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Definition of agroclimatic regions in Ireland using hydro-thermal and crop yield data

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Abstract

When compared to the agronomic aspects of agriculture the contribution of climate is poorly integrated into the body of scientific knowledge in Ireland. It is known that specific crops grow well in specific regions and that success of a crop can be related to climate factors. The aim of this paper was to derive agroclimatic regions of Ireland using hydro-thermal climate (as expressed by climographs using mean monthly rainfall and temperature) in conjunction with a statistical clustering technique (*k*-means clustering) to relate crop yield, estimated using mathematical simulation models for grass, barley, maize, potato and soybean to hydro-thermal climate data. A dataset, on a 10 km × 10 km grid, consisting of monthly radiation, rainfall, maximum temperature and minimum temperature was used to drive crop simulation models to predict average yields, for each grid square. Results showed that the crops simulated were sensitive to either available water or length of growing season. As there are few objective measures of the ideal number of clusters to use in order to create agroclimatic regions, clusterings to 3, 4 and 7 regions were evaluated against known properties of the Irish climate and crop responses. A seven cluster agroclimate region map was thought to be a good basis for describing Ireland's agroclimates and was compared with climate data for the national synoptic station network. Results suggested a reasonably good correspondence between clusters and their associated synoptic observation stations. Some anomalies were observed. The resulting agroclimatic map could be used for extrapolation of empirical research findings, for agri-environmental experimental design and as a framework for assessment of the impact of climate change on Irish agriculture.

Keywords: Agroclimate; *k*-means clustering; Climograph; Ireland

1. Introduction

Climatology is the scientific study of climate: the distribution and regional pattern of weather. Climate includes concepts of mean values of weather variables determined over long time periods (usually 30 years or more) as well as the probabilities of the occurrence of specific events (e.g. storms, specific winds, cyclones). Integrated into the concept of climatology is the notion of the weather's "... contribution to the environment of life" (Monkhouse and Small, 1978). In other words climatology should include ideas of how weather affects biological function. In the case of agriculture, agroclimatology is specifically concerned with understanding how climate influences agricultural production. An agroclimatic region can be defined as a zone with a characteristic interrelationship between

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agronomy or farming system and climate (White et al., 2001).

In the 1960s, scientists considered that agricultural research was well advanced. There was much descriptive science (biology, chemistry and physics) detailing the integration of soils, plants, diseases and pests which has formed the bases of extensive empirical experimentation that in turn gave rise to a body of information for agricultural management (Bunting, 1968). Compared to the agronomic aspects of agriculture, the contribution of climate was poorly integrated into the scientific domain. Most farmer or advisory knowledge was descriptive and locally based. Since that time there has been a significant increase in our knowledge of crop interaction with weather to the point where mathematical models (empirical or mechanistic) can be used for simulation and prediction (Holden, 2001). Plant (and animal) growth models take a general form:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = f(W, P, E_{\mathrm{M}}, E_{\mathrm{W}}) \tag{1}$$

where W is weight, t the time, P are properties of the organism, E_{M} are controllable environmental variables and E_{W} weather variables (France and Thornley, 1984). Such models, once applied to specific crops, can be used for research, management and policy planning. General growth models provide a method of integrating climate data with agricultural systems in order to establish the interrelationshp between the two; it is therefore possible to use simulation models as the basis of the definition of agroclimatic regions (White et al., 2001)

Keane (1986) pointed out that specific crops grow well in specific regions and that success of a crop can be related to climate factors (e.g. frequency of frost damage, growing season length, total rainfall), physical factors (e.g. soil, slope, aspect) and economic factors (i.e. all the aspects included in Eq. (1)). He suggested that a better understanding of the interaction of plants with soil and weather would allow better management decisions; such understanding is necessary on a regional scale. White et al. (2001) suggested that in developing countries, research efforts and investments be targeted at specific agroclimatic zones where the maximum benefit can be derived. For this to occur the agroclimatic zones must have previously been defined. While there is much empirical knowledge about what crops grow well in various parts of Ireland (based on both farmer experience and advisory service knowledge) there has been no concerted effort to define agroclimatic regions that can be related to a range of crops. It should be noted that there are weather interactions that are specific to particular crops (e.g. frost and soft fruit, humidity and potato blight), but there are also climate aspects that are applicable to most crops such as the hydro-thermal characteristics of an area (the rainfall and temperature) (Petr, 1991).

Lee (1994) analysed the soils of Ireland in an agroclimatic context regarding grass, arable farming and forestry. Hough (1990) looked at the agrometeorology of Ireland from the perspective of crops. In England and Wales agroclimatic data have been compiled to compliment soil survey information (Jones and Thomasson, 1985) and used for zonation (White and Perry, 1989). Similar work has been conducted throughout the European Union region (Verhaye, 1989) and is now being conducted over much of the world. The exact nature of the zonation depends on the desired outcome and the limiting factor. Water availability, thermal stress, rainfall and radiation are among the common agroclimatic factors used as a basis for zonation. Agroclimatic factors are also used as an element of sustainability assessment (Baier and Dumanski, 1991).

In Ireland, Keane (1998) defined 20 agroclimatic regions based on the representativeness of the synoptic observation network. These regions are however, as defined, not related to any agricultural system, rather they are simply areas that can be considered applicable to particular observation stations. As part of work conducted by Holden and Brereton (2003b) climatic regions were defined using a statistical distribution analysis of climatic rainfall and temperature data (developed by Sweeney and Fealy, 2003) that had been interpolated onto a 10 km × 10 km grid over Ireland. The map produced was very useful in that it permitted crop data to be interpreted in terms of zones or regions. It was however limited for agroclimatic purposes because it made no specific reference to the demands of crops grown in Ireland with respect to hydro-thermal climate and yields that can be expected.

A question that arises is whether agroclimatic information on a meso-scale, regional basis is appropriate for agriculture? The answer is probably yes at the outset of the process of zonation. It is at the mesoclimate scale that specific calculations can be made to define agroclimatic regions. Petr (1991) defined three climatic regions (based on temperature sums) for what was the country of Czechoslovakia, but within each of these agroclimatic regions further sub-divisions were defined either on the basis of local temperatures or the hydro-thermic coefficient. By using suitable agricultural crop models it is theoretically possible to integrate climate and agronomic factors to get a general picture of agroclimatic response without getting lost in too much site-specific detail.

The aim of this paper is to derive agroclimatic regions of Ireland using data for the period 1961–1990. The approach taken was a novel one that used hydro-thermal climate (as expressed by monthly rainfall and mean temperatures) and crop yields in conjunction with a statistical clustering technique. The method integrated crop yield data, estimated using mathematical simulation models for grass, barley, maize, potato and soybean, with site hydro-thermal climate in order to derive generalised agroclimatic regions. The resulting regions integrate critical climate and agricultural factors using descriptive, statistical and simulation modelling approaches combined. The methodology could be applied anywhere in the world and with different types of data to those used in this instance.

