 2012), which have been downscaled to cover smaller geographical domains at higher horizontal resolutions. HiResIreland covers Ireland at a horizontal resolution of approximately 4 km (Nolan and Flanagan, 2020), while the high-resolution EURO-CORDEX dataset (EUR-11) covers Europe at a horizontal resolution of approximately 12.5 km (Jacob *et al.*, 2014).

CMIP5 outputs were evaluated in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change and use Representative Concentration Pathways (RCPs) to define future scenarios (Chen *et al.*, 2021; Taylor *et al.*, 2012). Data for two RCP scenarios – RCP4.5 and RCP8.5 – are available for both HiResIreland and EURO-CORDEX datasets. RCP4.5 is a stabilisation pathway to a radiative forcing level of $4.5\,\mathrm{W\,m^{-2}}$ without overshoot by 2100, corresponding to approximately 1.4°C of global mean surface temperature increase by the mid-21st century, while RCP8.5 is a rising pathway to a radiative forcing level of $8.5\,\mathrm{W\,m^{-2}}$ by 2100, corresponding to approximately 2.0°C of global mean surface temperature increase by the mid-21st century (Stocker *et al.*, 2013; van Vuuren *et al.*, 2011). RCP8.5 is considered a highly unlikely outcome, but it was used in this study to represent the worst-case, high-risk baseline scenario with no mitigation policies; RCP4.5 reflects a more-plausible trajectory with modest mitigation policies (Hausfather and Peters, 2020), but it would still be likely to exceed the Paris Agreement goal of limiting the global mean temperature increase to well below 2°C (Stocker *et al.*, 2013; United Nations, 2015).

The RCMs used to generate the climate model data are COSMO5-CLM for HiResIreland and RCA4 for EURO-CORDEX. These outputs were driven by four global climate model–ensemble pairs: HadGEM2–ES (r1i1p1), EC–Earth (r12i1p1), MPI-ESM–LR (r1i1p1) and CNRM–CM5 (r1i1p1). The notation in parentheses refers to the particular ensemble member's model realisation/initial conditions (r), initialisation procedure (i) and physical parameterisations (p). The historical climate runs of the HiResIreland COSMO5-CLM RCM have been validated using observational weather data from Met Éireann and the UK Met Office and the ERA-Interim reanalysis dataset (Nolan and Flanagan, 2020), while those of the EURO-CORDEX RCA4 RCM have been validated using the ERA-Interim reanalysis dataset and a number of observational datasets (Strandberg *et al.*, 2014).

3.3.2 Reanalysis weather dataset – Met Éireann Reanalysis

MÉRA is a high-resolution regional climate reanalysis dataset operated by Met Éireann, the Irish National Meteorological Service, which geographically covers Ireland, the UK and part of northern France (Gleeson *et al.*, 2017; Whelan *et al.*, 2017, 2018). The dataset, which is archived at a 3-hour frequency, is available for the years 1981–2019 and has a horizontal grid spacing of 2.5 km. The spatial resolution, temporal coverage and prior validation of MÉRA make it suitable as a historical dataset for evaluating grass growth models. Data from the 3-hour forecast data stream, which comprise 1-, 2- and 3-hour forecast data (Whelan *et al.*, 2017), were used to generate daily frequency meteorological input data for ModVege.

3.3.3 Grass growth measurements – PastureBase Ireland and GrassCheck NI

Grass growth measurements were used to evaluate ModVege simulations. PastureBase Ireland (PBI),[2] developed by Teagasc, has historical grass growth data for Ireland, starting from the year 2013 (Hanrahan *et al.*, 2017). PBI is a farm management application used by commercial farmers around Ireland to report measurements, such as dry matter percentage, farm cover and grass demand, to Teagasc. Participating farmers use PBI to report grass cover estimates on a weekly basis, which are then used by PBI to estimate daily grass growth rates. These data are aggregated at county level and are available at a weekly frequency (Hanrahan *et al.*, 2017).

Similar weekly frequency grass growth data for Northern Ireland are available through the GrassCheck NI[3] project, which is operated by AgriSearch and the Agri-Food and Biosciences Institute (Huson *et al.*, 2020). This dataset covers the main grass-growing season, from March to October, and regional summary measurements are available in published bulletins, starting from the year 2017 (Huson *et al.*, 2020). Regional summaries are calculated from weekly growth rates for individual farms participating in the project (Huson *et al.*, 2020). Forty-five commercial farms across Northern Ireland were participating in the GrassCheck NI project as at 2020 (Huson *et al.*, 2020). While PBI data also include measurements for some of the six counties of Northern Ireland, these were removed in favour of GrassCheck NI data, which had better overall coverage.

3.3.4 Climate data preparation

The list of variables from climate model datasets used in the study is shown in Table 3.1. For some variables, the units must be converted prior to being used as inputs to the ModVege model. The precipitation unit of $\mathrm{kg\,m^{-2}\,day^{-1}}$ is equivalent to $\mathrm{mm\,day^{-1}}$, assuming a water density of $1000\,\mathrm{kg\,m^{-3}}$. Hail and snow were not separated from total precipitation to simplify the analysis. Simulations driven by these climate model datasets were run for the historical (1976–2005) and future (2041–2070) reference periods.

Photosynthetically active radiation is a variable required by ModVege but is unavailable in most climate datasets. To approximate this variable, the global radiation was multiplied by an irradiance ratio of 0.473, which is a value derived by Papaioannou *et al.* (1993) based on irradiance measurements over 12 months in Athens, Greece. The surface downwelling shortwave radiation in EURO-CORDEX is equivalent to the global radiation; for HiResIreland, this was calculated by summing the averaged direct and diffuse downwards shortwave radiation components. As the MÉRA dataset does not include evapotranspiration, this was instead estimated using the FAO Penman–Monteith equation (Allen *et al.*, 1998). The climate data files were subsetted

Table 3.1. List of climate model dataset variables used in this study

Dataset	Variable	Unit	Unit conversion
EURO-CORDEX	Precipitation rate	$\mathrm{kg\,m^{-2}\,s^{-1}}$	× 86,400 ($\mathrm{mm\,day^{-1}}$)
HiResIreland	Total precipitation amount	$\mathrm{kg\,m^{-2}\,day^{-1}}$	× 1 ($\mathrm{mm\,day^{-1}}$)
EURO-CORDEX	Potential evapotranspiration	$\mathrm{kg\,m^{-2}\,s^{-1}}$	× 86,400 ($\mathrm{mm\,day^{-1}}$)
HiResIreland	Evapotranspiration	$\mathrm{mm\,day^{-1}}$	None
EURO-CORDEX	Near-surface air temperature	K	− 273.15 (°C)
HiResIreland	2 m temperature	K	− 273.15 (°C)
EURO-CORDEX	Surface downwelling shortwave radiation	$\mathrm{W\,m^{-2}}$	× 0.0864 ($\mathrm{MJ\,m^{-2}\,day^{-1}}$)
HiResIreland	Averaged direct downwards shortwave radiation at the surface	$\mathrm{W\,m^{-2}}$	× 0.0864 ($\mathrm{MJ\,m^{-2}\,day^{-1}}$)
HiResIreland	Averaged diffuse downwards shortwave radiation at the surface	$\mathrm{W\,m^{-2}}$	× 0.0864 ($\mathrm{MJ\,m^{-2}\,day^{-1}}$)

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[2] PBI website: https://pasturebase.teagasc.ie (accessed 5 February 2024).

