# Mechanistic Modelling of Bioenergy Resource Potential in Ireland

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# 1. Introduction

The literature review from IE-NETs WP1 (Price et al., 2018) concluded that a preferred strategy that emerges for deploying NETs in Ireland appears to be to maximise afforestation and reafforestation (AR), with minimal harvesting, in the immediate term (perhaps up until 2035) while supporting the development of BECCS, with the view of allocating AR harvest biomass to BECCS when CCS costs are lowered and/or AR stocks (land, biomass and soil) have saturated. However, it must be emphasised that this would rely on little or no harvest of the accumulating forest biomass during this period (for any purpose that could not guarantee the continued long term preservation of the captured carbon stock), which would imply fundamental changes in current AR support policies. However, current policies are failing to recognise that removing forest carbon stocks for bioenergy leads to an initial increase in emissions and that the periods during which atmospheric $CO_2$ levels are raised before forest regrowth can reabsorb the excess emissions are incompatible with the urgency of reducing emissions to comply with the objectives enshrined in the Paris Agreement. Therefore, avoiding biomass uses which are worse for the climate than fossil fuels requires new international governance systems to be established which regulate out high-risk feedstocks and ensure best practice (e.g. use of organic wastes and genuine agricultural or forestry residues, and certain perennial crops grown on marginal land). Applying stricter governance to limit feedstocks to those with short payback periods may thus have substantial implications for the industry and limit its scale, presenting governments and regulators with a major challenge. Nevertheless, the alternative is to see further expansion in a practice which is not only economically expensive but fails to achieve the core objective of renewable energy policy to reduce GHG emissions.

Bioenergy is a term used to describe any kind of renewable energy generated from material derived from recently living organisms which includes any plants, animals and their by-products. Bioenergy use today is being increasingly expanded to provide not only sustainable alternatives to fossil fuels but also additional income for rural communities where jobs are generated through feedstock production and harvesting on farms, and in transport and processing (EASAC, 2012). Of the renewable energy options, biomass is arguably the most flexible. Biomass can provide energy in solid, liquid and gaseous forms. Energy can be released by combustion of solid biomass. Combustion of biomass, often burned together with coal, generates electricity and electricity/steam in district heating systems proved for office and apartment buildings.

Biomass can also be converted to liquid fuel and biogas, referred to collectively as 'biofuel', which can be used in a range of already developed facilities from single-family units up to industrial scale. Biogas is also produced by fermentation of biomass. Biogas is a mixture of methane and $CO_2$ produced by anaerobic digestion of biomass raw materials which can be used to generate electricity or can be upgraded to methane to use in transportation. As future increases in global average temperature will be determined largely by the cumulative emissions of $CO_2$ it will be necessary for net global $CO_2$ emissions to reach near zero in order to limit temperature change. However, a number of Net Emissions Technologies (NETs) are likely to be important in reaching net zero emissions to counterbalance from continued greenhouse gas (GHG) emissions from other activities including food production.

So-called Bio-Energy with Carbon Capture and Storage (BECCS) is recognised as one of the more plausible potential technological pathways to achieve net negative emissions at significant global scale within this century (Smith et al. 2015). Among currently considered NETs, BECCS is particularly relevant to Ireland given the potential to substitute indigenous bio-energy for imported fossil fuel energy, thus enhancing energy security, balance of trade, and indigenous employment (assuming internationally competitive biomass production costs). However, it is unclear whether the possible indigenous biofuel production capacity could be sufficient to achieve net negative emissions (after economically preferred allocation to displacement of direct fossil fuel use in heating and transport, which would be expected to have lower marginal abatement costs than bio-energy electricity generation with or without CCS). Importation of biofuel to support BECCS operations in Ireland can also be considered; however, that would forfeit the economic co-benefits of indigenous biofuel production (security, employment etc.). International trade and emission accounting rules (to reflect the implied territorial separation of atmospheric drawdown and long-term storage) are also currently unclear. Accordingly, assessment of maximum feasible indigenous biofuel production is an essential component of assessing the potential for effective BECCS deployment in Ireland.

Biofuel crops can take many different forms and can be utilised in a variety of ways from simple combustion to complex bioconversion processes. At present, most of the so-called 'first generation' feedstocks for biofuel production are produced from crops that are used primarily for food production (for example sugarcane and maize), but this is unsustainable given the need to increase food production to feed increasing global populations. The three distinct goals associated with development of biofuel feedstocks are: maximising the total amount of biomass produced per hectare per year, maintaining sustainability while minimising inputs, and maximising the amount of fuel that can be produced per unit of biomass. The grand challenge for biomass production is to develop the second generation energy crops which have a suite of desirable physical and chemical traits which enable them to meet these goals. Furthermore, in order to reduce competition with food crops for land use it is likely that these crops will be grown on marginal land ( Jones et al. 2015), defined as 'an area where a cost-effective agricultural production is not possible, under given site conditions (e.g. soil productivity), cultivation techniques, agricultural policies as well as macro-economic and legal conditions'.