2. Materials and methods

2.1. Climate and crop yield data

A dataset, on a 10 km × 10 km grid, for the climate period 1961–1990 (defined as baseline by IPCC for assessment of climate change) consisting of monthly radiation, rainfall, mean maximum temperature and mean minimum temperature was developed by Sweeney and Fealy (2003) as part of a nationally funded climate change impact assessment programme. These data were used to drive crop models to predict average yields for each grid square of grass, barley, maize, potato and soybean. Grass was simulated using the 'Johnstown Castle Grass model' (Holden and Brereton, 2002), barley using 'ceres-barely' (Holden et al., 2003), potato using 'substor' (Holden et al., 2003) maize using 'ceres-maize' (Holden and Brereton, 2003a) and soybean using 'cropgro' (Holden and Brereton, 2003a). Daily weather input data for each model were derived from monthly mean values using a stochastic weather generator to create 99 sets of daily weather data from the monthly mean values. The mean crop yields for the 99 replicates for sites below 150 m mean altitude and mineral soil were then used. Details can be found in Holden and Brereton (2002, 2003b) and Holden et al. (2003). The climate data were also used to define summarising variables: (i) R_g: rainfall (mm) during potential growing period (defined as rainfall between 23 March, the day specified for spring sowing in the crop models, and harvest around the end of September); and (ii) and D_8: duration of warm growing season (in days) (defined as the period with temperatures on average greater than 8 °C estimated using linear interpolation between monthly means assumed to be on the middle day of each month). R_g summarises the hydro- and D_8-thermal aspects of the growing season hydro-thermal regime for each grid square.

2.2. Theoretical basis of the agroclimatic regions

The description of a climate can be summarised in terms of a climograph: a plot of two climatic elements (in this case monthly precipitation versus mean monthly temperature). The shape and position of the climograph provides an index of the climate at the location represented (Monkhouse and Small, 1978). By relating the modelled crop yield in a given grid square to the climograph for that square, the climograph can be used as the basis of the definition of agroclimatic regions (a similar approach was taken by Fussel (1992) when developing a species selection method for the tropics).

In order to classify each grid square of the dataset into an agroclimatic class, and to define agroclimatic regions, the following procedure was used:

1. Define "seed" sites which were thought to represent a given type of climate. The seed sites could be selected based on: geographical location, known properties, or a combination of both. The number of seed sites could also be variable—the number of classes defined must be related to estimates of known variability, end use and amount of data being classified. In this work site properties, but *not* geographical location were used for seed site selection.

2. Use *k*-means clustering (implemented by McQueens's algorithm: Johnson and Wichern, 1992 in Minitab 13) to allocate each grid square into a cluster. *k*-Means clustering is a non-hierarchical clustering method that functions best when given a starting point ("seeds"). The procedure takes each sample, compares it to each seed and allocates it to the cluster of the least different seed. The centroid of the cluster is then calculated and the procedure continues. A sample is not bound to a cluster but can be re-allocated if it becomes more similar to a different one, thus by the end of the procedure, all clusters are as similar internally, and as different as possible from each other.
3. Plot maps of cluster allocation (note, up to this point there is no geospatial information used in the procedure so there is no guarantee that adjacent sites will be allocated to the same cluster unless there is actual validity to the procedure).
4. Compare the quality of the cluster allocations based on maps produced by different combinations of data. The *k*-means algorithm can use two or more variables in its function. To assess which combination of variables was best (just climate; just yield; climate and yield; climate summaries and yield) a preliminary assessment was undertaken based on four-seed clusters (detailed later) and the resulting maps compared. An objective measure of the resulting map quality was not found, however it was possible to assess the maps produced based on knowledge of the environment of Ireland. It is worth noting that the resulting maps (presented later) were all grossly similar; the differences were in the minor details.

The agroclimatic regions, once defined by climograph and *k*-means clustering were assessed by statistical analysis. One-way ANOVA (H_0: no significant difference between variable (climatic/yield) based on clusters defined) was used to determine that the clusters were significantly different. Correlation was used to confirm which crops were most closely related to hydro or thermal aspects of the climate.

2.3. Climographs of extremes of hydro-thermal climate and yield

To establish the extremes of climate found in Ireland, the hydro-thermal database of monthly rainfall and mean temperature for Ireland (Sweeney and Fealy, 2003) was used. The sites with extreme and average summer climate characteristics were identified, the climographs examined to determine the number of separable clusters and the sites used as seeds for *k*-means clustering. The climate extreme and average sites were those with: (i) maximum summer rainfall; (ii) minimum summer rainfall; (iii) maximum summer temperature; (iv) minimum summer temperature; (v) minimum deviation from mean annual precipitation; and (vi) minimum deviation from mean annual temperature. Summer values only were used because all crop simulations (except grass) were for spring sown crops and summer water stress was thought to be important (Holden and Brereton, 2002).

The sites with minimum and maximum yield for grass, barley, maize, potato and soybean were also identified from the dataset, the climographs inspected and the number of clusters established for seeding the *k*-means algorithm. It was observed that the same 10 km × 10 km grid cells were identified from two sources on a number of occasions, such as maximum potato yield being predicted to occur in the same cell as minimum grass yield, minimum potato yield as minimum summer rainfall and minimum soybean as minimum summer temperature.

An examination of the cluster mean value climographs suggested that, while there were various attributes that summarised differences between the climographs, February rainfall was a good indicator of the general nature of the whole climograph. It should be noted that February rainfall is not necessarily a unique identifier of a climatic region; its selection as a discriminator was based only on visual examination of the climograph data. The reason that February stood out was because of the documented fact that January-to-February rainfall change is most marked (compared to differenced between other months) over the whole of Ireland (Collins and Cummins, 1996). In fact, February represents the start of the "drier-part" of the year (February–June). Of the 852 records in the dataset used for this research, 851 had the greatest difference between adjacent monthly rainfall occurring between January and February. It was decided to investigate February rainfall as a separator variable to increase the number of defined agroclimatic regions. On the basis of the total range of February rainfall values (48–150 mm) and the clusters defined from crop climographs, 7 seed values could be identified. The sites with February rainfall nearest 48, 70, 76, 93, 108, 120 and 150 mm were found in the dataset and used as seed values for *k*-means clustering. The seed climographs were intended to isolate the extreme dry and wet areas (around 48 and 150 mm rainfall) and to establish the presence of a rainfall gradient in the south-west of the country (120 mm).

In all, three scales of agroclimatic regions were examined using the methodology: a three-cluster map based on climate only, a four-cluster map based on yield extremes, and a seven-cluster map based on February rainfall.

3. Results and discussion

3.1. Three agroclimatic regions based on climate characteristics

Using the average and extremes of the growing season hydro-thermal database, three distinct types of climographs were apparent based on rainfall (Fig. 1, labelled 1, 2 and 3): label 1 represented a climate that has relatively low rainfall all year and is always relatively warm; label 2 represented a climate that was moderately wet but could perhaps be subdivided into a cooler and a warmer phase; label 3 represented a climate that was always very wet and relatively warm. Using the separation of rainfall into three classes for seeds and *k*-means clustering with crop yield, R_g and D_8, a map with three agroclimatic regions was produced (Fig. 2). Statistical analysis revealed that the three clusters were significantly different with respect to each crop yield, monthly rainfall and monthly temperature (minimum, maximum and mean). After *k*-means clustering the three agroclimatic regions produced were:

Cluster 1: Dry with a moderately long growing season (a north-south trend could be expected in growing season length)—favours no particular crop; can support a good yield; barley and potato both likely to suffer water stress in this area; grass and maize yield also potentially reduced by water stress.

Cluster 2: Wet with a short growing season—grass, maize and soybean yields poor due to short growing season; may have field access limitations.

