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Original article

Use of soil and climate data to assess the risk of agricultural drought for policy support in Europe

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Abstract – This paper describes the use of soil and climatic data for assessing the risk of drought in Europe. Soil moisture regimes are defined for soil classification purposes and these can be used to delineate areas with the same type of soil climate. Maps showing the distribution of arid soils in USA and dry areas in Southern Europe are presented. In the case of agricultural drought, it is the soil water available to plants (SWAP) that is the most important soil factor in assessing this risk and a simple model for estimating this is described. This model can be linked to spatial and point data from the European Soil Database. In the absence of sufficient soil water retention measurements, preliminary maps of SWAP in Europe have been produced using pedotransfer rules. The study concludes that basic soil maps can be used to identify some areas where agricultural drought is likely to be a problem. However more precise modelling of droughtiness, based on interactions of soil available water with the average soil moisture deficit, estimated from meteorological data, is needed, to support policy making today.

soil / climate / drought / risk / policy / Europe

Résumé – Utilisation de données pédo-climatiques pour l'évaluation du risque de sécheresse agricole en Europe. Cet article présente un exemple d'utilisation de données pédo-climatiques dans le but d'évaluer le risque de sécheresse agricole en Europe. Une délimitation de zones présentant un comportement pédo-climatique similaire est réalisée en s'appuyant sur une classification des régimes d'humidité du sol. La quantité d'eau disponible pour la plante dans le sol (SWAP, en anglais) est le facteur pédologique le plus important dans l'évaluation du risque de sécheresse pour les zones agricoles d'Europe. Un modèle simple d'estimation de cette variable est présenté. Ce modèle peut être relié aux données géoréférencées de la Base de Données des Sols d'Europe. Une première carte du SWAP a été réalisée pour l'Europe sur la base de fonctions de pédo-transfert. Cette étude montre que bien qu'une carte simple puisse être utilisée pour identifier les zones agricoles susceptibles d'être affectées par la sécheresse, une modélisation plus précise est aujourd'hui nécessaire pour aider à la prise de décision.

sol / climat / sécheresse / risque / décision / Europe

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1. Introduction

A drought is a decrease in water availability in a particular period over a particular area [3]. Research by Wilhite and Glantz [34] in the early 1980s uncovered more than 150 published definitions of drought. The definitions reflect differences in regions, needs and disciplinary approaches. They categorised their collection of definitions into four basic approaches to measuring drought: meteorological, hydrological, agricultural and socio-economic. The first three approaches deal with ways to measure drought as a physical phenomenon. The last deals with drought in terms of supply and demand, tracking the effects of water shortfall as it ripples through socio-economic systems.

Droughts are usually described in terms of their impact or by their duration, severity and probability of reoccurrence [4, 34]. A combination of meteorological factors, mainly precipitation and temperature, produces drought conditions. Thomasson [27] describes drought as a lack of rain and drought conditions result from a lack of an expected amount of precipitation.

In addition to the different types of drought, namely meteorological, hydrological, and agricultural droughts, the term soil droughtiness [27] has also been applied in an agricultural context. An agricultural drought, sometimes referred to as an agro-meteorological or agroclimatic drought, occurs when there is insufficient moisture in the root zone to sustain plant growth. It can be estimated and/or quantified by considering three aspects: climate or weather, soil water properties and plant or crop requirements. Soil droughtiness can be regarded as an important component of, if not synonymous with, agricultural drought.

Because of its importance in soil processes, soil moisture is also used as a fundamental criterion for soil classification, in both international [7, 8, 25] and national systems (for example those of the UK, Germany, France, The Netherlands). A lack of soil water is used to define arid soils and the occurrence of these soils can be expressed in map form. In this respect, soil maps can be used to some extent to identify areas that are likely to suffer agricultural droughts.

This paper describes the use of soil and climatic data for assessing the risk of agricultural drought in Europe. The main objective is to show how drought risk can be assessed at the continental scale in a manner that should be of interest to researchers and policy makers alike. There have been many detailed studies of drought [34] but this paper attempts to use the knowledge gained from research in this field to produce assessments in a spatial context. The first part of the paper describes the basis for mapping arid soils and hence those that can usually be associated with drought conditions. This is followed by a more rigorous quantified approach to assessing the risk of agricultural drought in Europe based on soil-climate interactions.