It is now widely recognised that perennial rhizomatous grasses (PRGs), such as *Miscanthus,* possess these desirable characteristics and it is likely that they will become the dedicated bioenergy crops for the future. The most productive of the PRGs have $C_4$ photosynthesis, a particular type of photosynthesis which uses light, water and nutrient resources very efficiently. Currently, the second generation bioenergy crops are largely undomesticated and have not been subject to centuries of improvement, as have our major food crops. Breeding of appropriate species and genotypes to suit specific climates and soil conditions will be required.

The aim of WP2 is to use state of the art mechanistic modelling to estimate realistic yields of perennial rhizomatous grasses, including *Miscanthus* and short rotation forestry (willow) for coterminous Republic of Ireland. Compared with long established food crops, productivity trials of *Miscanthus* and willow are limited in number and extent. In introducing dedicated energy crops it is important to be able to forecast their productivity and stability under a wide range of different environments including changing climate, with a particular emphasis on marginal land. There is therefore a need to develop and parameterise crop models that can provide reliable predictions of carbon assimilation, growth and yield of *Miscanthus* (Robertson et al. 2015) In this modelling process the productivity trials still play an important role in validating the outputs from the models.

Nair et al. (2012) carried out a survey of the literature and identified 14 models that have been used to simulate bioenergy crops. All of them simulate biomass production, but only a small number simulate soil water, nutrient, and carbon cycle dynamics and could be classified as ecosystem models. Broadly speaking, models have been developed using either an empirical or mechanistic approach or a hybrid of the two.

## 1.1 Empirical models

An empirical approach involves statistical extrapolation of plot measurements to larger areas. For example Richter et al. (2008), developed an empirical yield model based on a multiple regression of experimental yields from 14 experiments across 10 different sites in the UK, with soil available water capacity (SAWC) and long-term monthly climate data (precipitation, temperature, radiation) for each field. Harvestable yields of *Miscanthus* established for at least three years across the UK ranged from 5 to 18 Mg $ha^{-1}$ and the overall national average yield was 9.6 Mg $ha^{-1}$. They concluded that in the UK, *Miscanthus* yields are clearly water-limited in many areas and that spatial and temporal variation in yield can be explained by water availability. Richter et al., (2016) combined empirical yield modelling with soil mapping and remote sensing (satellite imagery) to assess on-farm productivity of *Miscanthus* and used on-farm yield surveys at the field and farm scales to verify outputs of the productivity models which had been parameterised and validated using experimental plot-scale observations. This work identified a 'yield gap' between the actual achievable on-farm yields and the model predictions. The actual on-farm yields averaged around 9.0 Mg $ha^{-1}$, with a coefficient of variation of 34%, while the yield potential estimated using the empirical model averaged 11 Mg $ha^{-1}$. The yield-gap was larger on clay soils than on sandy or loamy soils (37% v 10%). It was concluded that overall in the UK, heavy soils are potentially the most productive with yields greater than 16 Mg $ha^{-1}$ but they also had the most variable stand density (patchiness) which is most likely influenced by wet and dry soil at planting. This patchiness was a cause of reduced yields.

## 1.2 Hybrid models

Many models actually cross the boundaries between empirical and mechanistic models. A modelling and mapping system that falls into this category is called PRISM-ELM and has been developed by Daly et al. (2018). PRISM-ELM is a hybrid model that uses both empirical and mechanistic approaches to determine how climate and soil characteristics affect the spatial distribution and long-term production patterns of potential biomass resources across the coterminous United States. However, unlike mechanistic models this approach does not require detailed data on plant characteristics and physiology. Daly et al. (2018) suggest that this form of hybrid model is becoming more powerful as high quality climate, remote sensing, land-use and soils data becomes available. The hybrid model employs a limiting factor approach, where productivity is determined by the most limiting of the factors addressed in sub-models that simulate water balance, winter low-temperature response, summer high-temperature response, and soil pH, salinity, and drainage. Yield maps are developed through linear regressions relating soil and climate attributes to reported yield data. The conclusion from this modelling exercise was that the yield projection maps of Miguez et al., (2012) should be revised to show the greater regional suitability of *Miscanthus.* The resulting maps are used as inputs to analyses comparing the viability of a range of biomass crops, including *Miscanthus*, under various economic scenarios across the United States. In general PRISM-ELM maps show regional patterns that are more similar to those produced by mechanistic models than with statistical models, probably as a result of more effective treatment of water balance and effects of water stress (Daly et al., 2018). The areas of greatest disagreement among models are located along the edges of the crop's distribution, where validating field trials are largely absent.