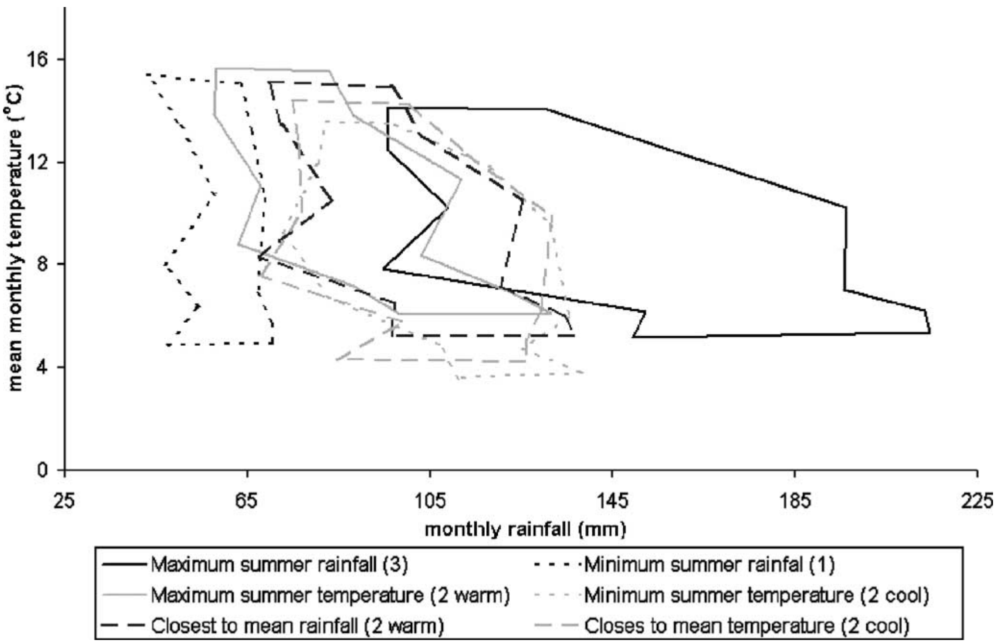


Fig. 1. Climographs based on climate extremes and averages of rainfall and temperature. Three types of climographs (labelled in brackets in the legend) are apparent: (1) low rainfall and relatively warm; (2) moderately wet with a warm and cool phase; and (3) very wet and warm.

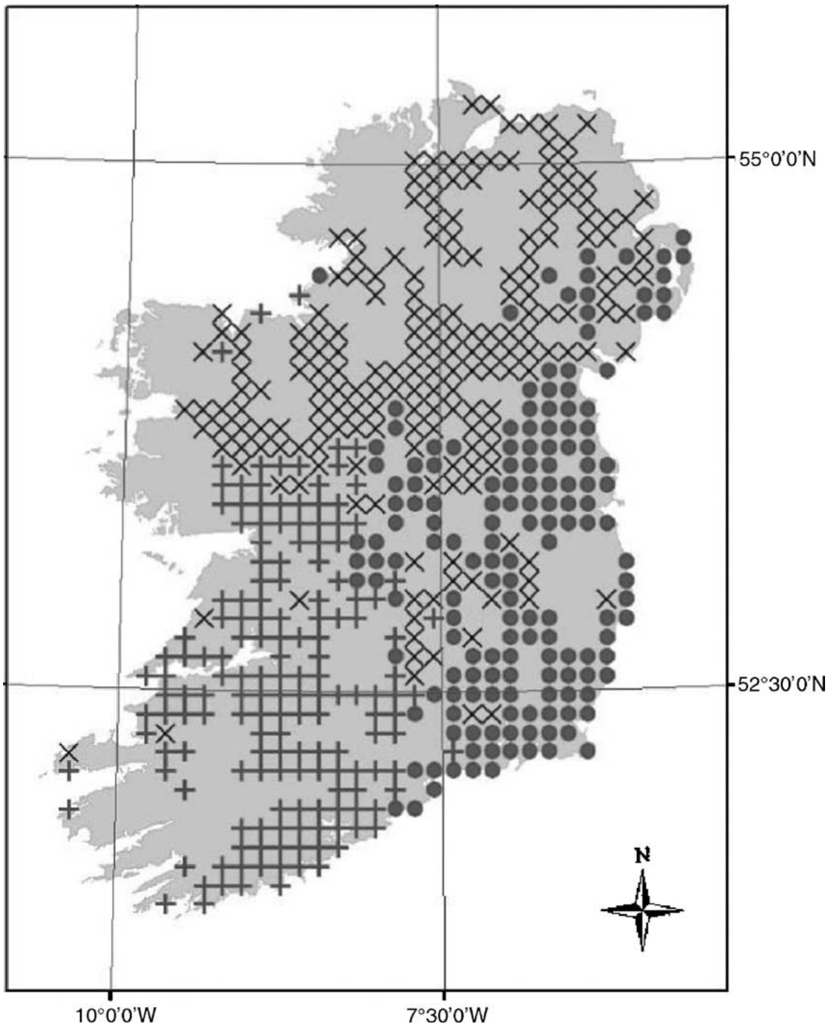


Fig. 2. Three cluster agroclimatic region map based on summer temperature and precipitation extremes and average sites ((●) cluster 1; (×) cluster 2; (+) cluster 3).

Cluster 3: Wet with a long growing season—favours all crops; may have practical limitations due to field access for mechanised operations and crop damage (not explicitly included in the simulation modelling).

The three agroclimatic regions defined make sense in that they represent areas where crops are limited by either water availability in the summer (cluster 1) or by the short duration of a warm growing season (cluster 2 versus cluster 3). The map produced is consistent with the known distributions of crop performance in Ireland, and in conjunction with a soil map would allow crop selection and management decisions to be undertaken. The nature of the three regions suggests that where rainfall is low, the length of growing season becomes less important (in the eastern half of the country). There is however more detail that could be extracted from the dataset.

3.2. Four agroclimatic regions based on crop yield

The sites with extremes of crop yield revealed very similar climographs to those identified based on just

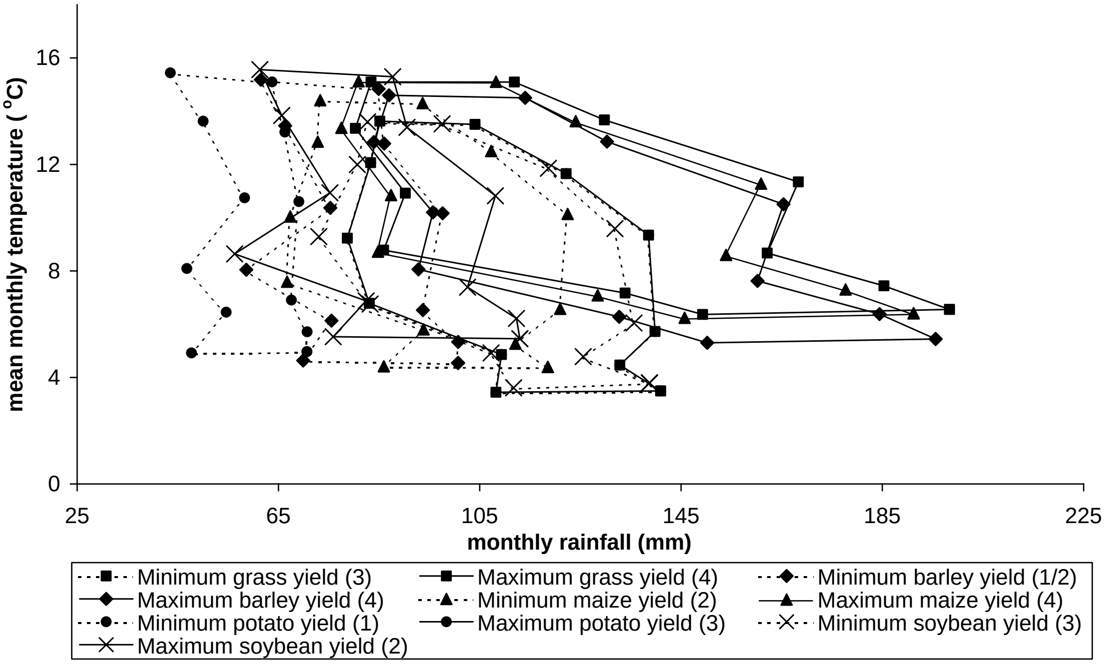


Fig. 3. Climographs (types labelled in brackets in the legend) based on yield extremes. Label 1: dry and warm; label 2: moderately dry and moderately warm; label 3: moderately cool and wet; and label 4: very wet and warm.

