CLIMATIC SOIL MOISTURE DEFICIT - CLIMATE AND SOIL DATA INTEGRATION IN A GIS

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Abstract. This paper discusses a GIS based implementation of a model for soil droughtiness assessment evaluating the impact of possible climate change. It focuses, in particular, on the development of a methodology for mapping Available Water Capacity. An assessment of the Soil Drought Susceptibility for Scotland in the year 2030 is made and illustrated with maps and derived statistics.

1. Introduction

This paper describes the development of a geographic Information Systems (GIS) based methodology for assessing the possible impacts of climate change on the susceptibility of Scotlands soils to drought.

This work forms part of a wider development of a GIS based climate change impacts screening procedure for Scotland. The research is responding to requirements for a regional policy level evaluation of climate change impacts. A screening procedure of this type imposes several principles defining the implementation of the component drought assessment. First any assessments must be based on climatic and soil parameters mapped across the region, thus eliminating models demanding large numbers of infrequently measured or highly spatially variable parameters. The second principle is that the components of previously implemented land capability assessments (Bibby *et al.*, 1982, 1988; and Ragg *et al.*, 1985) should be disaggregated. Once disaggregated and stored within a GIS these elements can then be manipulated independently. Previously the mapping of land capability was paper based with a strong component of expert knowledge based on field experience. This made the testing of scenarios and hypotheses impractical. The development of a GIS based protocol was sought to enable a rapid and systematic assessment of the range of climatic predictions available from general circulation models (GCM's). This linkage to GCM predictions and the scenario testing approach forms the third principle of the implementation. Within this system the drought susceptibility assessment (Jones and Thomasson, 1985) forms one of the key components for the climate change impacts screening procedure.

The elements of Jones and Thomasson methodology are set out in Figure 1. The focus of this paper is on the derivation of the Available Water Capacity surface. This requires the integration of point sampled soil profile data with soil survey

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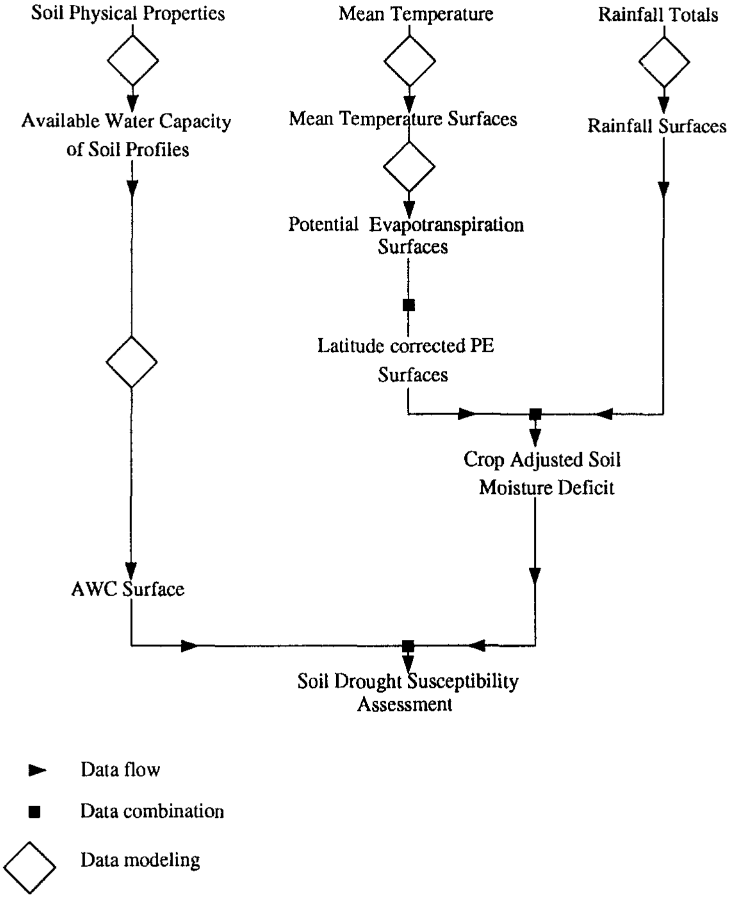

Fig. 1.

mapping units (Soil survey of Scotland, 1984) to produce a map with a spatial resolution compatible with the meteorological variables.