[3] GrassCheck NI website: https://agrisearch.org/grasscheck (accessed 5 February 2024).

spatially using boundary data for Ireland derived from Nomenclature of Territorial Units for Statistics regions.[4]

3.4 Model Localisation and Implementation

Although the ModVege model is mechanistic rather than empirical, some calibrations were made to the model's empirical functions and default parameters, as recommended in Hurtado-Uria *et al.* (2013b), to make it more suitable for the Irish case study; the Auvergne region for which ModVege is parameterised, while temperate, is landlocked and mountainous, and therefore differs from the conditions in Ireland. These include site-specific model parameters, such as the sum of temperature thresholds at the beginning and end of the reproductive period and the seasonal effect (SEA). Perennial ryegrass makes up 95% of forage grass seeds sold in Ireland, making it the most important and commonly used grass species (Department of Agriculture, Food and the Marine, 2021), and therefore the ModVege grassland community in this study was assumed to grow only perennial ryegrass. Some parameters, such as the bulk densities of the structural compartments of biomass, minimum and optimal temperatures for grass growth, organic matter digestibility ranges and leaf lifespan, were assumed to be the default values for functional group A (suitable for perennial ryegrass), as defined in Jouven *et al.* (2006a).

3.4.1 Grass-growing season

The seasonality of grass growth differs across Ireland. An example of a study that has explored this is Connaughton (1973), in which the start and end dates of the grass-growing season were derived for a number of representative locations with meteorological stations across Ireland, based on soil temperature thresholds using measurements for the years 1954–1968. Some locations in Ireland had very long or continuous grass-growing seasons, such as Valentia Observatory, County Kerry, and Roche's Point, County Cork, while the locations with the shortest grass-growing seasons were Moneydig, County Derry, and Hillsborough, County Down (Connaughton, 1973). This corresponds to a grass-growing season ranging from about 8 months in the north-east to up to 11 months in the extreme south-west (van den Pol-van Dasselaar *et al.*, 2020).

ModVege defines the grass-growing season as the period between two sum of temperature thresholds, which are the accumulated temperatures from 1 January at the beginning (ST_1) and end (ST_2) of the reproductive period (Jouven *et al.*, 2006a). An empirical function is used to describe the SEA using sum of temperature thresholds, with the onset of growth occurring when the sum of temperatures is 200°C d (degree-days) (Jouven *et al.*, 2006a). To dynamically derive the start of the grass-growing season for each location and each year in terms of ST_1, the definition by Nolan and Flanagan (2020) was used, where the grass-growing season begins at the first occurrence of at least 6 consecutive days with a daily mean temperature of at least 5°C. Rather than using a similar definition for the end of the grass-growing season, ST_2 was assumed to equal the sum of temperatures on 31 December; grass was assumed to continue growing until the end of the year, as the end of the grass-growing season may occur between November and January (Connaughton, 1973). Since the grass-growing season in Ireland begins between January and March, ST_1 will always be less than the 200°C d threshold for the onset of growth defined in ModVege, which makes the SEA function unsuitable for Ireland. Therefore, SEA was assumed to be a constant value of 1 to simplify modelling.

Daily time series meteorological data for Met Éireann's Valentia Observatory meteorological station[5] for the years 2019–2021 were used to test model outputs during this parameterisation, as this station had more complete readings of evapotranspiration, and Valentia is a location characterised by a very long or continuous growing season (Connaughton, 1973).

3.4.2 Leaf area index

The leaf area index (LAI) in ModVege is a function of the specific leaf area, the percentage of laminae in the green vegetative compartment and the standing biomass of the green vegetative compartment (Jouven

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[4] Nomenclature of Territorial Units for Statistics and statistical regions 2021: https://doi.org/10.2785/321792

[5] Met Éireann Valentia Observatory daily data: https://data.gov.ie/dataset/valentia-observatory-daily-data (accessed 5 February 2024).

et al., 2006a). It was noted that using this function causes the simulation values to converge to zero over time, particularly when there is no grass cutting height specified, meaning that the grass is left to grow without any harvesting. This causes the green reproductive biomass to accumulate and reduces the proportion of green vegetative biomass, which LAI is dependent on, and the growth rates do not recover to normal levels over time. To address this, the LAI was instead calculated using the sum of the green vegetative and green reproductive compartments.

3.4.3 Site-specific characteristics

Two site-specific characteristic inputs of ModVege, namely the nitrogen nutritional index (NNI) and soil water-holding capacity (WHC), were derived from European Soil Database and soil properties data collated by the European Soil Data Centre (ESDAC)[6] (Panagos *et al.*, 2012, 2022).

The NNI was estimated using a map of soil chemical properties at European scale based on topsoil data from the Land Use and Cover Area frame Survey 2009/2012, which provide soil nitrogen content modelled using Gaussian process regression from 22,000 sample point data across Europe (Ballabio *et al.*, 2019). Soil organic carbon, vegetation, climate, soil texture and agricultural land use influence the soil nitrogen distribution (Ballabio *et al.*, 2019). To derive the NNI from topsoil nitrogen data, the values were normalised between 0.35 and 1.0, as required by ModVege (Jouven *et al.*, 2006a). Low values of NNI indicate poor soil fertility, while high values show that nitrogen is not limiting growth (Hurtado-Uria *et al.*, 2013b).

Soil WHC was estimated using European Soil Database data, which include a map of the total available water content (mm) derived using a pedo-transfer function (Hiederer, 2013a,b). Data are available at 1 km resolution. The total available water content is a function of the available water content, depth and presence of coarse fragments, and describes the water content between field capacity and permanent wilting point (Hiederer, 2013a,b). Maps of the soil data gridded for the HiResIreland dataset are shown in Figure 3.2.