climate properties (Fig. 3) but these climographs suggest 4 (labelled) clusters. The climographs labelled 1 and 4 are essentially the same as 1 and 3 labelled in Fig. 1. The middle area became sub-divided into two: a warmer-drier area (labelled 2) and a cooler–wetter area (labelled 3). Using these sites as "seeds" for *k*-means clustering, four separate maps were produced (Fig. 4) each of which was assessed as a basis of agroclimatic classification:

(A) Clustered using: monthly mean temperature, monthly rainfall, monthly radiation and crop yield (five crops)(Fig. 4A): it was observed that cluster 1 did not extend far enough north and that the inclusion of radiation as a clustering variable had a dominating effect which make the structure very regular and not of a form that represented expected agroclimatic regions.
(B) Clustered using: monthly mean temperature, monthly rainfall, and crop yield (five crops) (Fig. 4B): this map was thought to have a good structure and probably represented the agroclimatology quite well but relatively dry sites over such an extent on the west coast are not realistic even though the map does capture the known rainfall anomaly of Shannon Airport (location shown on Fig. 7b) where rainfall is unusually low for the region).
(C) Clustered using: crop yield (five crops) (Fig. 4C): this map was thought to be quite good but the middle of country did not look right. Cluster 4 seemed to extend too far north and the warmer–drier area (cluster 2) was constrained to a northern location.
(D) Clustered using: crop yield (five crops), R_g, and D_8 (Fig. 4D): this map was thought to be a reasonable representation of agroclimate at the scale being considered. Cluster 1 extended up to Ards Penninsular which is known to be dry and somewhat similar to the eastern Leinster coastal area (Betts, 2002). Cluster 2 occupied a central geographical location. Cluster 3 was thought to perhaps extend too far east in Ulster, but cluster 4 occupied a reasonable area in south-west Ireland.

The map based on crop yield, R_g, and D_8 was therefore judged to be the most suitable. Statistical

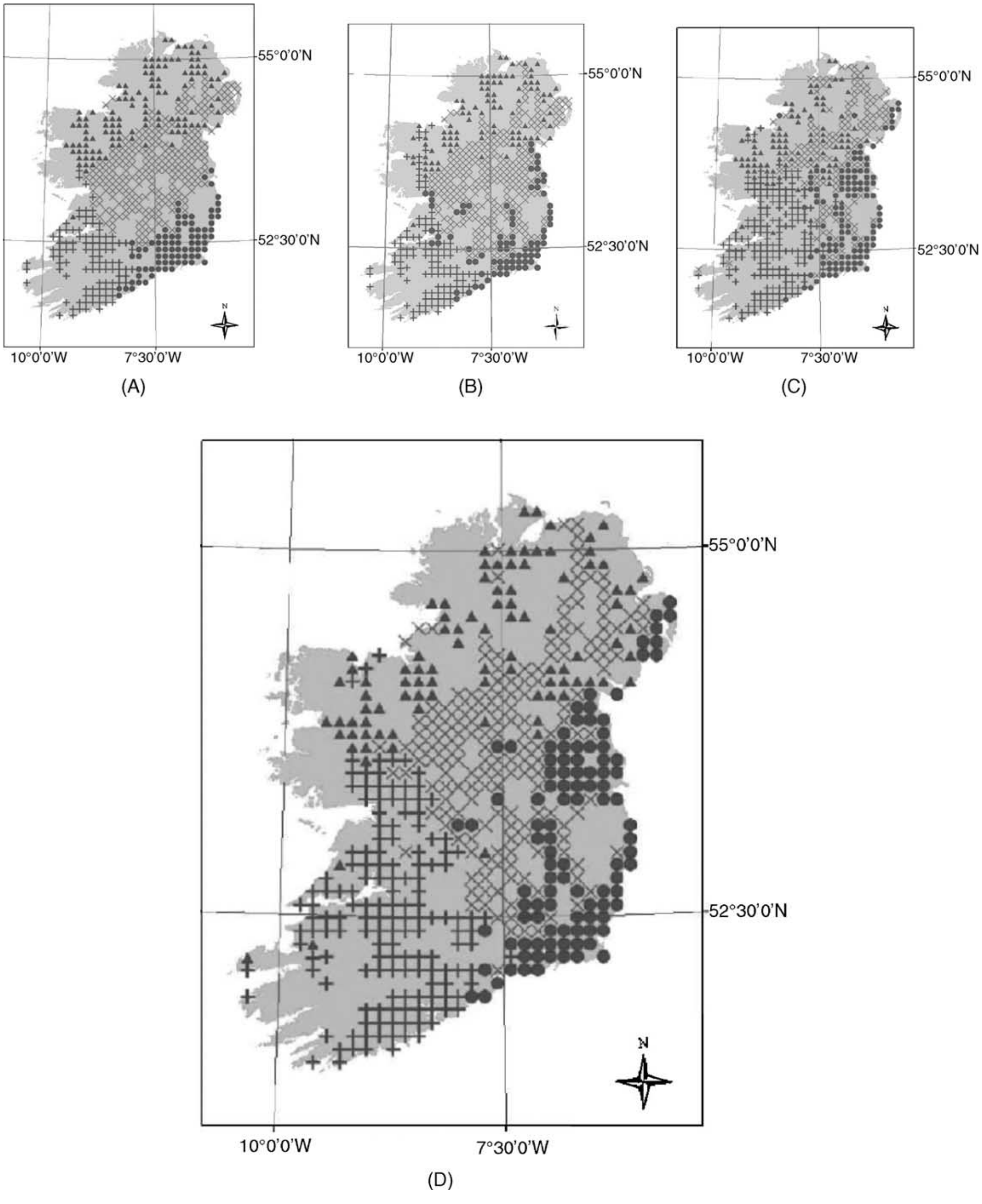


Fig. 4. Comparison of maps created by various combinations of data and four-seed *k*-means clustering ((●) cluster 1; (×) cluster 2; (▲) cluster 3; (+) cluster 4). (A) Clustered using monthly mean temperature, monthly rainfall, monthly radiation and yields. (B) Clustered using monthly mean temperature, monthly rainfall and yields. (C) Clustered using yields. (D) Clustered using yields, R_g and D_8.