## 1.3 Mechanistic models

In mechanistic models, predictions of yields are developed from first principles of plant processes including photosynthesis, respiration and assimilate distribution. The theoretical potential yield of a crop is controlled only by the biophysical limits in the location it is cultivated, so that the model is driven by environmental and edaphic parameters. At larger scales ecosystem process-based models have been developed to simulate ecosystem carbon, nitrogen and water dynamics through the descriptions of physiochemical processes. Such models can be used to extrapolate crop performances from farm scale to regional scales to assess global scale production potential and the environmental impacts of energy systems. Generally, these models have similar process descriptions but the parameters in the models can be adjusted to match the site specific data.

An early attempt at mechanistic modelling of *Miscanthus* was MISCANMOD, developed by Clifton-Brown et al. (2000). This was a simple spreadsheet-based model, using the robust and straightforward approach of assuming that there is a direct link between intercepted radiation, radiation use efficiency and total biomass production over the annual growth period as demonstrated by Monteith (1977). Radiation use efficiency is defined as biomass produced per unit of intercepted photosynthetically active radiation (g $MJ^{-1}$). MISCANMOD was applied across Europe to predict biomass production of *Miscanthus*.

When the MISCANMOD model was used to explore the likely productivity of *Miscanthus* in Illinois in the Midwestern US, projections of peak annual biomass prior to senescence ranged from 27 to 44 t $ha^{-1}$ (Heaton et al., 2004b). A meta-analysis of the effects of management factors on *M. x giganteus* growth and biomass production in Europe (Miguez et al., 2008), has shown that one of the simplest models for predicting potential biomass production based on the thermal units accumulated during the growing season provides a remarkably good fit to the observed data. The data indicate that once the normal agronomic practices such as weed control and water availability are in place, temperature accounts for most of the variation in growth patterns.

The critical factors in the development of these mechanistic models to determine yields of *Miscanthus* for different climatic conditions are variation in radiation use efficiency with soil water availability, temperature and drought as well a frost tolerance. Models are being continuously improved to increase their applicability in a wider range of environmental and management scenarios. For example, Hastings et al., (2009a) developed a new model called MISCANFOR that is based on the same processes as MISCANMOD but with improved descriptions of light interception by the canopy and the impact of temperature and water stress on the radiation use efficiency in photosynthesis. They also added genotype specific descriptions for the plant growth phase, photoperiod sensitivity, frost-kill predictions, nutrient repartitioning to the rhizome and moisture content at harvest. When predictions made with MISCANFOR were compared with MISCANMOD for 36 experimental data sets for a wide variety of soil and climate conditions in Europe, MISCANFOR matched field experiments with an $r^2$ of 0.84 compared with 0.64 for MISCANMOD. Furthermore, the comparisons between the two models using the mean weather conditions for the period 1960 to 1990 in Europe showed that the previous estimates of peak yield made with MISCANMOD had been underestimated in the temperate regions by 20% and grossly overestimated yields in the arid regions. In order to assess the impact of future climate on

*Miscanthus* production MISCANFOR has also been run forward for 2020, 2050 and 2080 using IPCC climate projections (Hastings et al., 2008). In order to achieve maximum energy yield with minimum GHG emissions only arable land that is surplus for food production was used for biofuel production.

Robertson et al. (2015) identified five ecosystem models, incorporating carbon cycle dynamics and in particular the soil carbon dynamics, and parameterised for *Miscanthus.* These are: WIMOVAC (Miguez et al. 2009), BioCrop (Miguez et al. 2012), Agro-IBIS (VanLoocke et al. 2010), DayCent (Davis et al. 2010) and DNDC (Gopalakrishnan et al. 2012). Of these models, WIMOVAC, BioCro and Agro-IBIS were originally created to simulate biomass production, but subsequently had soil biochemistry and soil carbon transformations incorporated in their simulations. Conversely, DayCent and DNDC were originally designed to simulate belowground nutrient cycling but subsequently more complex plant growth routines were incorporated. The justification for the requirement of the models to simulate carbon dynamics was because assuring the commercial viability of a *Miscanthus* plantation and assessing its impacts on greenhouse gas emissions are essential before a landowner can decide whether to establish *Miscanthus* at the expense of other income generating land uses. A review of the five process-based crop models parameterised for *Miscanthus* found that they differed both in their design, computational power and spatial scale but none was vastly superior and the main differences were their ability to deal with the specific research questions they were designed for.