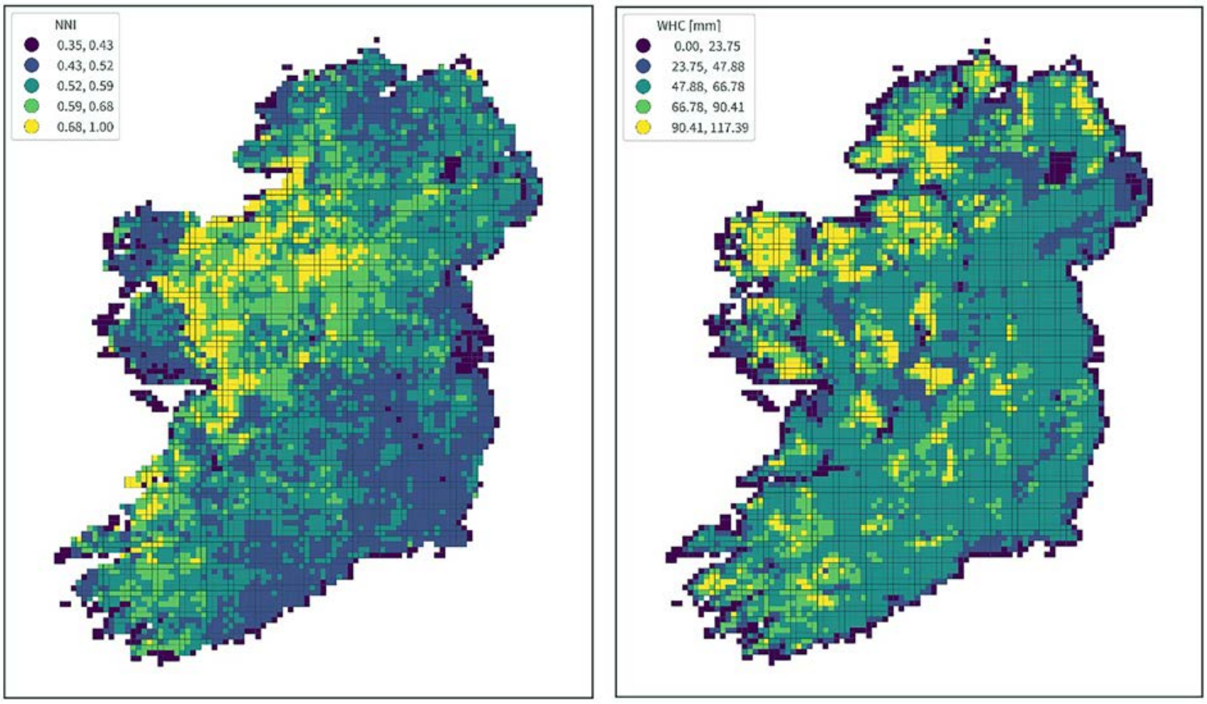

Figure 3.2. NNI (left) and soil WHC (right) derived from ESDAC soil data and gridded for the HiResIreland climate model dataset.

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[6] ESDAC website: https://esdac.jrc.ec.europa.eu/ (accessed 5 February 2024).

3.4.4 Management factors

Teagasc recommends that residual grass be maintained at a height of 4–5 cm post-grazing (O'Riordan, 2016); therefore, the default minimum residual grass height of 5 cm used in ModVege was preserved. The model is adapted to include grazing as an additional management factor.

The total amount of grass grazed per day (kg DM ha^{-1} day^{-1}) is quantified using the product of the stocking rate (LU ha^{-1}) and the amount of grass consumed per livestock unit per day (kg DM LU^{-1} day^{-1}). The stocking rate was calculated by dividing the number of livestock units by the grassland area in hectares in each electoral division or ward in Ireland,[7] using the latest available Census of Agriculture for the Republic of Ireland (Central Statistics Office, 2022b) and the Agricultural Census in Northern Ireland (Department of Agriculture, Environment and Rural Affairs, 2019). Livestock units were calculated as the sum of the total number of cattle in the division/ward multiplied by the livestock coefficient for cattle and the total number of sheep in the division/ward multiplied by the livestock coefficient for sheep. Based on Eurostat (2022) definitions, a livestock coefficient of 0.8 was used for cattle, as the cattle population was assumed to include both dairy and non-dairy cattle, while a livestock coefficient of 0.1 was used for sheep. A map of the stocking rate data on the HiResIreland grid is shown in Figure 3.3.

The average amount of grass consumed per LU is estimated to be 13 kg DM day^{-1} based on Teagasc data (Kavanagh, 2016) and estimates used by Broad and Hough (1993) for dairy cows; one dairy cow is equivalent to one LU (Eurostat, 2022). Selective grazing has been observed in cows, and the amount of available forage and its digestibility influence the degree of selection (Mohammed *et al.*, 2009). The organic matter digestibility, which is calculated in ModVege for each biomass compartment, was therefore used to determine the proportion of biomass compartments that make up the grass consumption of 13 kg DM LU^{-1} day^{-1}.

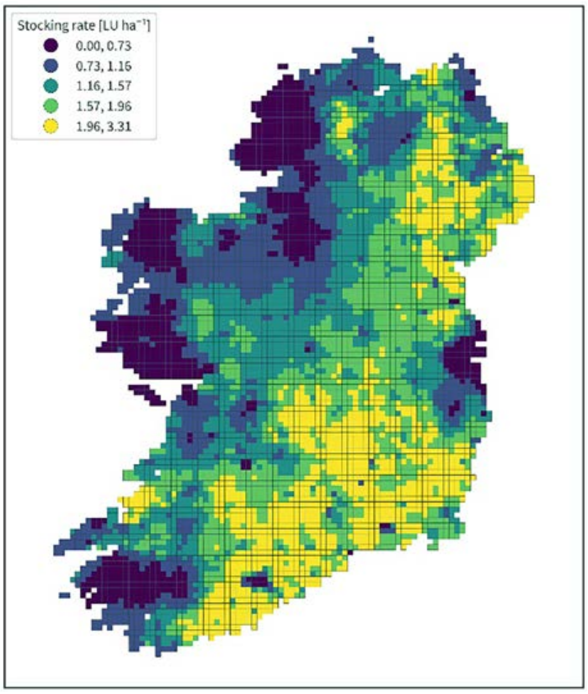

Figure 3.3. Stocking rate derived using the Census of Agriculture for the Republic of Ireland and the Agricultural Census in Northern Ireland and gridded for the HiResIreland climate model dataset.

The grazing season is not equivalent to the grass-growing season, as there must be a delay between the start of the grass-growing season and the grazing season to allow sufficient plant cover for grazing, as well as to enable animals and machinery to pass over the land (Nolan and Flanagan, 2020). Based on Broad and Hough (1993), the start of the grazing season was implemented as 10 days after the beginning of the grass-growing season. The grazing season was assumed to continue as long as enough biomass was available for consumption, with all grazing stopping on 1 December, as all animals are housed by late November (Kavanagh, 2016). A single harvesting event would take place before the end of the grazing season, which harvests any surplus grass, leaving residual grass at a height of 5 cm. As recommended by Jouven *et al.* (2006a), biomass losses during grazing and harvesting events were assumed to be 10%.