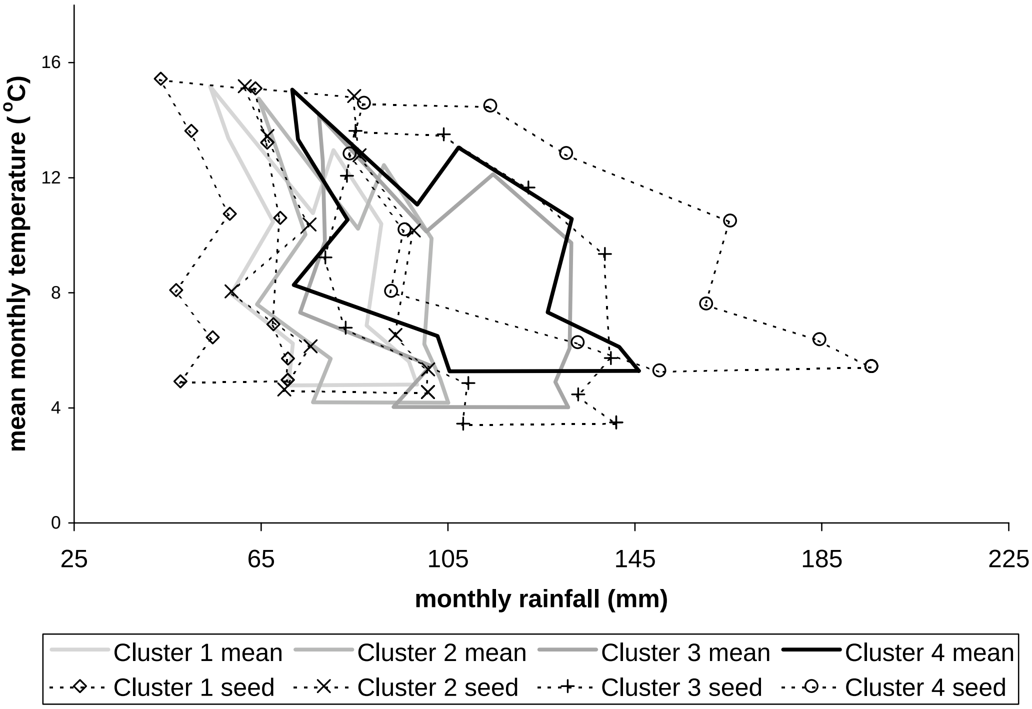


Fig. 5. Climographs of the four extreme yield sites and the resulting cluster mean climographs.

analysis revealed that the four clusters were significantly different ($P < 0.001$) with respect to yield, rainfall and temperature properties. The mean characteristics of each cluster in terms of mean monthly temperature and rainfall were determined, and representative climographs plotted (Fig. 5). All clusters have similar April to July temperatures and a progressive increase in rainfall (cluster 1 to cluster 4) over the same period. Clusters 1 and 4 have similar winter temperatures but cluster 4 is much wetter. cluster 3 represents the coldest region in winter. The four clusters had the following properties:

Cluster 1: Low rainfall, summer water stress but long, warm growing season (426 ± 23 mm rain in growing season, 202 ± 8 growing days >8 °C); water stress may reduce grass performance; good for maize; poor for potato and barley; irrigation requirement in some years.

Cluster 2: Average, not excessively wet or dry, moderate growing season length (484 ± 24 mm rain in growing season, 194 ± 4 growing days >8 °C); adequate for all crops; financial return will depend up on market values, specific seasonal risks and other environmental resources available; wide range of choices for the farmer.

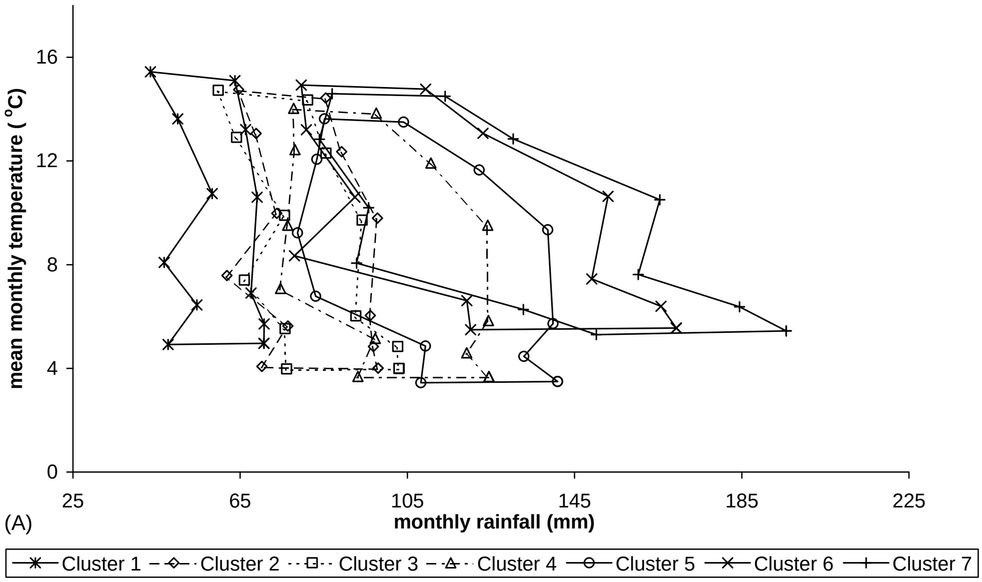
Cluster 3: High rainfall in growing season but relatively short period of warm weather restricts growth and plant development (563 ± 47 mm rain in growing season, 188 ± 6 growing days >8 °C); favours barley and potato; not good for maize and grass.

Cluster 4: Long, wet growing season (547 ± 51 mm rain in growing season, 209 ± 10 growing days >8 °C); favours potato and grass; barley should be adequate; potential crop damage and protection issues; soybean at its best because of long warm season but still poor yield.

It can be concluded that the four cluster agroclimatology is an improvement over the three cluster version. It follows very much what is expected and provides a formalised representation of the general characteristics of crop growth that can be expected in Ireland. There is however potential in the dataset to extract greater detail and to examine agroclimatic classification of Ireland at a slightly finer resolution. For this reason, a classification into seven clusters was conducted.

3.3. Agroclimatic regions based on February rainfall

The seed climographs (Fig. 6A) produced mean climographs (Fig. 6B) after *k*-means clustering with crop yields, R_g and D_8. The extreme values (47 and 150 mm rainfall) were not preserved in the cluster means, but did serve the purpose of separating classes that made sense. A one-way analysis of variance revealed that the seven clusters were significantly different ($P < 0.001$) with respect to hydro-thermal monthly data, R_g, D_8 and crop yields.



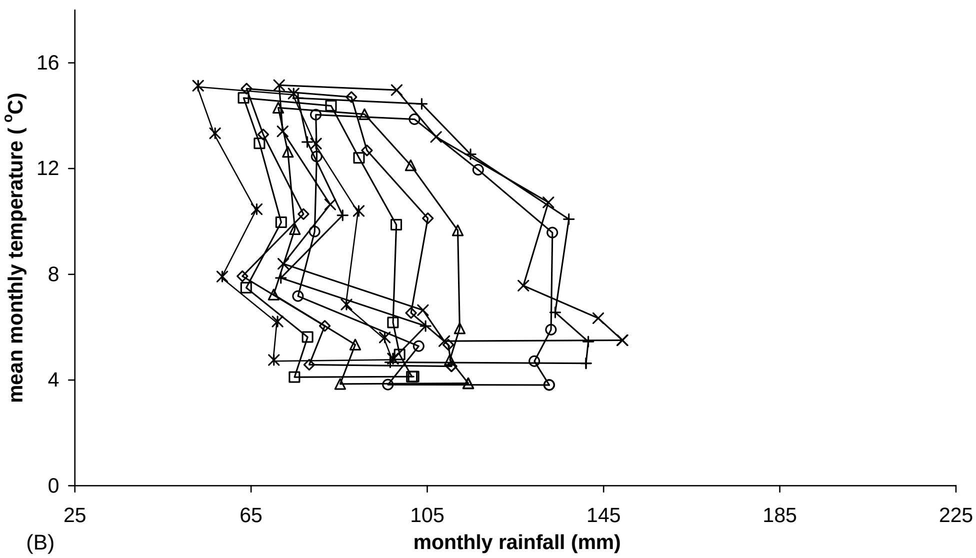


Fig. 6. (A) Seed climographs based on February rainfall values. (B) Mean climographs derived from *k*-means clustering of yields, R_g and D_8.