2. Primary Datasets

2.1. *Meteorological Data*

The rainfall maps used for mapping drought susceptibility are derived from the 1941–70 average monthly total rainfall record compiled by the Meteorological Office in the U.K. These were the most recent data compiled for 30-year monthly averages when the project began. The data are from 1500 rainfall stations across Scotland associated with Meteorological Office, Hydro-electric, and River Purification Board Stations. Mean monthly temperature data, for the period 1951–80 came from Meteorological Office records, with 150 being used.

The meteorological records are point (geographically specific) data and are spatially interpolated to a one kilometre resolution grid covering Scotland using a hybrid model for spatial interpolation (Matthews *et al.* (in press)). This hybrid model interpolates data values for kilometre grid squares by first analysing trends within the point data set using stepwise multiple linear regression, (Schulze, 1982; Aspinall and Miller, 1990), with geographic location, altitude and distance to the sea as independent variables. This 1 km resolution surface is then deformed to model local conditions using point kriging of the residual values (Oliver *et al.*, 1989). This hybrid method thus takes into account deterministic components of climate related to topography and coarse resolution geographical characteristics of Scotland, and random spatially dependent elements that operate locally. Benefits of this method are (i) that the surface provides an exact interpolation at the data points, without resorting to the use of high order polynomial terms in the regression; and (ii) the limits of the surfaces are defined and available for testing model sensitivity to data inputs. The hybrid spatial interpolation model thus enables the production of baseline rainfall and temperature surfaces for each month; these form the primary climatic dataset on which the soil drought susceptibility assessments are based.

2.2. *Available Water Capacity (AWC)*

The total available water capacity of a soil is defined as the amount of water that is held between tensions of 0.05 bar and 15 bar with easily available water held between 0.05 and 2 bar. The value for a particular soil horizon can be determined experimentally but, in the absence of directly measured values in the soils database, an empirical approach set out by Thomasson (1979) has been used. According to this model the ability of soils to retain water is determined largely by texture, structure, organic matter and stone content. With all these characteristics available in the database the AWC values for each mineral soil horizon have been calculated.

3. The Climate Change Scenario

The climate change scenario used within this work is for the year 2030, obtained from the first report of the U.K. Climate Change Impacts Review Group (DOE, 1991). This is an agreed standard scenario for methodological development and impact assessment within the research group. The changes are:

Temperature: Winter +2.6 °C Summer +1.4 °C
Rainfall: Winter −5% Summer −11%

The values for individual months of the year are derived by linear interpolation. The climate change scenario has been applied as a uniform change in values across Scotland. It is recognised that this is not the ideal method for integrating GCM predictions with regional climate mapping and evaluation of scenarios in the future will use more sophisticated links to the underlying structure of the climate surfaces (Matthews *et al.* (in press)).

4. Potential Evapotranspiration

The method used to calculate potential evapotranspiration (PE) is that developed by Thornthwaite (1931, 1948) and reviewed by Palmer and Havens (1958). The Thornthwaite method established an empirical relationship between mean monthly temperature and monthly potential evapotranspiration. PE for each month could thus be derived within the GIS using the baseline temperature dataset. Other methods such as that of Penman (1948) have been developed to allow calculations for shorter periods and for more particular circumstances. These, however, rely on the availability of daily data for several other weather variables, for example windspeed and vapour pressure. These demands for data could not be met within the context of this study, the objective of which was to calculate the mean monthly potential evapotranspiration values for each one kilometre grid square for the whole of Scotland. A criticism of the Thornthwaite method is that it makes assumptions about the correlations between temperature and other pertinent weather variables (Palmer and Havens, 1958). Palmer and Havens conclude that the validity of this assumption is entirely dependent on the circumstances of the application. With the present application set in terms of 30 year means, monthly totals of potential evapotranspiration, and covering the whole of Scotland, the degree of stability of the correlations was expected to be sufficient to justify the use of the Thornthwaite method.

Inherent in the Thornthwaite methodology is the need subsequently to modify the results from the calculation to take account of the stronger relationship between PE and radiation than between PE and temperature. If the correction factors are not applied then there was seen to be a positive shift of one month in the phasing of potential evapotranspiration when calculated results are compared to values calculated at meteorological stations. The correction factors used within this paper were derived from 'effective day length' calculations (expressed in units of 30 days of 12 hours each) (Thornthwaite 1931, 1948). The correction factor also includes an increased minimum solar azimuth (effectively shortening the day), found to be important in correctly estimating summer values of PE at the latitude range that includes Scotland (Holmes, 1981). As these correction factors are latitude specific there is also a residual correction as the factors were only available for one mid-range latitude.