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[7] Boundary data from the following sources were used: Electoral Divisions – National Statutory Boundaries – 2019 (https://data-osi.opendata.arcgis.com/datasets/osi::electoral-divisions-national-statutory-boundaries-2019/about; accessed 12 March 2024); and Wards (December 2022) Boundaries UK BFC (https://geoportal.statistics.gov.uk/datasets/ons::wards-december-2022-boundaries-uk-bfc; accessed 5 February 2024).

3.4.5 *Computer implementation*

The Python programming language[8] was used to process data, implement the grass growth model and analyse results.[9] The ModVege model used in this study was adapted from an open-source Python implementation.[10] The model was then run by iterating over each grid point, extracting the variables as daily time series data, calculating the sum of temperature thresholds defining the grass-growing and grazing seasons, and simulating grass growth for the grid point.

Estimates of the sward status were used at the beginning of the simulation. In addition, water reserves and 10-day moving average temperatures at the beginning of the simulation were also needed. The water reserves at the beginning of the simulation were assumed to equal the soil WHC, and the actual temperatures were used for the first 9 days of the simulation in place of the 10-day moving average temperatures. As the sward status was estimated, an additional year of climate data were used as inputs for the first simulation year of each model run to spin-up the ModVege model, allowing the model outputs to converge from the second simulation year.

Model outputs include daily grass growth rates ($\mathrm{kg\,DM\,ha^{-1}\,day^{-1}}$) and standing biomass ($\mathrm{kg\,DM\,ha^{-1}}$), which is the amount of grass available (i.e. not harvested or grazed) on the farm on a given day. Non-pasture areas as identified in CORINE (Coordination of Information on the Environment) Land Cover 2018 data (Copernicus Land Monitoring Service, 2020) for Ireland were masked out of maps showing the model simulation results.

3.5 Model Evaluation, Climate Data Assessment and Analysis

3.5.1 *Grass growth model evaluation*

To evaluate the ModVege model simulations, grass growth rates simulated using the MÉRA time series were resampled at a weekly frequency, averaged at county level,[11] and compared with PBI and GrassCheck NI weekly measured grass growth data. It is worth noting that, since the grass growth measurement data were generated using raw inputs by farmers, the readings may contain errors arising from visual assessments, lags in data transfers and delays or gaps in reports from individual farms (E. Ruelle, Teagasc, personal communication, September 2022). As the PBI and GrassCheck NI grass growth measurements are from managed farms, only grid points in the MÉRA dataset corresponding to pastures in the CORINE Land Cover 2018 data for Ireland were retained for comparison. The simulated and measured county-level time series of grass growth were compared. For overlapping data points, the root mean square error (RMSE) in the simulated grass growth per county was calculated, and linear regressions were performed for each season and for the overall data.

3.5.2 *Assessment of grass growth simulated using historical climate model data*

Simulations for the historical period driven by the climate model datasets were also compared with simulations driven by the MÉRA dataset to assess the results in terms of the performance of the climate model datasets in modelling grass growth. This step allowed the suitability of the climate model datasets for driving grass growth simulations to be determined. As the temporal coverage of MÉRA (1981–2019) does not match the historical reference period (1976–2005), this analysis was completed for a 25-year period (1981–2005) instead, so that data were available for both climate model and reanalysis weather datasets. The difference between the long-term averages of the simulations was then calculated and presented for each driving climate model, as well as for the ensemble.

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[8] Python website: https://www.python.org/ (accessed 5 February 2024).

[9] Code for this project is open-source and hosted on GitHub: https://github.com/ClimAg (accessed 5 February 2024).

[10] Code for the open-source ModVege Python implementation: https://code.europa.eu/agri4cast/modvege (accessed 5 February 2024).

[11] Boundary data from the following sources were used: Counties – National Statutory Boundaries – 2019 (https://data-osi.opendata.arcgis.com/datasets/osi::counties-national-statutory-boundaries-2019/about; accessed 12 March 2024); and OSNI Open Data – Largescale Boundaries – County Boundaries (https://www.opendatani.gov.uk/dataset/osni-open-data-largescale-boundaries-county-boundaries; accessed 5 February 2024).

3.5.3 Analysis of future projections of grass growth under climate change

The differences between historical and future (RCP4.5 and RCP8.5) grass growth simulated using climate model datasets were used to determine the risk to grass production from climate change. According to Green (2019), comparing grass growth in a given year with the long-term average can act as a national fodder shortage indicator. To evaluate the likelihood of fodder crises occurring in the future, changes in grass growth were identified by comparing long-term ensemble means of daily grass growth under future scenarios (2041–2070) with those of the historical period (1976–2005). As Teagasc recommends a closing farm cover of 500–600 kg DM ha^{-1} to ensure that there is sufficient grass for grazing in the following spring (Trayers, 2021), the closing farm cover in December, calculated as the long-term ensemble mean of the standing biomass in December for both historical and future reference periods, was also used as a fodder shortage indicator.

4 Evaluation of Modelled Grass Growth

4.1 Root Mean Square Error

The RMSE in predicted grass growth was used to evaluate the model performance. The RMSE was calculated using simulated grass growth driven by the MÉRA time series and the measured PBI and GrassCheck NI grass growth data at county level (Figure 4.1). This showed that, in terms of grass growth RMSE, County Leitrim and County Dublin are the two worst-performing counties, but this may be attributable to these counties having fewer measured data points. The model outputs most closely matched the reported grass growth data for counties in the south-west as well as County Donegal. The overall RMSE for all counties was 20.2 kg DM ha^{-1} day^{-1}. The RMSE also varied by season, with the overall RMSE in autumn being the lowest (14.9 kg DM ha^{-1} day^{-1}), followed by summer (22.2 kg DM ha^{-1} day^{-1}) and spring (26.9 kg DM ha^{-1} day^{-1}); winter growth was not considered, as growth rates are very low.