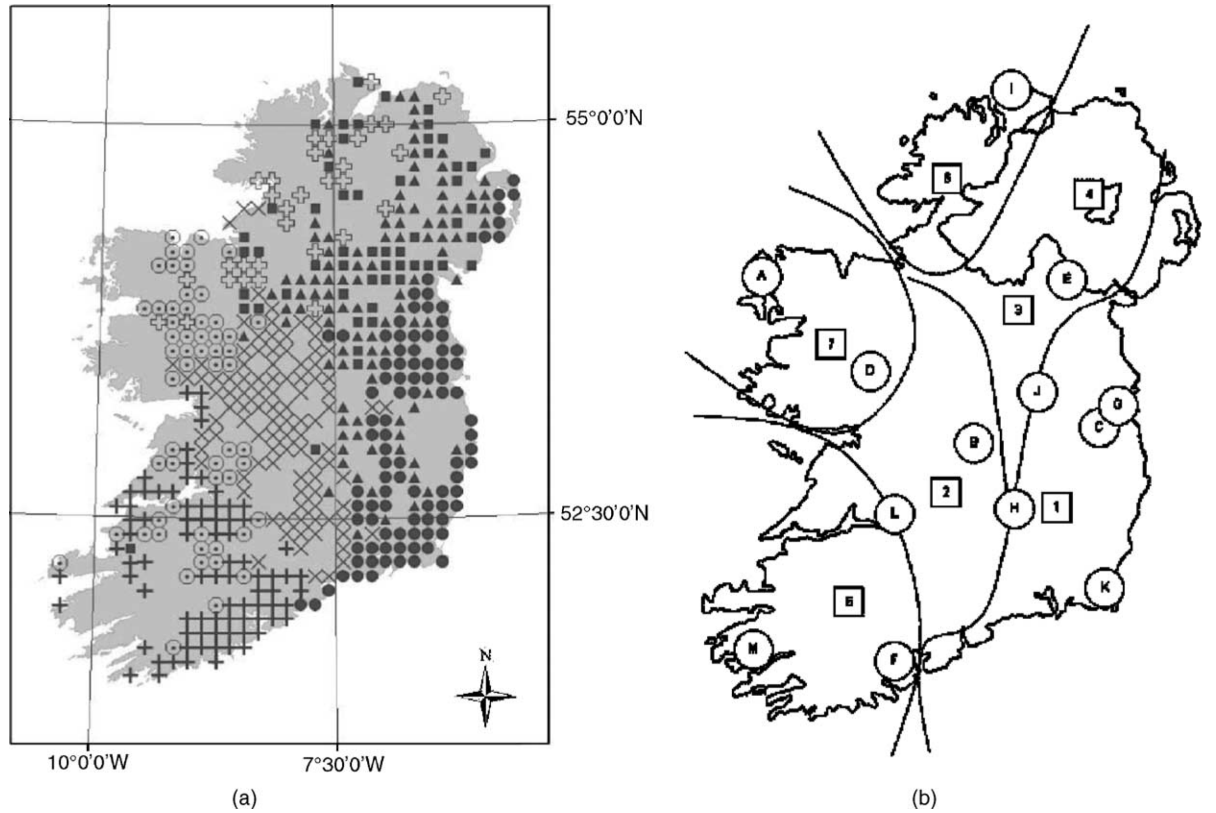


Fig. 7. Seven agroclimatic regions defined by February rainfall: (a) derived from *k*-means clustering ((●) cluster 1; (×) cluster 2; (▲) cluster 3; (■) cluster 4; (✚) cluster 5; (+) cluster 6; (⊙) = cluster 7); and (b) generalised interpretation (A: Belmullet; B: Birr; C: Casement; D: Claremoris; E: Clones; F: Cork Airport; G: Dublin Airport; H: Kilkenny; I: Malin Head; J: Millingar; K: Rosslare; L: Shannon Airport; M: Valentia). Note the region defined by 3 and 4 is an intermixing of these two clusters and a generalised demarcation was not possible.

The clusters created from the February rainfall seeds (Fig. 7) occupy distinct geographical regions and have clear climate and crop response characteristics:

Cluster 1: East Ulster, East Leinster. Warm (ca. 9.5 °C) and relatively dry (75 mm) causing water stress in grass, barley and potato, and to a lesser extent in maize.

Cluster 2: Central Connaught. Moderate temperatures (8.5–9.0 °C) and average rainfall (86 mm) resulting in moderate to good yields of grass, barley, maize, potato and soybean. Average conditions with few extremes, little (if any) water stress and few growing season length limitations.

Cluster 3: Intermixed with cluster 4 in Central Ulster. Moderate temperatures (8.5–9.0 °C) and dry to average rainfall conditions (82 mm) lead to moderate to good barley yield but poor to moderate grass, maize and potato yield. Some water stress limitations.

Cluster 4: Intermixed with cluster 3 in Central Ulster. Cool (<8.5 °C) and average to wet (92 mm) (cooler and wetter phase of the intermixture of clusters 3 and 4) results in relatively poor grass, maize and soybean yield, but good barley yield and moderate potato yield. There are some growing season length limitations.

Cluster 5: West Ulster. Cool temperature (<8.5 °C) and relatively wet (105 mm) conditions lead to poor grass, maize and soybean yields but good barley and potato yields. There are some growing season length limitations.

Cluster 6: South and south-west Munster. Warm temperatures (9.5–10.0 °C) and relatively wet conditions (106 mm) lead to good grass, barley and maize yields and provide conditions with potential for crops like soybean. Potato yield is limited.

Cluster 7: North-west Connaught. Moderate temperatures (ca. 9.0 °C) and wet conditions (107 mm) permit moderate yields of grass, maize and soybean but good yields of barley and potato. There is a possible temperature/season length limitation.

The seven cluster agroclimatology is an improvement over the three and four cluster versions. It has permitted the extraction of a region to the east of the country that is defined as warm and dry (cluster 1) which is know to exist and is noted by Keane (1998). It also created a series of regions that reflect a south-west to north-east gradient across the county (wet and warm to slightly dryer and cooler) (clusters 2, 3, 4 and 6) and a temperature gradient in the wet north-west (clusters 5 and 7). The regions defined using the statistical clustering differ from those of Keane, 1998 because he addressed the problem the opposite way. He asked what areas of land can be best represented by the Met Éireann observations stations? In this case, the approach asks what sites have similar climate and crop growth potential? There is no objective measure (other than statistical similarity tests) that can be used to