5. Crop Adjusted Values

Both the profile available water capacity, obtained by summing the values for individual horizons, and the potential soil moisture deficit, obtained by subtracting the potential evapotranspiration from the rainfall, require adjustment in order to produce realistic values for an annual crop over the course of the physiologically significant growing season. For the determination of crop specific available water capacity, generalised values for rooting depth for the particular crop e.g. 120 cm for cereals, 70 cm for potatoes, are used to limit the summation of horizons unless a root-impenetrable layer is encountered, in which case the summation is stopped at that depth. In addition root architecture is represented by using the total available water capacity to a selected depth followed by only the easily available water to the final depth. For the crop-adjusted potential soil moisture deficit the length of growing season is used to limit the months over which the calculation is performed whilst the ground cover factor is used to take account of the fact that the loss of water from bare or partially covered soil is less than from full canopy coverage.

Combination of these crop-adjusted values then enables the calculation of soil drought susceptibility assessments on a crop specific basis.

6. Available Water Capacity Mapping

An ability to map AWC values across Scotland is a prerequisite for making the soil drought susceptibility assessment (SDSA). The SDSA is the difference between the AWC and the Crop Adjusted Water Deficit and thus reflects the soil moisture regime.

The AWC profile values used in the mapping are calculated for soil profiles on an orthogonal square grid with five kilometre spacing throughout Scotland. The requirement to integrate this dataset with the climate data at 1 km resolution imposes the need to define values for locations between the 5 km grid points. Statistical interpolations to generate these AWC values are inadequate as they fail to take into account the spatial structure of the variation in soils between grid points. Linear interpolation, for example, would allow the calculation of values between AWC samples but could not take into account the spatial heterogeneity of soil types. To map AWC it was essential to establish the relationship between the AWC profiles and the 1 : 250,000 scale Soil Map of Scotland held as a 100 m resolution grid that acts as a carrier for the AWC information.*

The 1 : 250,000 Soils Map of Scotland is composed of 580 Soil Mapping Units based on parent material, major soil subgroup, landform and vegetation (Soil Survey of Scotland 1984). These map units have two principal advantages in defining the structure of the variation in AWC values. The first and most important is that they have an existence in the landscape, that is actual changes in agriculture and landuse practices are linked to their properties. The second is that they represent a fundamental level of disaggregation of the land surface to which AWC can be related. This latter feature is important, as units can be simply amalgamated to form larger units but reverse operation is impossible without resorting to field survey methods.

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* This was the only soil map of Scotland in digital form with sufficient coverage, (95% compiled), available at the time of the research.

The decision was made at the outset of the work not simply to reclassify the Soil Mapping Units by calculating the average AWC for each. Within the GIS it would have been possible to achieve this by superimposing the grid of AWC values onto the soil mapping units and cross-tabulating. This approach was judged to be unsatisfactory on two counts. The database does not hold sufficient samples to allow meaningful calculation of statistics for each soil mapping unit, some of which are represented in only a single kilometre grid square. Second, the output maps are to represent boundaries of change in AWC values rather than Mapping Unit boundaries. The aim was thus to classify the profiles on the basis of the factors determining AWC and to then link these to the map base by establishing the relationships between the mapping units and the AWC classes.

The classification of the profiles into available water capacity classes was carried out using TWINSPAN (Hill, 1979b). The 690 AWC profiles used in the classification* retained the full range of information on their constituent horizons but assignments to classes were made at the profile level. The program was limited to four levels of division (a possible sixteen end groups), with a maximum of four properties to define the group, and with no group being subdivided unless it contained more than forty samples. These limits were designed to allow the calculation of meaningful statistics for the end groups. Preliminary work revealed the need to scale each of the properties to the same numeric basis, (in this case as percentages), to avoid the domination of the classification by a single property.** Texture classes were redefined in terms of mid-range percentages of sand and clay (the third silt percentage being assumed from the others), stone content values were simply converted into their ranges of percentages and depth was converted to percentage scales by defining depths relative to the maximum profile rooting depth of 120 cm. The only remaining nominal scaled variable was structure which was not amenable to redefinition in terms of percentages.*** The TWINSPAN classes defined, the properties used in the allocation, and the structure of the hierarchy can be seen in Figure 2.

Following the use of TWINSPAN to classify the profile a second program DECORANA (Hill, 1979a) was applied to enable a graphical interpretation of the classes produced. The classes were plotted as ellipses with centres at the mean of their DECORANA axis scores (x) and their AWC values (y) with radii of one standard error of each (Figure 3).‡ The plot reveals several points of interest to the AWC mapping. First there are significant ranges of values within most classes of AWC. This reinforces the need to consider ranges of values in further research.