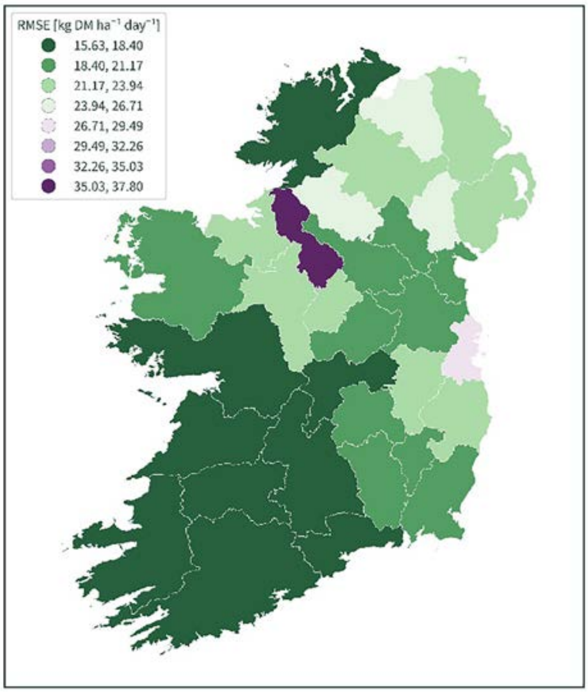

Figure 4.1. RMSE of simulated daily grass growth rates by county.

4.2 Time Series Comparison

County Wexford was used as a representative county, as its RMSE (20.3 kg DM ha^{-1} day^{-1}) is close to the overall model performance across all counties and it is a useful case study because the 2018 fodder crisis mainly impacted the south-east region of Ireland. In September 2018, 56% of farmers in the south-east reported fodder deficits, with an average reported shortage of 24% of the required level (Kavanagh, 2018). Time series plots comparing simulated and measured grass growth for County Wexford are shown in Figure 4.2. The time series plots show that the ModVege model outputs have delays in the start of the grass-growing season in spring. In comparison, the end of the grass-growing season in autumn is better aligned with the measured data, which indicates that the model predicts a shorter growing season. The peak growth values are modelled well, but spring growth is generally underpredicted. In addition, the model was found to exaggerate the effects of extreme weather events, e.g. the impact of drought on grass growth in the summer of 2018 can be seen in both simulated and measured values, but the simulated values drop to zero and do not recover to normal levels, remaining below average.

Time series plots comparing simulated and measured grass growth for the county with the lowest overall RMSE, County Kerry, are shown in Figure 4.3. Unlike County Wexford, the simulated grass growth curve for County Kerry matches the measured values very closely, with only slight underpredictions in the spring and autumn and some overprediction of peak growth. The exaggerated effects of the 2018 drought can also be seen in the simulated values.

Linear regression of simulated daily grass growth values against corresponding observations, pooled across the entire study area and all seasons, showed good overall linearity (slope = 1.0; R^2 = 0.63). When linear regression was carried out on a seasonal basis (except winter), the model performed best for autumn (September–November: slope = 0.98; R^2 = 0.58) and worst for spring (March–May: slope = 0.73; R^2 = 0.56).

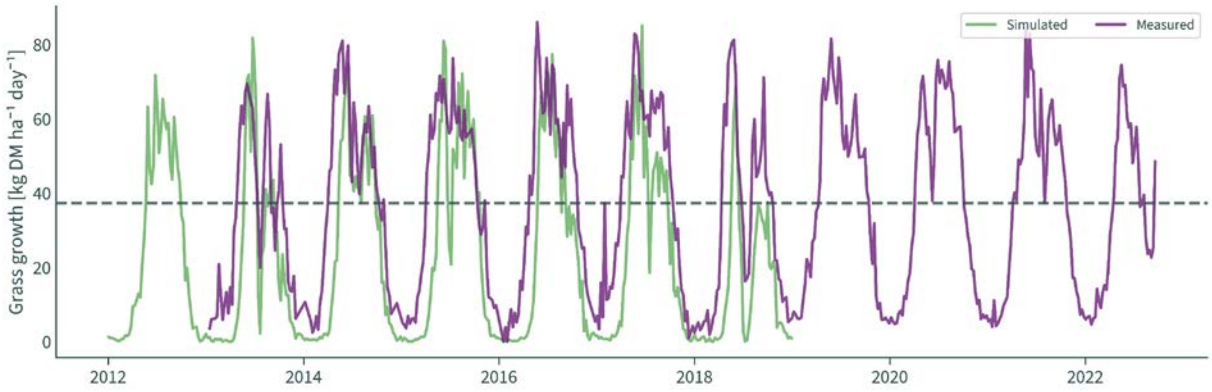

Figure 4.2. Representative weekly time series of simulated (MÉRA) and measured (PBI) daily grass growth rates for County Wexford for the years 2012–2022. The dashed line represents the average measured value.

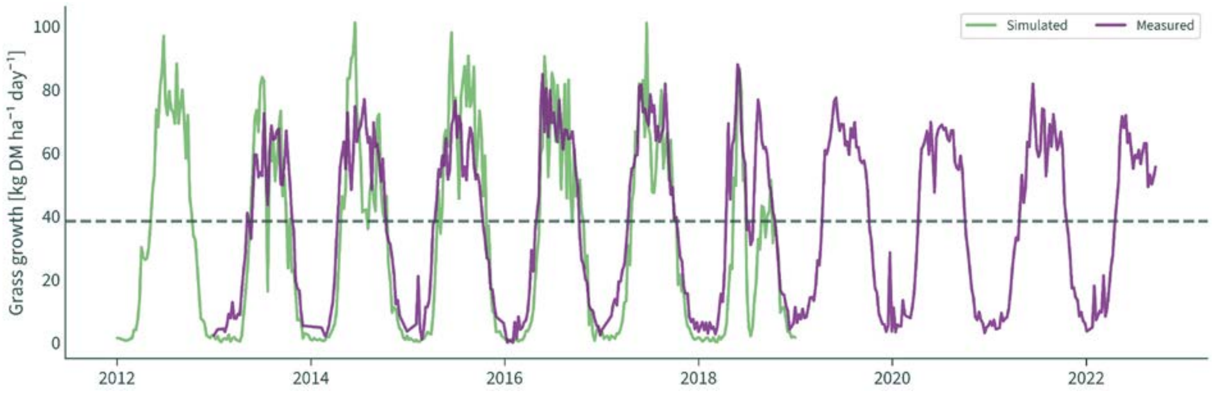

Figure 4.3. Representative weekly time series of simulated (MÉRA) and measured (PBI) daily grass growth rates for County Kerry for the years 2012–2022. The dashed line represents the average measured value.

Spring growth is delayed in the model, leading to underprediction because many of the simulated values are zero when the measured values show growth. As shown in the representative time series plots, the model may also overpredict peak growth values and exaggerate the effects of extreme weather events.