Increasingly, the outputs from these ecosystem models are being incorporated into coarser, global-scale integrated assessment models (IAMs) that perform cross-sectoral cost optimisation analyses. The IAMs are a suite of tools developed jointly by scientists and economists to answer central questions about climate change, from how the world could avoid 1.5$^{o}$C of global warming at the lowest cost, through to the implications of countries' current pledges to cut emissions. In relation to bioenergy crops, this integration enables an assessment of the potential for bioenergy and carbon capture and storage (BECCS) to contribute to GHG mitigation alongside competing energy technologies and other measures.

# 2. Methods

Through collaboration with Dr. Astley Hastings (University of Aberdeen) we employed the MiscanFor productivity model, first published in 2009 (Hastings et al, 2009), This model has previously applied in a more coarsely grained form across Europe, as well as the Central Valley of California, USA and North Island New Zealand. Figure 1 shows the major data inputs, calculation stages and outputs.

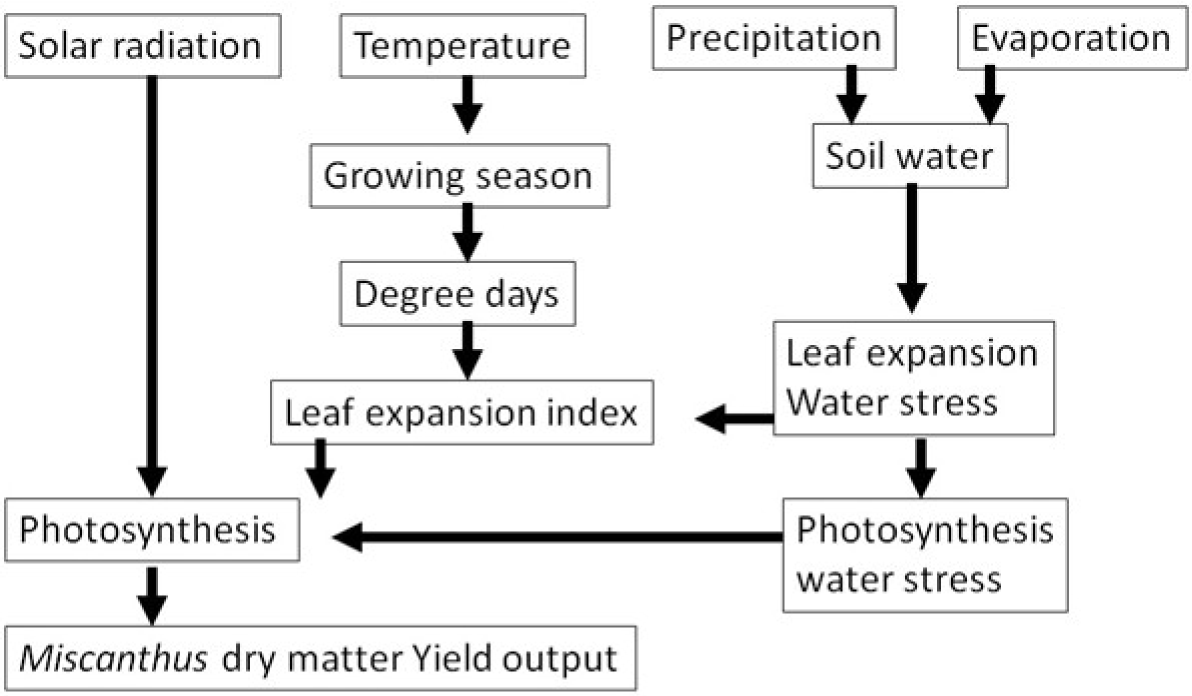


**Figure 1:** Block diagram of MiscanFor plant growth model showing the major data inputs, calculation stages and outputs.

For details of the Miscanfor model see Hastings et al., (2007). The model was designed to create data to be converted to rasters for visualisation as maps. The model was calibrated across Europe using daily growth measurements in Ireland, Denmark, Germany, and the Netherlands with monthly measurements of yields and meteorological data from crop experiments in Sweden, Portugal, Greece, Italy and England. To validate the model the outputs were compared to field experiments using the site specific meteorological data and the measured soil parameters and the daily incremental crop yield was compared to incremental harvests made during the growing season. The MiscanFor model was run using the 0.5 degree grid of future climate scenario data which provides climate projections for the four IPCC emission scenarios for the period 2000 to 2100 and yield maps are compared for time slices at 2020, 2050 and 2080.

The model has been under continuous development since 2009, including:

- Model parameterised for both willow and poplar.
- Model parameterised for different genotypes of *Miscanthus* and willow.