2. Materials and methods

2.1. Risk assessment

A risk is the chance of a bad consequence or loss. Another definition of risk is the chance that some undesirable event may occur. Risk assessment involves the identification of the risk, and the measurement of the exposure to that risk. The response to risk assessment may be to initiate categorisation of the risk and/or to introduce measures to manage the risk. In some cases, the risk may simply be accepted. Such risk management is a significant activity in the agricultural industry and has been so since very early times (5000 years ago).

The risk assessment addressed in this paper is the general or average risk that is likely to occur in most years based on a combination of soil factors and climate. Quantifying this kind of risk is of value for long-term planning. There is another kind of risk, within-season risk, that is the result of a combination of soil factors interacting with the weather during a particular season. This is also important for agriculture and a full risk analysis should include both average and seasonal risk. However, this paper only addresses average risk because, at the European scale, the weather data for assessing risk in the short term (during a season) are lacking at the spatial resolution that is needed.

2.2. Soil classification and drought risk

The USDA system of soil classification, Soil Taxonomy [24–26], has been developed over the past five decades. Although some would argue that it is not strictly an international system, it is in such widespread use throughout the world that we will consider Soil Taxonomy truly international for the purposes of this study. The system uses soil-climate characteristics for identifying soil taxa at suborder level, which is an important level in the identification of soil types. To make this possible, Soil Taxonomy identifies soil moisture regimes (SMR) based on moisture conditions in the soil moisture control section (SMCS). The intention in defining the SMCS is to facilitate estimation of soil moisture regimes from climatic data.

The SMCS is considered to extend approximately from:

(1) 0 to 30 cm below the soil surface if the particle-size class of the soil is fine-loamy, coarse-silty, fine-silty, or clay;

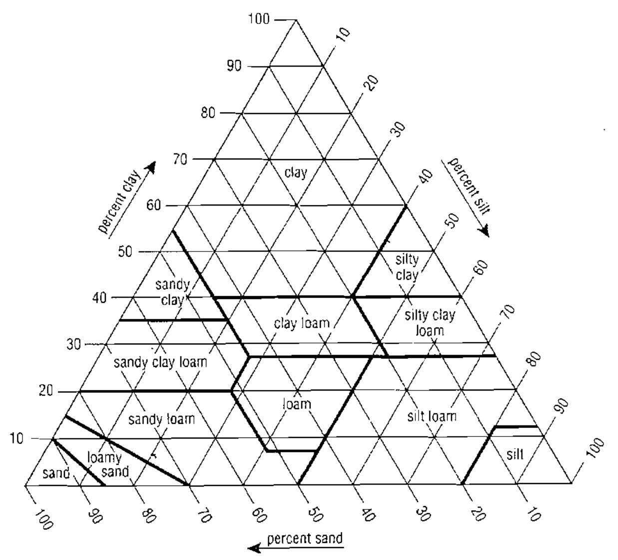


Figure 1. Soil texture classes (Schoeneberger et al. 1998).

(2) 20 to 60 cm if texture is coarse loamy;

(3) 30 to 90 cm for sandy soils.

These texture classes are broad categories that can be summarised as follows:

Sandy	loamy sand and sand
Coarse loamy	sandy loam, loam (< 20% clay)
Coarse silty	silt, silt loam
Fine loamy	clay loam, sandy clay loam, loam (> 20% clay)
Fine silty	silty clay loam
Clay	sandy clay, silty clay, clay.

The individual texture classes are shown in Figure 1.

The limits of the SMCS are affected not only by the textural composition of soils, but also by differences in soil structure or pore-size distribution or by other factors that influence the movement and retention of water in the soil.

Soil moisture regimes and, additionally soil temperature regimes (STR), are fundamental characteristics that are used for classifying soils at Order level in the Soil Taxonomy. Other soil classifications systems, such as the FAO Legends [7, 8] and the World Reference Base for Soil Resources or WRB [6] also use similar concepts. However, the FAO and WRB systems do not use climatic data per se directly for classification but instead use various soil climate criteria in the definitions of soil mapping units. This explains the emphasis given here to the Soil Taxonomy to illustrate how soil classification can be used as a first step in identifying drought prone areas.