5 Assessment of Historical Grass Growth Simulated using Climate Model Datasets

Figure 5.1 shows how closely simulations of grass growth driven by climate model datasets match those driven by the MÉRA dataset for the period of overlap, 1981–2005. Simulations driven by EURO-CORDEX generally overpredict grass growth. The simulations driven by HiResIreland more closely match those of the reanalysis weather data; however, there are notable differences between results from different driving climate models. In general, there is a higher degree of confidence in the accuracy of the simulations driven by HiResIreland data than those driven by EURO-CORDEX data. The reasons for the divergent performance of the two climate models are not clear but may relate to differences in the accumulated variables (i.e. precipitation and radiation) between the two datasets; the EURO-CORDEX dataset had higher precipitation and radiation values.

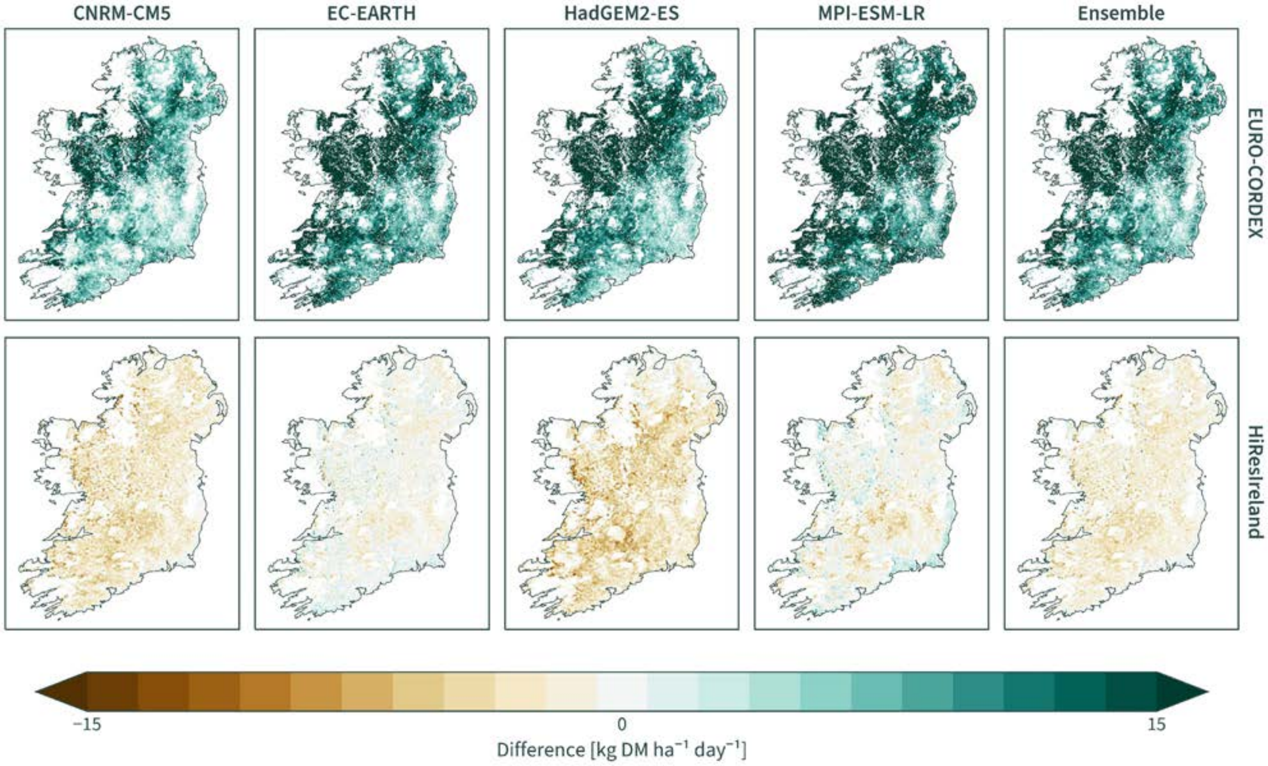

Figure 5.1. Difference in the long-term means (1981–2005) of historical daily grass growth rate simulations driven by the climate model datasets compared with those driven by the MÉRA dataset.

6 Future Occurrence and Severity of Fodder Crises under Climate Change

6.1 Annual Grass Growth Anomalies

This section focuses on differences between the means of simulated annual grass growth in the future period (2041–2070) and the historical period (1976–2005). These differences are presented as anomalies. A positive anomaly indicates an increase in annual growth under future climatic conditions, and a negative anomaly indicates a decrease. Anomalies are presented for both RCP4.5 and RCP8.5 climate change scenarios.

Figure 6.1 shows the anomalies calculated from the simulation outputs driven by two different climate model datasets under two different climate change scenarios. There are differences between the outputs from different driving climate datasets. Simulations driven by EURO-CORDEX data project an increase in future grass growth compared with the historical average throughout Ireland, except in the south-east and coastal areas in the east and south. Meanwhile, simulations driven by HiResIreland data predict a decrease in future grass growth throughout the island. The magnitude of the increase in future grass growth projected in the simulations driven by EURO-CORDEX is larger than the magnitude of decrease in future grass growth projected in the simulations driven by HiResIreland. In addition, the magnitudes of changes are larger under the RCP8.5 scenario than under the RCP4.5 scenario. As the HiResIreland data-driven historical simulations were shown to more closely match simulations driven by the MÉRA dataset (see Chapter 5), only HiResIreland-driven outputs will be presented in the remainder of this chapter.

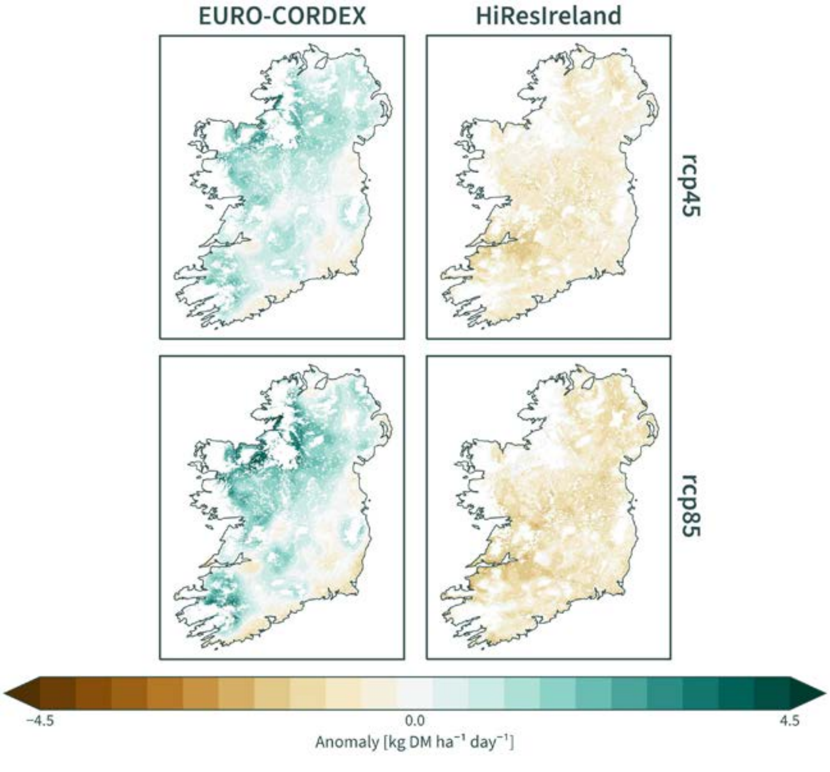

Figure 6.1. Anomalies between the long-term annual ensemble means of future (2041–2070) daily grass growth rates driven by the EURO-CORDEX and HiResIreland climate model datasets and those of the historical period (1976–2005).