- Modelling framework has been developed to map at a resolution of 1 $km^2$ the expected yields of both *Miscanthus* and willow.
- Enabled different meteorological data to be used including CRU 4.1 and the RCP2.6 scenarios.

Further developments that have been incorporated recently are:

- Adding a lapse rate correction for altitude and a data set to estimate ground water support.
- Adding a soil carbon model and a life cycle assessment model to be run spatially at the 1$km^2$ grid.
- Adding a "click and point" graphical "user friendly" human interface to enable non specialist used to predict growth in any country in the world.

The yield simulation model MiscanFor (Hastings et al., 2008), now parameterised for *Miscanthus* and willow, was used to project Irish specific *Miscanthus* and SRCW dry matter yields, at a resolution of 1 $km^2$. The model was run using climate data for current climatic conditions using University of East Anglia Climate Research Unit (CRU) (Hastings et al., 2008) CRU 4.2 scenario. Data for the soil parameter input to MiscanFor was obtained from the Food and Agriculture Organisation of the United Nations 'Harmonised World Soil Database (HWSD) v 1.2' (FAO, 2019). Change in *Miscanthus* yield in Mg $ha^{-1}y^{-1}$ from today to 2050 was run with the RCP 2.6 scenario climate from the HADGEM model.

# Results and Discussion

Yield maps for the island of Ireland derived from the MiscanFor outputs are shown as Figures 2 and 3. The maps show that under current climate the maximum projected yields of *Miscanthus* are 24 t $ha^{-1}$ $yr^{-1}$ while the maximum yields of Willow are 16 t $ha^{-1}$ $yr^{-1}$. The areas where maximum yields of both *Miscanthus* and Willow occur are in the south and south-east of Ireland. For *Miscanthus*, 37% of the land would produce very low or no viable yields of less than 8 t $ha^{-1}$ $yr^{-1}$. Of the remaining 63% of land cover, then 33.4% is in the range from 12-16 t $ha^{-1}$ $yr^{-1}$. Table 1 shows the proportion of land cover producing yields in yield -categories in increments of 4 t $ha^{-1}$ $yr^{-1}$, and Table 2 shows the same analysis for Willow.

**Table 1.** *Miscanthus* yield (t $ha^{-1}$) categories and proportion of total land area (%) per category.

| | **Yield category (t $ha^{-1}$ $yr^{-1}$)** | | | | | |
|---|---|---|---|---|---|---|
| | 0-4 | 4-8 | 8-12 | 12-16 | 16-20 | 20-24 |
| **% of total area** | 36.76 | <1 | 26.78 | 33.41 | 2.50 | <1 |

When Hastings et al. (2008) ran MiscanFor for the entire European Union 27 the mean peak yields was 16.3 t $ha^{-1}$ $yr^{-1}$ with a standard deviation of 2 t $ha^{-1}$ $yr^{-1}$ due to interannual variation in climate. Yields in Ireland are therefore somewhat lower than the average across Europe as anticipated by the lower mean summer-time temperatures.

The distribution of the highest willow yields reflects its greater tolerance of cool and moist conditions so that, in Ireland, despite the model predictions which show that *Miscanthus* can, in suitable locations, significantly out-yield willow it is likely that willow will be the preferred energy crop in cooler and wetter parts of the country. Areas with an annual rainfall of 900-1000 mm appear to be optimal for willow production, as well as areas where the crop has access to ground water (Caslin, 2010).

**Table 2.** Willow yield (t $ha^{-1}$) categories and proportion of total land area (%) per category.

| | **Yield category (t $ha^{-1}$ $yr^{-1}$)** | | | | | |
|---|---|---|---|---|---|---|
| | 0-4 | 4-8 | 8-12 | 12-16 | 16-20 | 20-24 |
| **% of total area** | 0.77 | 13.27 | 71.65 | 14.3 | - | - |

Although, in the current exercise, willow yields in Ireland have been projected using MiscanFor the model has not, so far, been run for the whole of Europe. Consequently, comparisons of the differences in productivity between *Miscanthus* and willow across the European continent are difficult to make. Mola-Yudego and Aronsson (2008) have developed a willow productivity model for biomass plantations in Sweden and have shown that for the best growers, they are able to achieve from 5.4 to 7.1 t $ha^{-1}$ $yr^{-1}$ in 4-year rotations of the second cutting cycle. These yields are close to those predicted for most of Ireland. Mola-Yudego and Aronsson (2008) point out that numerous studies have shown higher rates of production of willow, up to as much as 30 t $ha^{-1}$ $yr^{-1}$, but these were for intensively irrigated and fertilised research plots in southern Sweden. They suggest that such findings may have contributed to over-optimistic predictions of the yield in willow plantations.