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* The maximum number of samples permitted by the software at the time.

** Profile depth with a continuous range from one to 120 cm tended to dominate the other properties, structure, texture and stone content then defined as nominal classes.

*** In the event structure still played its part in the classification scheme despite its narrower range of values.

‡ The links between the AWC values, the DECORANA axis scores and the AWC classes is the profile national grid reference. This is maintained throughout the calculations by using the national grid reference as the species name.

TWINSPAN classification of the AWC profiles.

Plain values are the numbers of profiles in each class.
Circled values are the Class identifiers.
Bracketed values are profile numbers.
Where no condition is indicated all remaining profiles not meeting the criteria are allocated to that class.

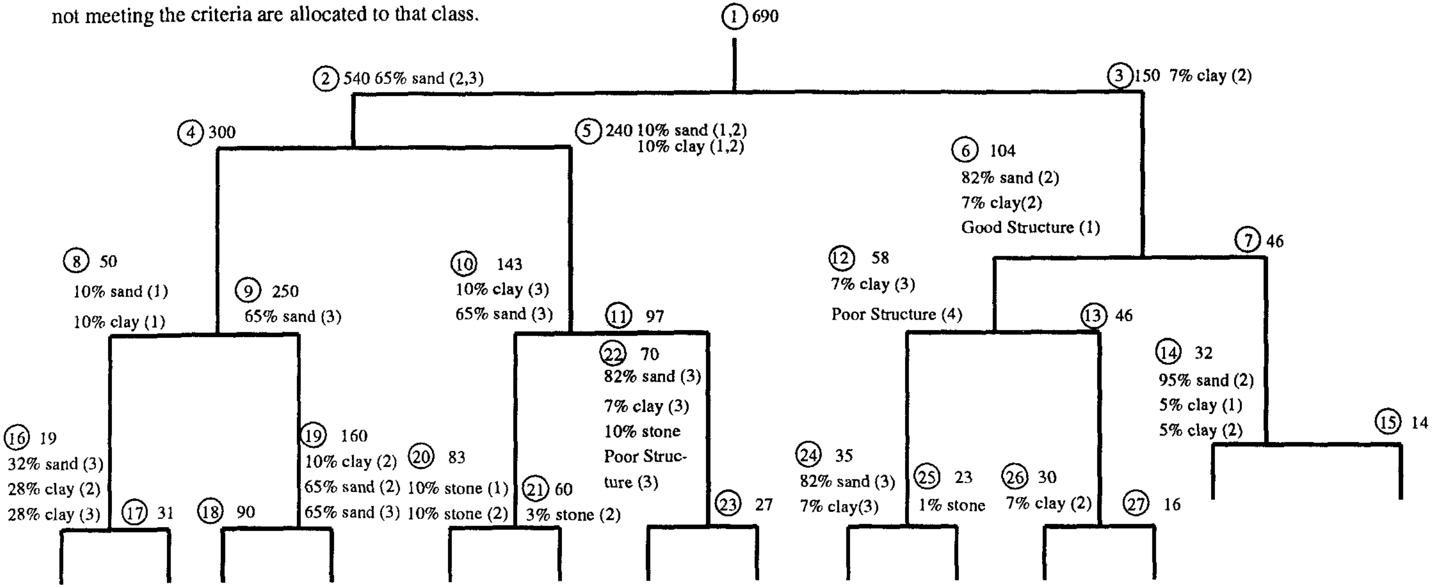

Fig. 2. TWINSPAN classification of the AWC profiles.