6.2 Seasonal Grass Growth Anomalies

Figure 6.2 shows anomalies between seasonal grass growth rates for the period 2041–2070 and the historical period, 1976–2005, by season and climate change scenario. Winter anomalies are not shown, as growth rates were very low compared with the other seasons. Widespread positive anomalies are present in spring (MAM, March–May) and negative anomalies

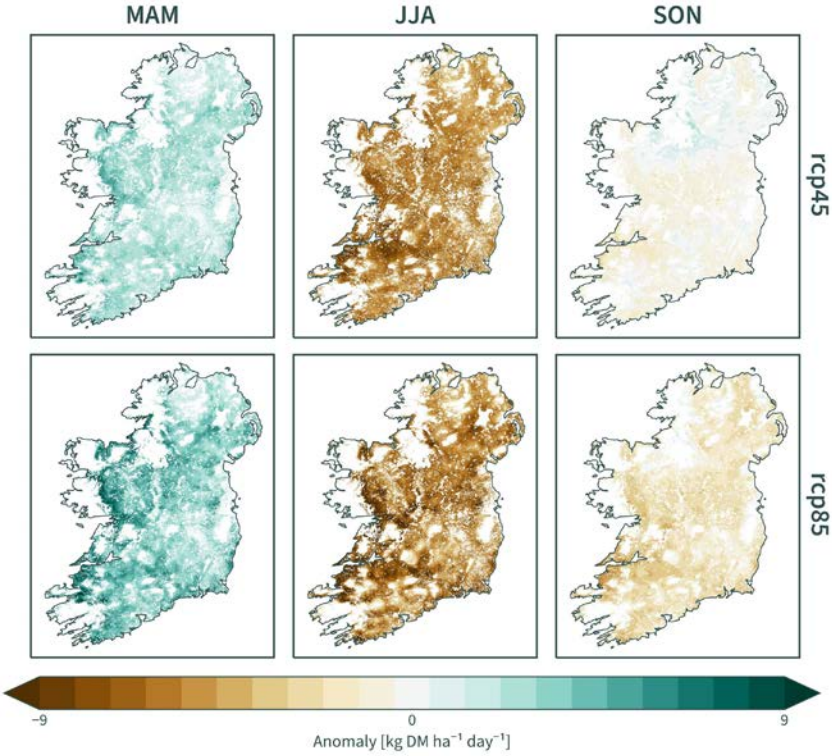

Figure 6.2. Anomalies in the long-term ensemble means between future (2041–2070) daily grass growth rates driven by the HiResIreland dataset for spring (MAM), summer (JJA) and autumn (SON) and those for the historical period (1976–2005).

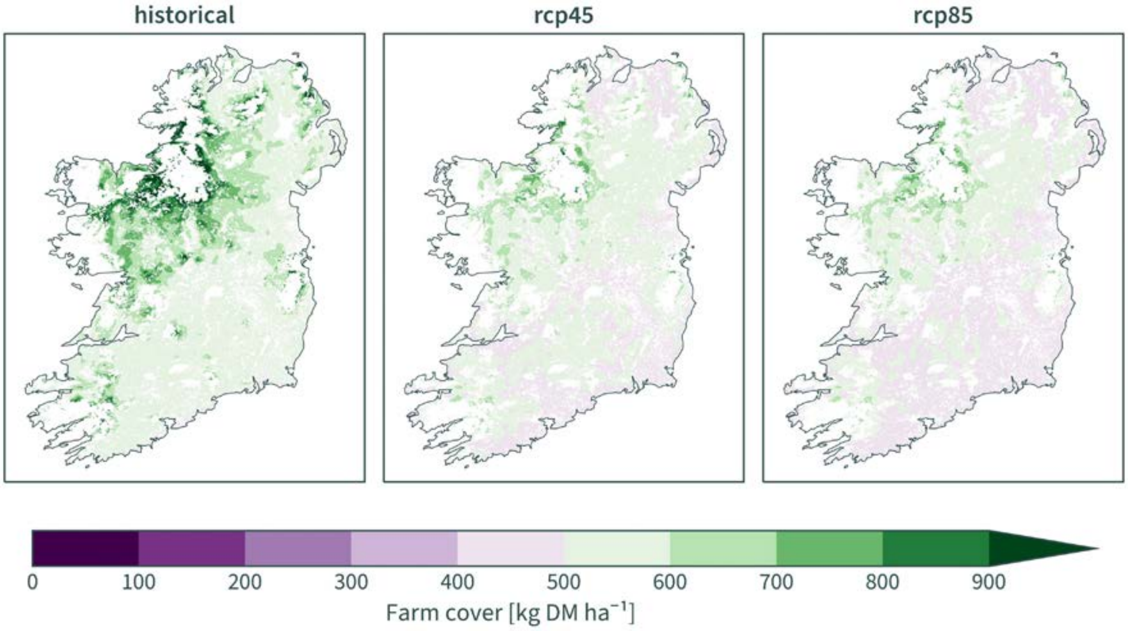

Figure 6.3. Closing farm cover in December for the historical (1976–2005) and future (2041–2070) periods under RCP4.5 and RCP8.5 scenarios, driven by the HiResIreland dataset.

in summer (JJA, June–August). This is consistent with an earlier start to the growing season and more frequent dry conditions in summer; however, some of this is probably due to the model's poor representation of the early growing season, indicating delayed growth in the model and shifting growth from the spring into the summer. Simulations generally project an increase or no change in future autumn (SON, September–November) grass growth in the north-west of Ireland, and a decrease in the rest of the island.

6.3 Closing Farm Cover

Another fodder shortage indicator used was the closing farm cover, calculated as the long-term ensemble mean of the standing biomass in December. Figure 6.3 shows that December farm cover decreases in the future period (2041–2070) under both climate change scenarios and in most areas of the country. In many areas the cover falls below the Teagasc-recommended value of 500–600 kg DM ha^{-1} (Trayers, 2021). This indicates increased vulnerability in the following year, in that spring growth may be delayed.