Distribution of arid soils

The spatial distribution of soils in the dry areas, i.e. arid soils, reflects the soil classification system used. In the USDA Soil Taxonomy, the soil moisture regime (SMR) classes used for separating soils at Order level, are defined in terms of the seasonal presence or absence of water held at a tension of 1500 kPa in the moisture control section (SMCS). A tension of 1500 kPa approximates to wilting point. It is assumed in the definition that the soil supports vegetation according to its capability i.e. crops, grass, or native vegetation, and that the amount of stored moisture is not being augmented by irrigation or by leaving land in fallow. These practices significantly affect the soil moisture conditions for as long as they are continued. The classes of SMR related to dry areas are described in the sections below.

Aridic and Torric (L. *aridus*, dry, and L. *torridus*, hot and dry). These terms are used for the same regime but in different categories of the Soil Taxonomy. In the aridic (torric) moisture regime, the SMCS in a normal year, is:

(1) Dry in all parts for more than half of the cumulative days per year when the soil temperature at a depth of 50 cm from the soil surface is above 5 °C; and

(2) Moist in some or all parts for less than 90 consecutive days when the soil temperature at a depth of 50 cm is above 8 °C.

A "normal year" is defined as a year that has plus or minus one standard deviation of the long-term (30 years or more) mean annual precipitation [25, p. 33].

Soils that have aridic (torric) moisture regimes normally occur in areas of arid climate. A few are in areas of semi-arid climates and either have physical properties that keep them dry, such as crusty surface that virtually precludes the infiltration of water, or are on steep slopes where run-off is high. According to Soil Taxonomy, these soils are named Aridisols. They occur in the western parts of the USA, Africa and Asia. They receive very little precipitation such that normal agriculture is precluded.

Ustic (L. *ustus*, burnt, implying dryness): is intermediate between the aridic regime and the udic regime (L. *udus*, humid). This definition is based on the concept that moisture is limited, but is present at a time when conditions are suitable for plant growth. This concept is not applied to soils that have permafrost conditions. Ustic criteria are described very precisely in the Soil Taxonomy [25, p. 34], in climatic terms. Ustic moisture regimes are spread throughout Europe, but their main domain is in the southern parts of the continent. Irrigation is necessary if good yields of agricultural crops are to be obtained.

Xeric (Gr. *xeros*, dry) moisture regimes are typical in areas of Mediterranean climate, where winters are moist and cool, and summers are warm and dry. The moisture, which falls during the winter, when potential evapotranspiration is at a minimum, is particularly effective for leaching.

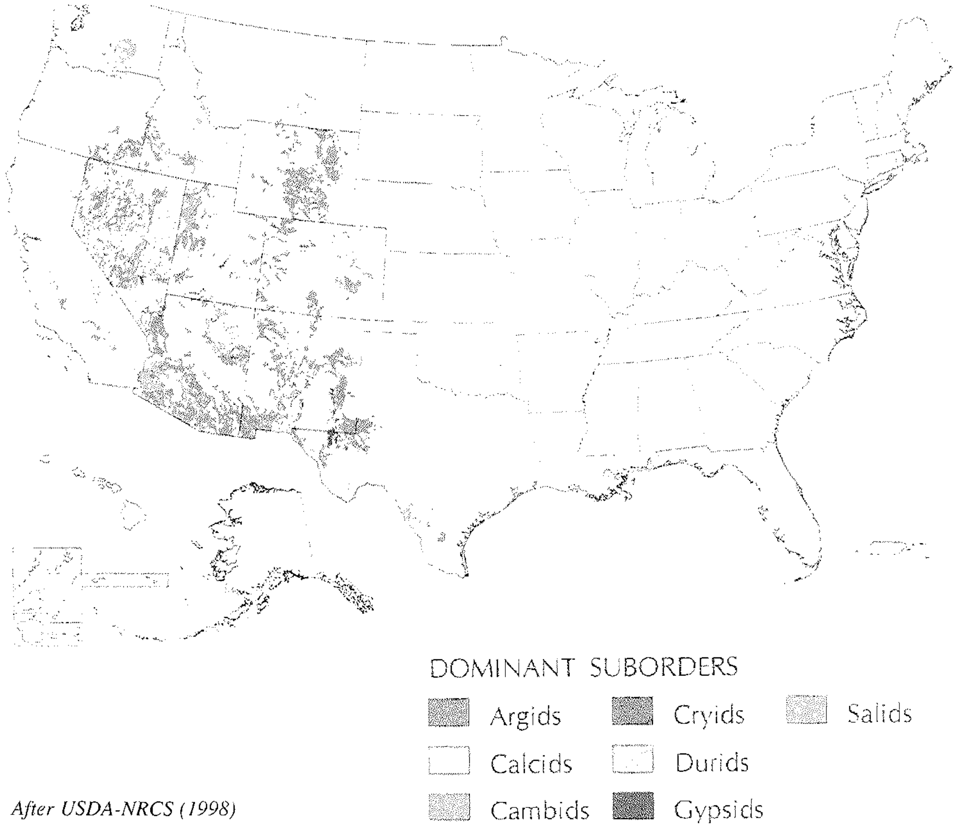
In areas with xeric soil moisture regimes, the SMCS, in normal years, is dry in all parts for 45 or more consecutive days in the 4 months following summer solstice, and moist in all parts for 45 or more consecutive days in the 4 months following winter solstice. The temperature criteria for xeric soil moisture regimes are defined precisely by Soil Survey Staff [25, p. 34].