High resolution mapping of the potential productivity of *Miscanthus* and Willow show that large areas of the island can produce economically viable yields. The threshold for economic viability is difficult to determine, but yields of at least 8 t $ha^{-1}$ $yr^{-1}$ could offer sufficient income for land-owners given appropriated subsidies. Physiological studies show that *Miscanthus* and willow have different optimal temperatures for growth and it would be expected that willow would be better suited than *Miscanthus* to a cooler and wetter climate. The yield maps confirm this with *Miscanthus* producing maximum yields 50% higher than willow.

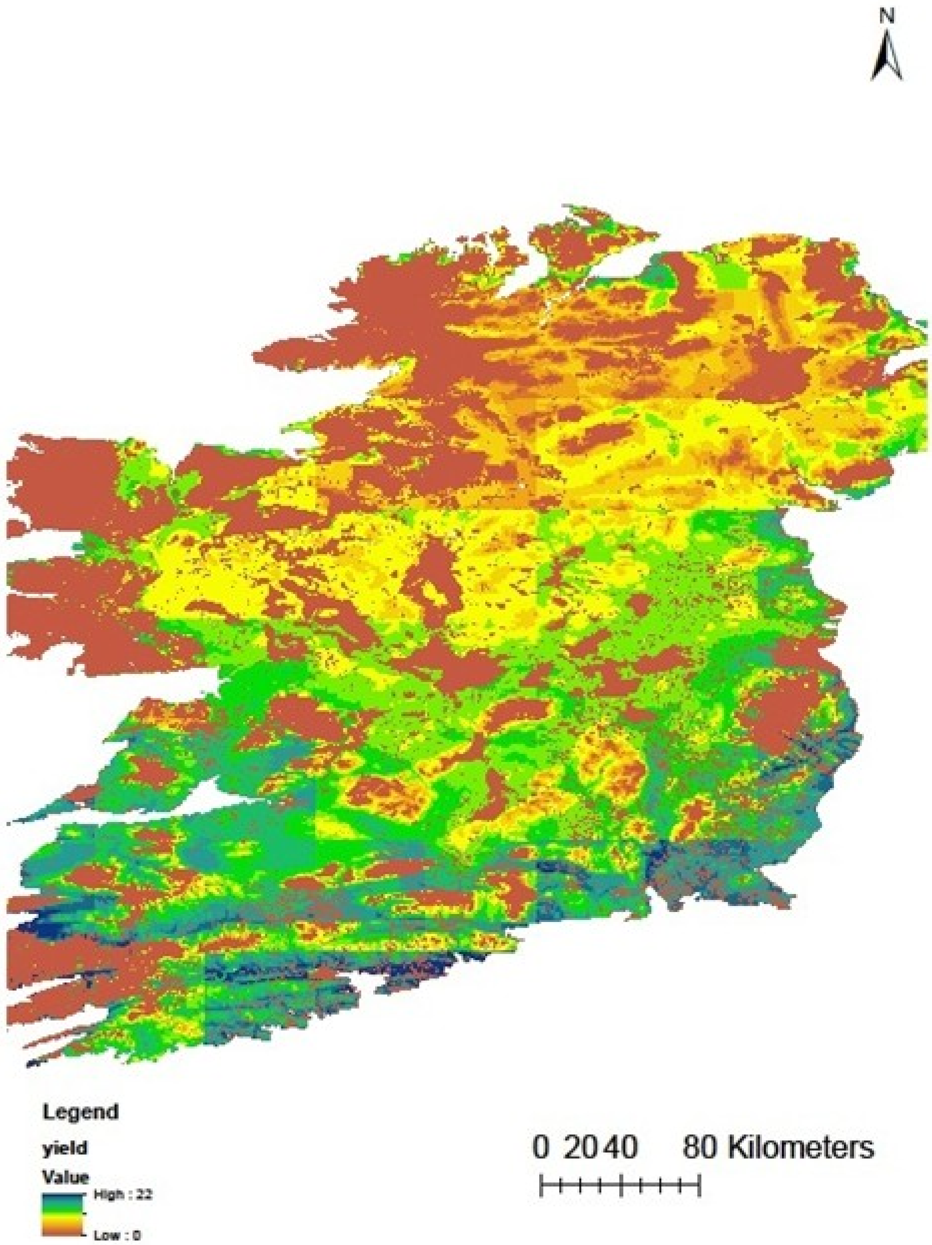


**Figure 2:** Map of potential yields (t $ha^{-1}$ $yr^{-1}$) *for Miscanthus* under current climate, using the MiscanFor model.