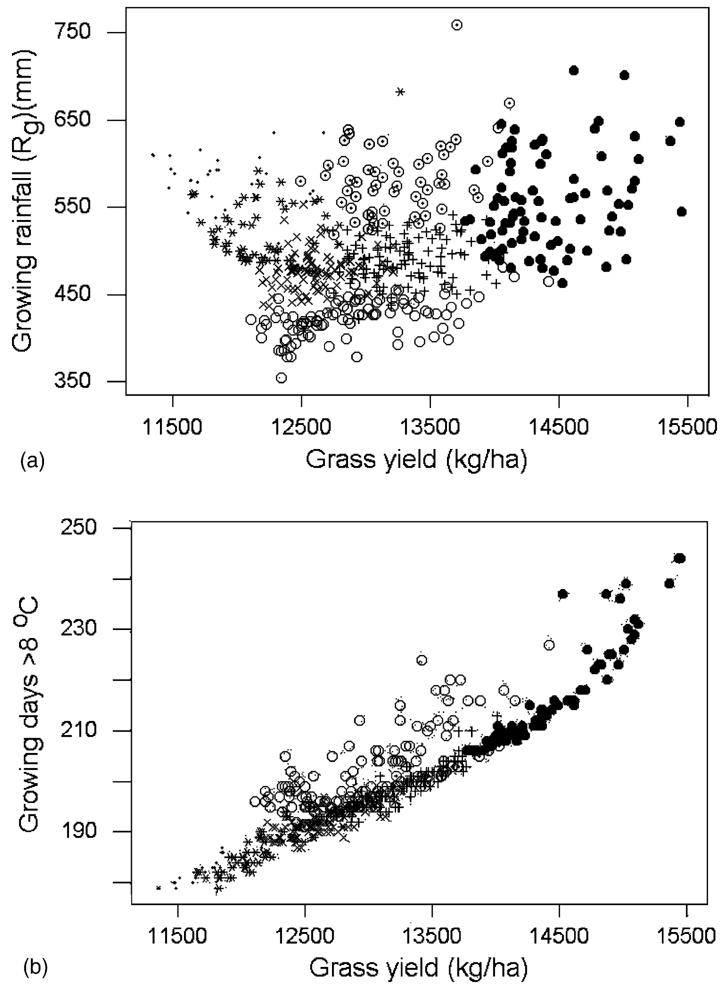


Fig. 8. Crop yield vs. R_g and D_8. for grass (a and b), barley (c and d), maize (e and f), potato (g and h), soybean (i and j) ((○) cluster 1; (+) cluster 2; (×) cluster 3; (∗) cluster 4; (·) cluster 5; (●) cluster 6; (⊙) cluster 7).

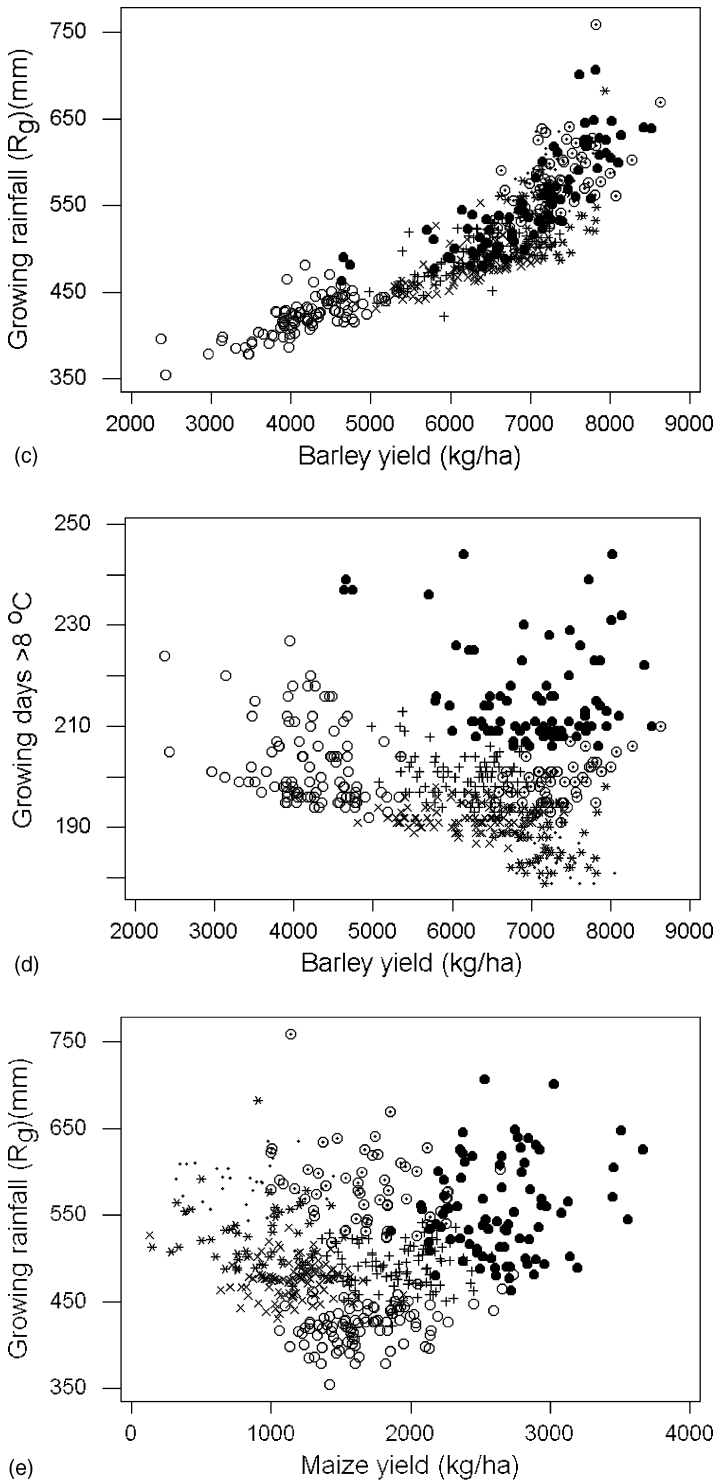
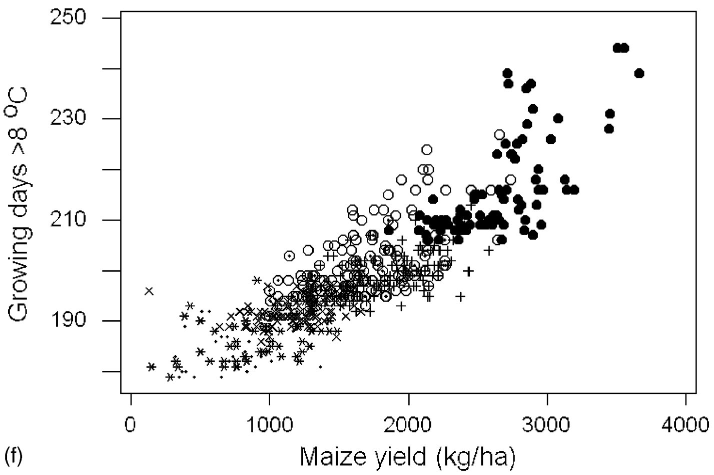
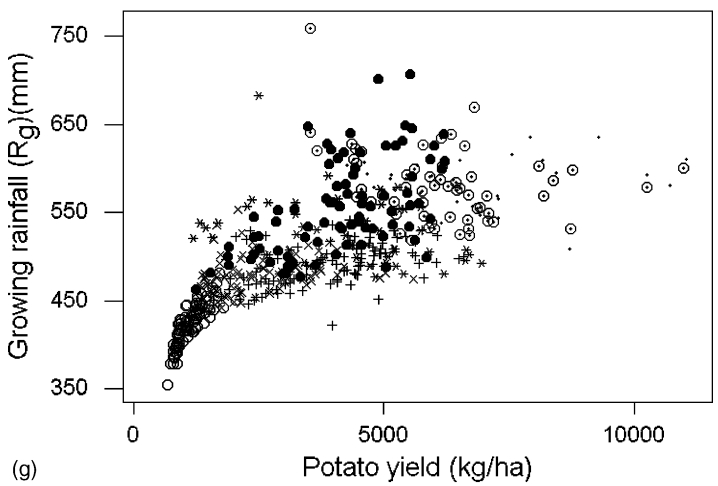


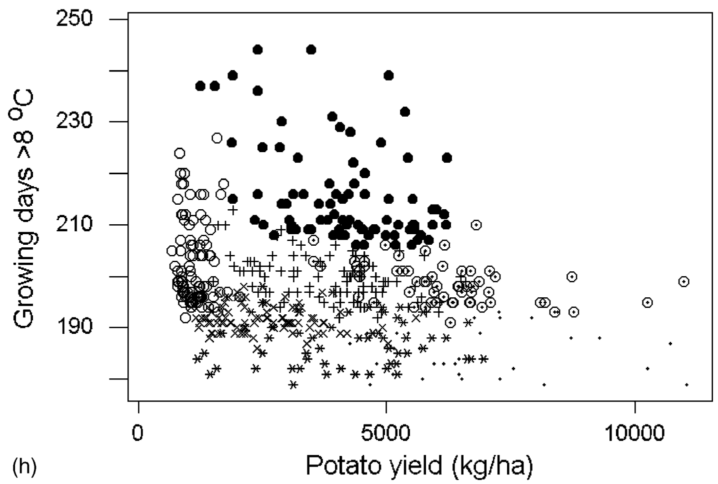
Fig. 8. (*Continued*).