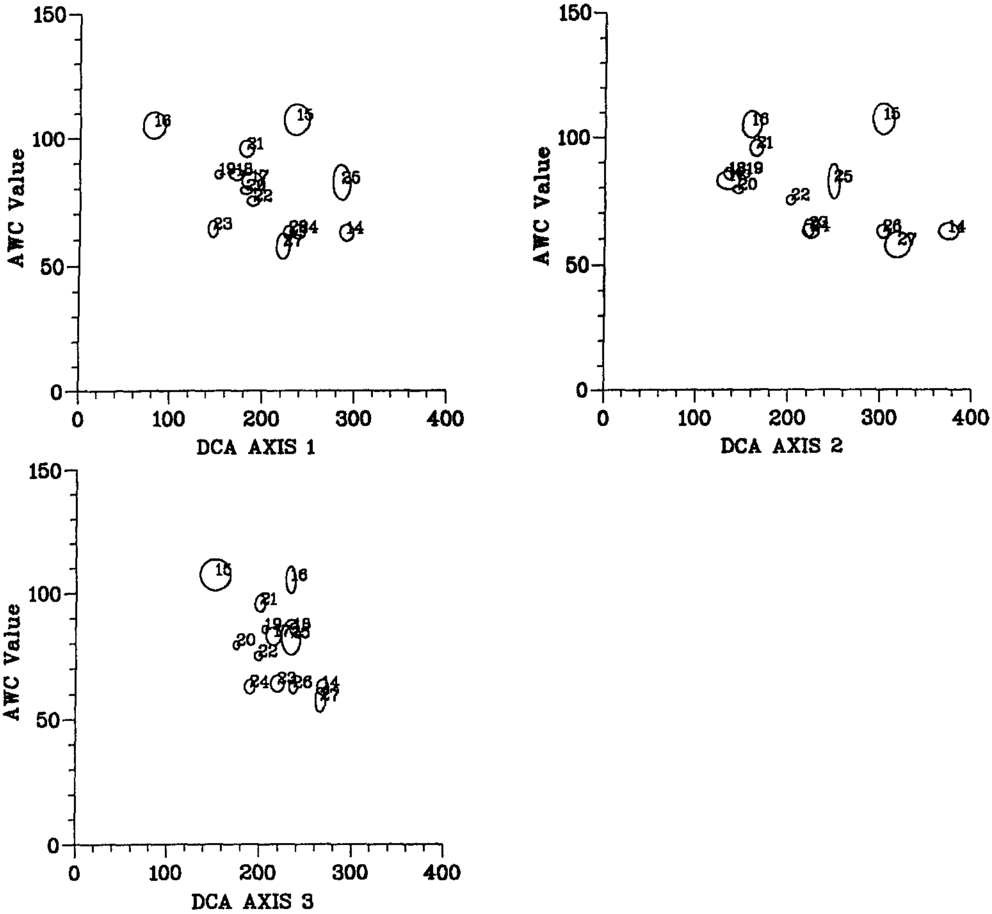

Fig. 3. Plot of TWINSPAN classes by their DECORANA/AWC scores.

Secondly, it shows that the same range of AWC values can derive from different combination of properties (the classes are separate on one or more of the DECORANA axes), for example classes 15 and 16. This tended to indicate that it would be possible to aggregate soil mapping units to produce larger units with homogeneous AWC characteristics. Finally, classes with little separation on the plot were found on examination to have similar profile features. The lack of reassignment of profiles to other groups after later sub-division and the independence of the branches of the tree were the probable causes of the similarities. The decision was thus made to treat the end groups as being semi-independent. Thus it was judged to be permissable to later combine AWC groups with similar properties otherwise separated by the tree structure.

Having developed a sufficiently robust classification scheme for the AWC profiles it was necessary to calculate the statistics for the classes and to forge the links between these classes and the units of the soil map. Because the sample size was too small to link directly to the soil mapping units it was necessary that the link be made at a soil association level. Soil associations were utilised as they represent the next level of aggregation above the soil mapping units, being grouped on the basis of parent material. A cross-tabulation of soil associations and AWC classes was examined and the rules for the recoding of the 1 : 250,000 Soils map of Scotland as an AWC map were developed.

The recoding first removed those areas not pertinent to this drought assessment. This group includes those Soil Associations unrepresented within the sample (2.24%), those soil associations not classifiable within the scheme (1.66%)* and those soils and soil associations not included in the AWC calculations (49.42%). This later group, composed of organo-mineral soils and peats, was excluded from the assessment as this study was restricted to evaluating mineral soils. The links between AWC class and soil association can be made at any level of the TWINSPAN tree (Figure 2) but with each step up the tree there is a corresponding widening in the range of possible values for the class. Certain soil associations were seen to be confined to one AWC class and this allowed a direct link between the two. This tended to be the case for the less extensive associations in which the range of soil conditions is relatively restricted. Other associations had an obvious core group with closely associated outliers. In this case the core group was taken as the dominant class and recoded accordingly. For the most extensive associations it was sometimes necessary to combine up to five classes to adequately represent the diverse range of soil properties seen within them. The statistics for these combined classes were calculated and as expected the range of AWC class values reflected the diversity of the soils physical properties.**

Once the soils map had been recorded into AWC Class values it was still necessary to match its resolution to that of the crop adjusted water deficit surfaces. This entailed a reduction in resolution from 100 m grid cells to 1 km resolution. The generalisation was on the basis of majority, that is the dominant Soil Association by area is taken to represent the grid square as a whole. A second coding of the Soils Map was also produced in which one standard deviation was subtracted from the mean AWC value used. This was designed to allow the assessment of the impact of drought on soils within associations with below average AWCs, due to factors such as limited profile depth.