Xeric moisture regimes are widely distributed in the Mediterranean region [5], occurring in Spain, southern France, southern Italy, Albania, Greece, the Middle and the Near East and North Africa. Zdruli et al. [36] have described xeric soils in detail for Albania. Some of the most typical soils of this area are classified as Rhodoxeralfs (Soil Taxonomy), or Chromic Luvisols [8]. They have the potential to be very productive if there is an adequate supply of moisture and if they are managed properly. If mismanaged, these soils will degrade rapidly through wind and water erosion.

Using the terminology of the Soil Taxonomy, the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) have produced a map of arid soils in the USA (Fig. 2). This map shows the approximate extent of arid soils and it is compatible with the conventional view of pedologists of where arid soils occur in North America.

In Europe, typical soils related to dry areas [7], are the Xerosols and Yermosols. They occur most widely under xeric soil moisture regimes. The distribution of these soils can be studied using the European Soil Database. This contains geographical data that represent the soils according to the FAO-UNESCO [7, 8] Legends. The geographical data are based on the EC Soil Map (CEC, 1985) that was originally prepared at a scale of 1:1 000 000.

After the FAO-UNESCO [7] Legend was revised [8], soils were grouped differently. However in many parts of the world, the lack of climate data



After USDA-NRCS (1998)

Figure 2. The approximate extent in USA of soils classified as arid according to soil taxonomy.

precludes the use of soil-climate properties as differentiating criteria. Therefore, in the FAO-UNESCO-ISRIC [8] system, dry soil types, i.e. those that generally occur in aridic conditions, or are physiologically droughty, are included in other soil units, as for example: the Calcisols, Gypsisols, Solonchaks, Solonetz, Arenosols, Vertisols, Luvisols, Cambisols and Ferralsols. To plot the distribution of arid soils in southern Europe, we have assessed the major soil groupings listed above on a national basis using the soil name attached to the soil map unit in the European Soil Database and the results are shown in Figure 3.

There is considerable scope for improving this map by further reappraisal of the soil map units on a regional (i.e. sub-national) basis and by superimposition of climatic data to identify areas of low precipitation more precisely. We propose to do this in a future project. However, the results presented here represent a first step in the translation of pedological terms, that are understood only by soil scientists, into terminology that can be readily understood by agronomists, planners and policy makers.

The World Reference Base (WRB) for Soil Resources [6] is effectively the latest version of the FAO classification system. It describes soils that occur in dry areas as Durisols, whilst other related soils, occurring in dry conditions, are included in several soil groups: Vertisols, Solonchaks, Solonetz, Ferralsols, Gypsisols, Calcisols, Albeluvisols, Luvisols, Cambisols and Arenosols. In common with the FAO-UNESCO system, WRB recognises the importance of soil-climate characteristics but does not use these criteria directly because climate data are so scarce in many parts of the world, where the system is likely to be used.