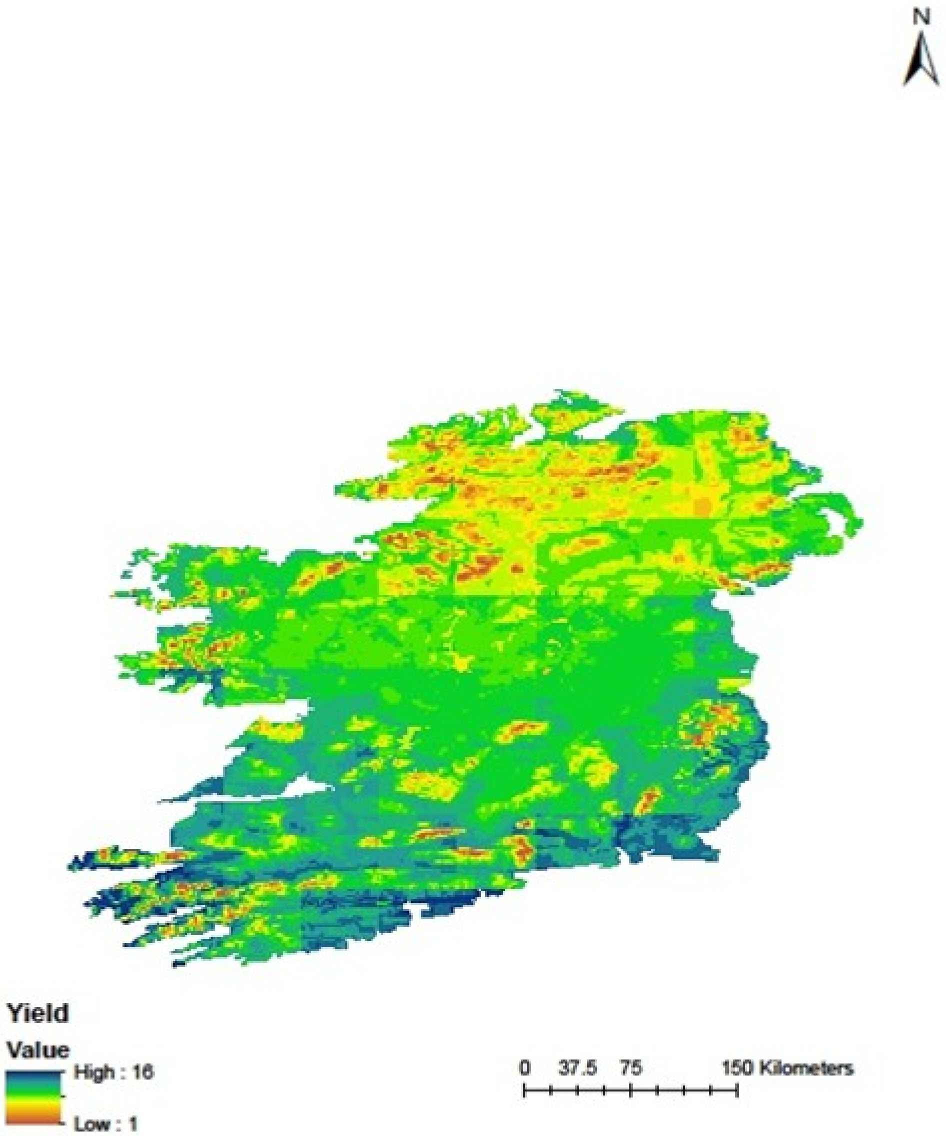


**Figure 3:** Map of potential yields (t $ha^{-1}$ $yr^{-1}$) *for Willow* under current climate, using the MiscanFor model.