7. Soil Drought Susceptibility – Results and Implications

The Soil Drought Susceptibility Maps were the difference of the AWC maps and the Crop Adjusted Water Deficit (Winter Wheat) Maps. Two illustrations of the output from this process are presented, (Figures 4 and 5), both based on the mean

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* This group is composed of associations with members in the majority if not all of the AWC classes. Principal among these was the Alluvial Soils association which exhibits a wide range of characteristics and AWCs.

** A full listing of the Association groupings are available in consultation with the authors.

TABLE I: Break down of the drought susceptibility assessment by area

Part 1: the assessment area

Class	% of Land area
Not compiled into digital 1 : 250,000 map	4.65
Land covered by standing water	2.61
Organo-mineral or peat	49.42
Not represented in the AWC sample	2.24
Not classifiable by TWINSPAN	1.66
Drought assessment area	39.42

TABLE II:

Part 2: Break down by percentage of the land area of Scotland

Moisture balance	Percentage land area
> −20 mm	4.07
−16 — −20 mm	11.79
−11 — −15 mm	10.42
−5 — −10 mm	2.95
0 — −5 mm	3.12
No change	7.07

TABLE III:

Part 3: Break down of the changes between the two periods

Moisture balance	Current climate	2030 climate
< −25 mm	0.0	0.01
−25 — 0 mm	0.03	1.21
1 — 25 mm	1.77	7.15
26 — 50 mm	9.69	14.63
51 — 75 mm	23.28	14.15
> 75 mm	4.65	2.27

values for AWC, the first for the current climatic regime and the second for the 2030 scenario. The statistics associated with these maps, calculated within the GIS, are presented in Table I. This dual presentation of the results as both statistics and maps was found to be the most effective in the interpretation of the potential impacts. The statistics provide the information on the magnitude of changes and the maps enable the assessment of their geographic extent.

Within the limits of a simple climatic change scenario the maps delineate six areas where average climatic and soil conditions would combine to produce a water deficit or marginal surplus (1–25 mm). These are: the valley of the River