7 Discussion and Recommendations

7.1 Key Results

A comprehensive review of factors driving the emergence and development of fodder crisis events in Ireland was carried out. The analysis was complemented with a detailed analysis of fodder crises in the period 1946–2022, for which detailed weather and impact data are available. Blocking anticyclones leading to low precipitation and high temperatures have been identified as a driving factor in several significant fodder crisis events in the study period. Several of the most severe events were multifactorial in nature. An impact-based fodder crisis severity index was developed and used to classify past occurrences of fodder crises.

An integrated modelling framework was developed and applied to simulate future risks to fodder production in Ireland. The framework couples high-resolution downscaled climate datasets with a mechanistic, dynamic model of grass growth. The model's performance was evaluated using highly accurate MÉRA data as input and comparing the outputs with reported grass growth data from PBI and GrassCheck NI.

Grass growth simulations driven by the HiResIreland dataset better matched observed historical grass growth patterns than simulations driven by EURO-CORDEX data. There was good agreement between grass growth rates derived from on-farm reports and from model simulations driven by historical reanalysis weather data and good agreement between the reanalysis data-driven model outputs and those driven by the historical period of HiResIreland climate data.

HiResIreland data-driven simulations predict a general decrease in future (2041–2070) total annual grass growth throughout Ireland compared with the historical period (1976–2005). The decrease in annual growth rate was more pronounced in the more extreme RCP8.5 climate change scenario than in the more probable and less extreme RCP4.5 scenario. RCP4.5 corresponds to an increase in global mean temperature of 1.4°C by the mid-21st century, whereas RCP8.5 corresponds to an increase of 2.0°C.

Growth limitation due to heat stress is unlikely to occur in any area of the country, even in the worst-case future climate scenario. However, interactions between drought and heat may lead to reduced growth in particular years. The predicted effects of climate change on grass growth are spatially variable. Fodder production and pasture systems in the north-west of the country are likely to remain more resilient than in the remainder of country under future climatic conditions, and decreases in production are most likely to occur in the south-east and during summer months in parts of the mid-west.

7.2 Further Discussion

The modelling framework performed well in general. There was a linear relationship between pooled model simulations and observations of daily grass growth rates for all locations. However, deviations between modelled and observed grass growth were observed, particularly at the start of the growing season (which was delayed in the model compared with the observed start of the season). The model predictions of spring growth rates were affected by this phenomenon. The model was also found to be over-sensitive to extreme weather events.

Widespread increases in grass growth rates under future climatic conditions were predicted for spring and widespread reductions predicted for summer. While this could be consistent with an earlier start to the growing season in spring and more frequent dry conditions in summer, caution is advised in interpreting these results, as it was seen that the model can struggle to accurately reproduce grass growth in the early growing season.

Autumn growth is particularly important for predicting fodder crises, as farmers rely on late-season grass growth for the subsequent year. Simulations driven by the HiResIreland dataset projected a general decrease in autumn growth, except in the north-west of the country, where an increase was predicted. In addition, average closing farm cover in December is projected to reduce in the future period, indicating an increased risk of fodder crises in subsequent years due to reduced levels of stored fodder and potentially slower resumption of grass growth in spring.

7.2.1 Proposed improvements to the model framework

Although the model simulated overall grass growth well, further modifications to the definition of the growing season in the model should be considered to better capture seasonal growth patterns. Defining the start of the growing season by a threshold value of accumulated temperatures works well for places with long or continuous growing seasons, such as County Kerry, but less well in the more seasonally variable conditions of County Wexford. Growing season may also be influenced by other climatic factors.

Variability in county-level model performance compared with the GrassCheck NI and PBI observations, based on RMSE, may be attributable to differences in measurement techniques or the aggregation and distribution of participating farms.

There are some limitations of the approach used to model the management factors. Farms in Ireland that are advised by Teagasc may follow several grassland management plans for each grass-growing period (Teagasc, n.d.). Between November and February, there is very little grass growth; therefore, to ensure that there is sufficient grass for grazing in the following spring, farmers are advised by Teagasc to grow and reserve grass in autumn, specifically in October, which can be achieved using the 60:40 autumn rotation planner (Trayers, 2021). The Teagasc-recommended closing farm cover is 500–600 kg DM ha^{-1}, which is equivalent to a residual grass height of 6 cm (Trayers, 2021). However, the model used in this study maintains a minimum residual grass height of 5 cm and harvests all surplus grass at the end of the grazing season. Further modifications to the harvesting and grazing functions of the model are required to more accurately portray the seasonal management regimes recommended by Teagasc for Ireland.

7.3 Recommendations

Based on the findings of Chapter 2, it is clear that many of the most severe fodder crises are multiannual in nature. The findings of this study also indicate an increased risk in future to the resilience of pasture systems from reductions in autumn growth and reduced cover at the end of the growing season, particularly in the south-east. Therefore, measures should be considered to mitigate such effects, e.g. earlier autumn closure or an increase in stored fodder provision.

An early warning system based on inputs such as autumn growing conditions and stock levels should be investigated to reduce the risk of low growth rates the following spring developing into a crisis situation if the weather conditions become unfavourable. If seasonal ensemble weather predictions become routinely available in the future, they could be used as inputs to the modelling framework developed in this project as a basis for an early warning system.

Multispecies swards offer clear environmental benefits, such as allowing lower nitrogen inputs. There is also some evidence that multispecies swards may be more resilient to droughts. The effect of sward composition on drought resilience should be considered in further research.

There is a need for a harmonised all-island approach to recording pasture grazing to allow consistent validation of model outcomes. Any new approach developed should also be backwards compatible, as far as possible, with the existing PBI and GrassCheck NI methods to allow consistency over long timescales.

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Abbreviations

CMIP5	Coupled Model Intercomparison Project Phase 5
CORINE	Coordination of Information on the Environment
ESDAC	European Soil Data Centre
EURO-CORDEX	Coordinated Downscaling Experiment – European Domain
INRAE	French National Research Institute for Agriculture, Food and the Environment
JJA	June–August (summer)
LAI	Leaf area index
LU	Livestock unit
MAM	March–May (spring)
MÉRA	Met Éireann Reanalysis
NNI	Nitrogen nutritional index
PBI	PastureBase Ireland
RCM	Regional climate model
RCP	Representative Concentration Pathway
RMSE	Root mean square error
SEA	Seasonal effect
SON	September–November (autumn)
ST_1	Sum of temperature threshold at the beginning of the reproductive period
ST_2	Sum of temperature threshold at the end of the reproductive period
WHC	Water-holding capacity

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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