(f)

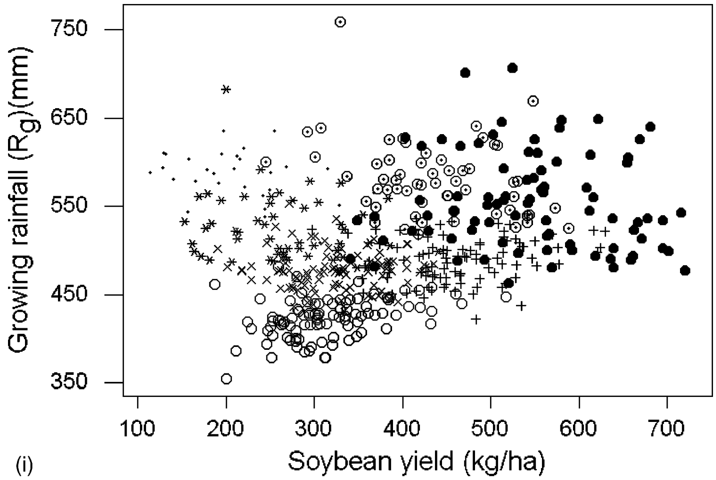


(g)

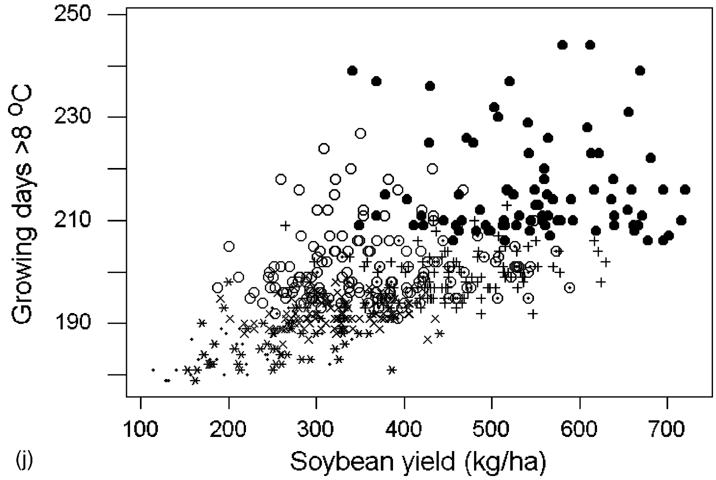


(h)

Fig. 8. (*Continued*).



(i)



(j)

Fig. 8. (*Continued*).

indicate the ideal number of clusters. The process has been stopped at seven because the map shows clearly defined regions (having not used georeferencing as a clustering criteria) and each region has a clearly defined crop response that can be related to the type of crop grown. Given the combination of national scale crop simulation modelling and statistical downscaling of climate data, it probably makes little sense to try and derive larger numbers of clusters. In order to create meaningful clusters at a smaller scale it would be necessary to examine the calibration of the various models used in much greater detail.

3.4. The relationship between crop response and agroclimatic classes

Plots of the various crop yields versus R_g and crop yield versus D_8, with the points subdivided by agroclimatic class (Fig. 8) reveal something of each crop's response to hydro-thermal conditions during growth. The division between crops that are water and growing season/temperature limited is apparent. Grass and maize (and to a lesser extent soybean) show a linear relationship between growing season length and yield (Fig. 8b and f). The spread of yields predicted for soybean reflect the fact that it is a marginal crop, not really appropriate for the current Irish climate (Fig. 8i and j). The results do however suggest that with relatively moderate climate change, soybean could become a viable crop in some regions. Barley and potato showed relationships with rainfall that were not linear (Fig. 8c and g) and can perhaps be explained by the role of soil influencing water availability both in reality and in the simulation modelling. The overlap between the two types of crop response can be seen by examining the grass and maize yields for cluster 1 (Fig. 8a and e) which were both less than expected. The low yield is probably due to a lack of water in the latter part of the growing season (Holden and Brereton, 2002, 2003a) causing some water stress in these crops.

3.5. The relationship between agroclimatic classes and Met Éireann synoptic weather stations

The climatic mean monthly temperature and rainfall for each of the seven agroclimatic classes was compared to similar data for each of the Met Éireann synoptic weather stations (locations marked on Fig. 7b) as published on the Met Éireann web site (www.met.ie). The RMSE was used to find which synoptic stations most closely represented the climatic distribution of rainfall and temperature. Perfect geographical correspondence was not achieved.

For cluster 1, Dublin Airport recorded far greater rainfall than was characteristic of the cluster (RMSE = 15 mm per month). Shannon Airport showed the closest correspondence at RMSE = 4.7 mm per month due to the known anomaly of unusually low rainfall for its geographical region. Roches Point, Rosslare and Kilkenny all showed reasonable correspondence. Dublin Airport temperature was most closely related to the cluster 1 mean monthly temperatures (RMSE = 0.2 °C). Likewise for cluster 2, the rainfall was not well reflected by observation records within the cluster area but temperature was well represented by Birr and Kilkenny. Cluster 3 was well represented by Clones for both temperature and rainfall and cluster 4 by Malin Head for rainfall and Clones/Mulingar for temperature. A lack of data for the north west means that this is an incomplete comparison. Cluster 5 rainfall was most closely related to Belmullet and Claremoris (RMSE = 10.6 mm) but was poorly related to the Malin Head record (RMSE = 17.1 mm). Temperature was also problematic being most closely related to the Claremoris, Clones, and Mulingar records (RMSE = 0.4 °C in all cases). Cluster 6 was well represented by Cork Airport, but the rainfall record for Dublin Airport was in fact most closely related. The rainfall and temperature records at Claremoris were in close agreement with the mean values for cluster 7.

It would be unreasonable to draw specific conclusions from the correspondence between mean monthly values averaged over extensive areas and those from specific observation locations. The general degree of correspondence was reasonably good however, the results do suggest that the current Met Éireann observation network is perhaps not as well suited to providing data for agricultural applications as it might be. The possible anomalies associated with observations at Shannon and Dublin Airports are particularly worrying in this respect.

4. Concluding remarks

The implications of this work are related to both agricultural production and agri-environmental research. With regard to field-based empirical production research, the spatial extrapolation of results and management system designs is largely related to the agroclimatic characteristics of the site of experimentation and the site to which the result is to be exported. The geographical spread of each of the agroclimatic classes defined should be a starting point when evaluating the value of research data for production management advise. For example, dairy management systems devised based on experiments conducted in the central southern part of the country (cluster 2) may not be as reliable for regions that are cooler and wetter towards the north (cluster 4) or suffer from water stress (cluster 1). Likewise, crop trials conducted in the south-east (cluster 1) may have little relationship with cooler or wetter areas, depending on the factors that limit crop growth. With regard to agri-environmental research, the value of having known and meaningful agroclimatic regions is that experiments can be designed to reliably encompass the full range of conditions found in the country, i.e. the regions can be used as strata in experimental design at a country wide scale. The defined regions and their mean properties can allow sites to be evaluated in terms of their regional representativeness and can be used to keep the number of sites needed to represent the country to a minimum. Finally, by having defined agroclimatic regions, research evaluating the impact of climate change (especially on agriculture) can be placed within this framework.

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