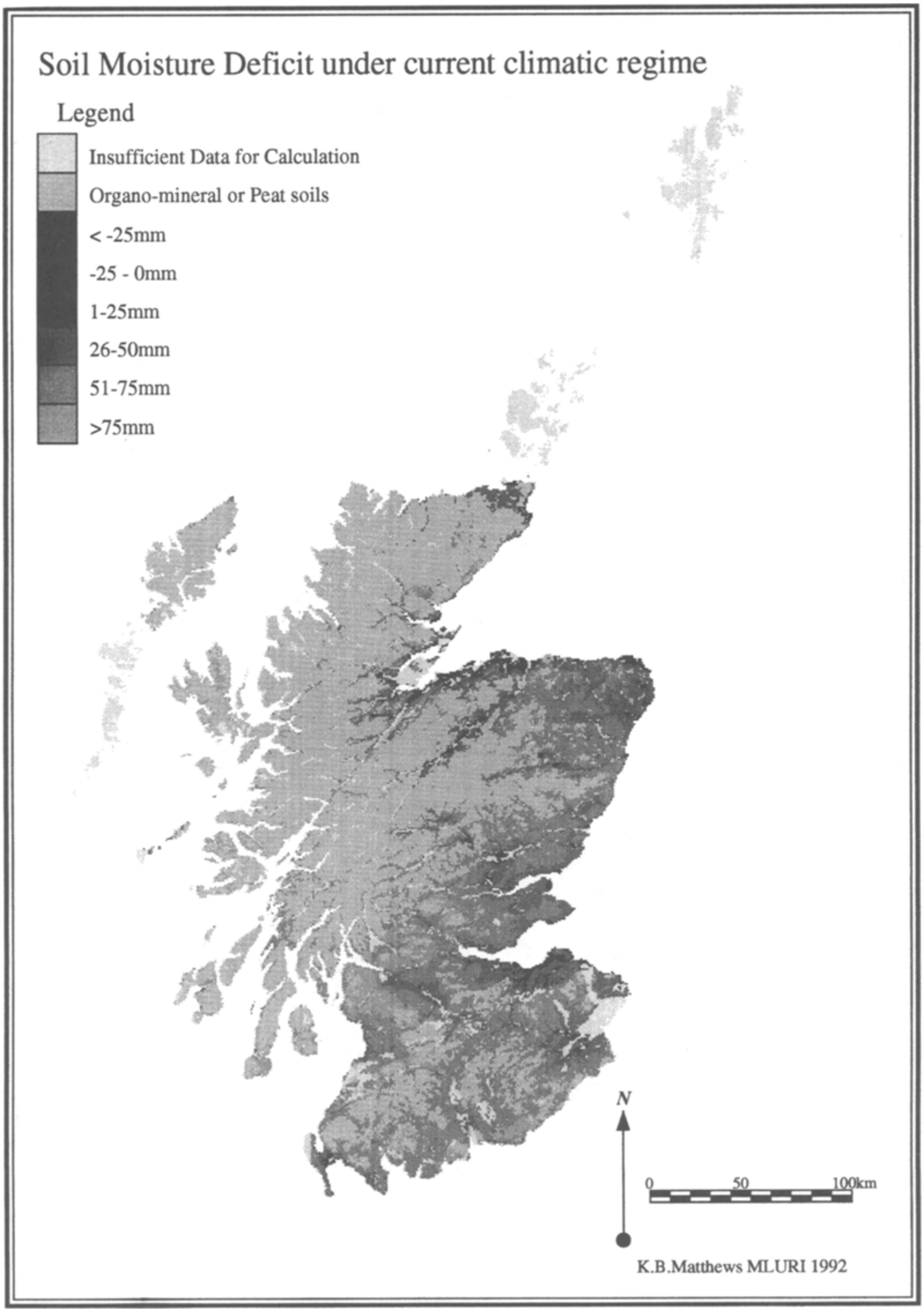

Fig. 4. Soil Moisture Deficit under current climate regime.