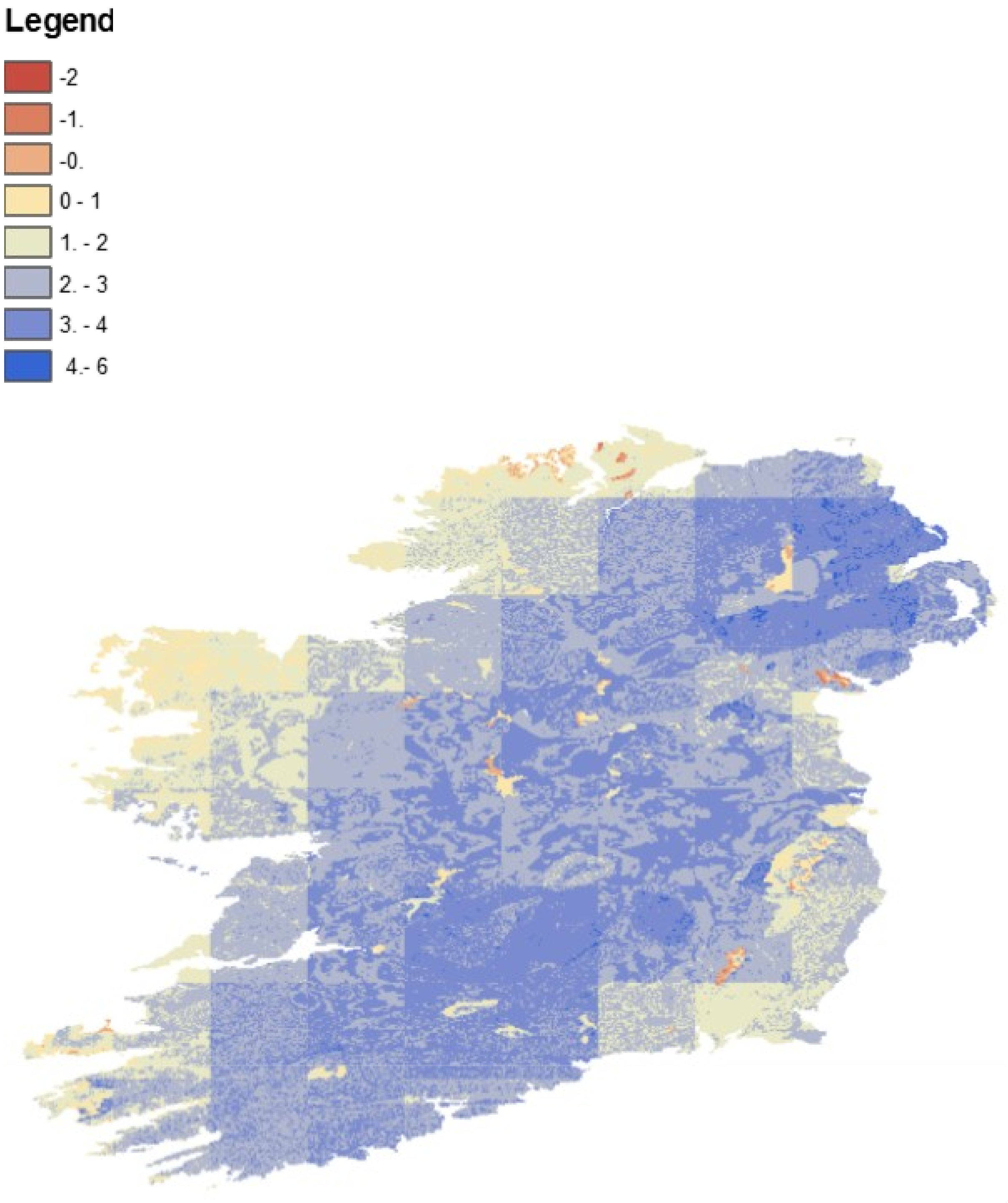


**Figure 4:** Change in *Miscanthus* yield in t $ha^{-1}y^{-1}$ from today to 2050 with the RCP 2.6 scenario climate from HADGEM model.

The high resolution mapping possible with MiscanFor has shown for the first time details of the potential yield distribution of second generation biomass crops across Ireland. Previous yield predictions have been at much coarser spatial scales (eg. Stampfl et al., 2007) and in many cases they have assumed a single average yield across the whole of Ireland. Using this information we are now in a position to identify the most suitable areas for growing *Miscanthus* and willow and make more reliable predictions about potential yields. This information is crucial for life cycle and economic assessments. Nevertheless, it should be recognised that the model output is a potential yield which is very likely to exceed the realised yield on a farm. The model assumes that the land is managed optimally to achieve a potential yield but the realised outputs will be lower and dependent on any deficiencies in less than optimal management.

Crop yields are strongly dependent on prevailing weather conditions so that the interannual variations in climate will inevitably result in variations in yield from year to year. One of the important uses of dynamic models such as MiscanFor is to examine the impacts of these year to year variations in climate. This has been beyond the scope of the model runs reported here but it will be important to assess these impacts in the future. However, we have examined the longer term impacts of predicted climate change on *Miscanthus* and simulated yields using the RCP 2.6 scenario climate from HADGEM model. Figure 4 shows the projected changes in yield between today and 2050 for *Miscanthus*. In general they show a projected increase in yields of up to 6 t $ha^{-1}y^{-1}$ by 2050. This presumably reflects the temperature driven increase in length of the growing season as the climate warms but it also shows that the predicted changes in rainfall have a limited impact on yield. The map of the distribution in yield changes also indicates that in the SE of Ireland there will be less of an increase and in some limited regions a decrease in yield. This is likely to reflect the possibility of increasing drought in this region as a result of lower summer rainfall by 2050.

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