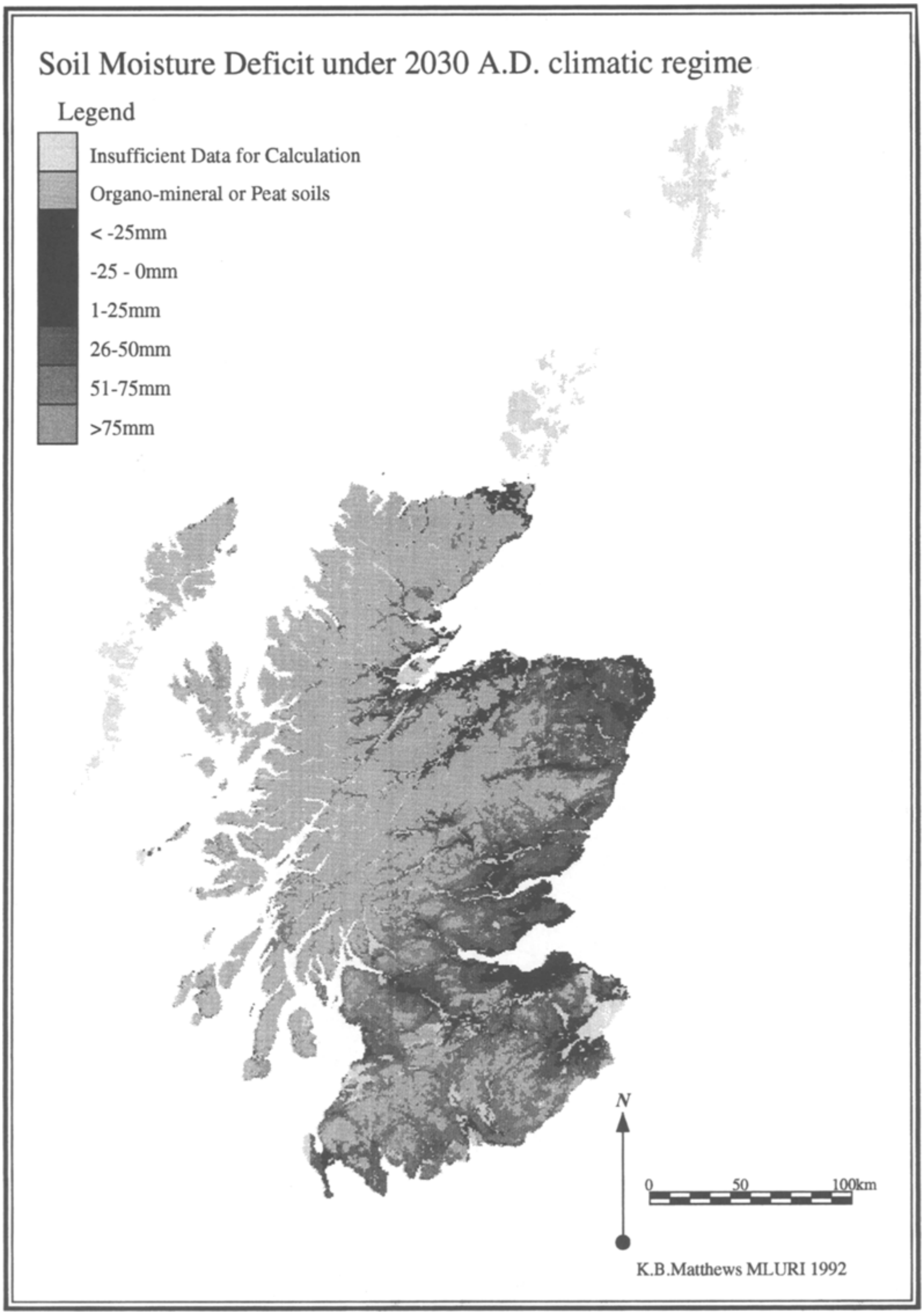

Fig. 5. Soil Moisture Deficit under 2030 A.D. climatic regime.

Tweed; a swath of Lothian centred on Edinburgh; the Fife and Tayside coasts; the Buchan Peninsula coast; the Moray coast; and the Spey Valley. In addition to these areas it is worth noting the increased drought susceptibility in several river valleys: the Dee; the Ythan; the Tay; and the Clyde. The areal statistics also point to the increased susceptibility to droughting with the area of deficit increasing from 0.03% to 1.22% and the area of marginal surplus increasing from 1.77% to 7.15%. The final part of Table I breaks down the changes between the two periods. While there are significant areas of no net change in drought susceptibility (7.07%) the bulk of the changes (22.21%) are between −11 and −20 mm.

From these results it seems clear that climatic change due to global warming would have a significant impact on the drought susceptibility of Scottish soils. The implications of this change for Scottish agriculture would most probably be felt in terms of the need to maintain yields in certain areas by irrigation, and in others the increased risk of yield reductions due to periodic drought stress. The use of water for irrigation could also lead to competition for water resources with other consumers with a consequent further increase in costs. These increased costs could be of sufficient magnitude to require changes in the patterns of landuse in the most affected areas.

8. Appraisal of the Methodology, and Future Developments

While the methodology presented is practical and believed to be fundamentally sound there were several areas where future applications could benefit from refinements.

An extension of the sample of profiles used in the AWC classification would help to refine the statistics available for the AWC classes. A more extensive profile set would also eliminate those areas of agricultural importance for which no values could be calculated (2.24%), for example the Black Isle and Tweed Valley. Combined with this an increase in the resolution of the final output from 1 kilometre to 100 m would permit the mapping of soils of limited extent but with significant local importance to agriculture, for example the soils of the raised beaches of the Sutherland coast.

Future developments could also take advantage of developing methodologies in classification. In particular the use of fuzzy-set classification to establish AWC classes and define the profiles' degree of membership within an AWC class would seem appropriate.

Refinement of the estimation of PE calcualtion is also possible. Initially this would focus on extending the latitude correction factors to cover the full range of latitudes. More fundamentally, however, the effective calculation of PE probably requires either further development of wider range of variables with a smaller temporal scale to permit the use of the Penman formulae or the use of a more robust formula for relating PE to basic monthly datasets.

The definition of the growing season for the calculation of CASMD is also a potential source of error. Intuitively there must be a geographic element to the definition of the seasonality of the crop. A further investigation of this would prove valuable as it would allow the use of geographically specific formulae for the calculation of CASMD.

In the presentation of the values from the calculation refinements would include the use of the known proportions of soils within the 1 km grid. If the SDSA is presented as a probability of exceeding a threshold value then all the soil information in the 100 m grid can contribute to the final value not the single dominant 1 km value. The proportions of the soils determine the degree of influence in the grid cell. This will be of particular importance where there are several soils of differing character with similar proportions. This probability approach also permits the inclusion of the range values within each AWC class, potential model and input data errors within the analysis (Aspinall, 1993).

Thus it is by establishing methodologies and structures for the successful integration of existing datasets that it is possible to begin to make assessments of the impacts of changes in the future climatic regime.

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