The examples described above illustrate the close link between soil mapping (and classification)

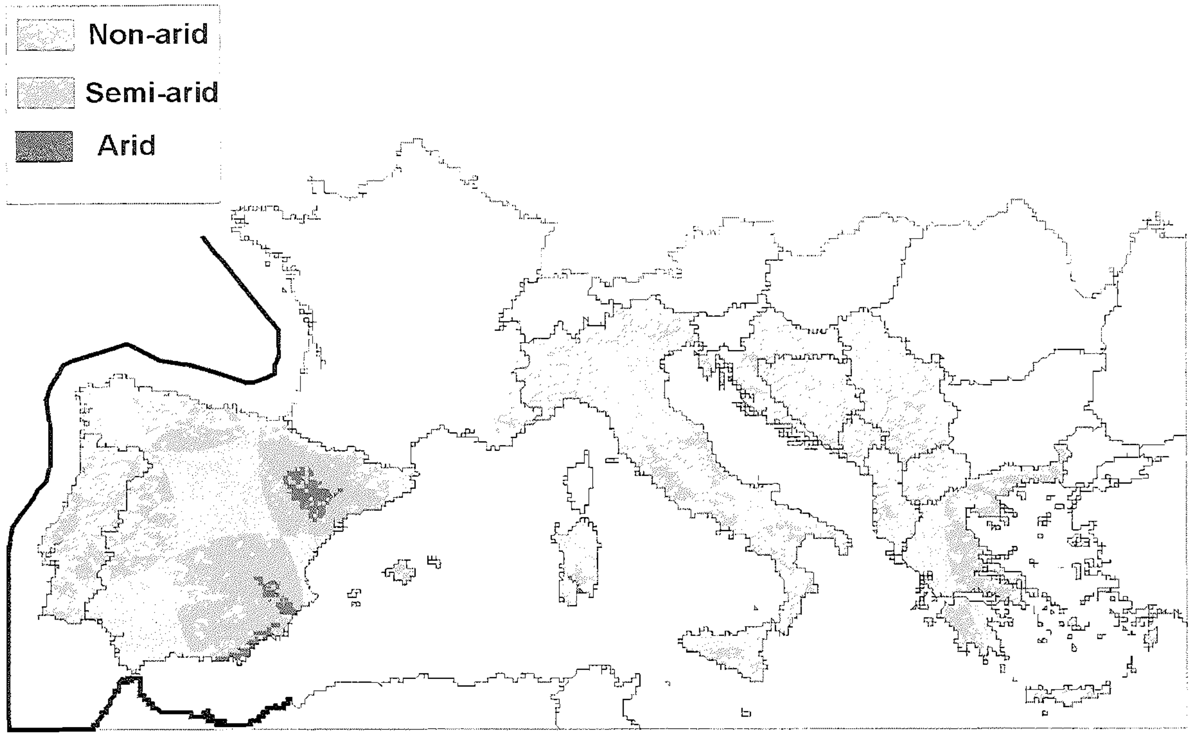


Figure 3. The approximate extent in Europe of soils inferred as arid from soil classification.

and soil climate characteristics. It has been shown that soil maps can be useful as a first step in delineating areas suffering from aridity. Therefore, such maps offer a starting point for identifying areas where there is a risk of drought and where drought mitigation practices may be needed. However, "arid or dry areas" are not exclusively associated with low precipitation. For example, saline areas in humid regions are considered to suffer from a form of drought because the quality of water prohibits crop growth.

2.3. Assessment of agricultural drought risk

In the case of agricultural drought, it is the water available to plants that is the most important soil factor that needs to be quantified. The following sections describe the calculation of the soil water available to plants and how this can used to estimate drought risk.

Soil available water

Thomasson [28] has comprehensively reviewed a range of models for estimating the soil available water, often called available water capacity (AWC) in the literature. He concludes that a simple "capacity" model is most appropriate given the current availability of data in Europe. Recognising the need for more flexibility, Thomasson defined a new term, the soil water available to plants (SWAP) for the total amount of water that can be considered to be extractable by the roots of different crop plants. The basic concepts of soil water availability and the calculation of SWAP in a European context are described in detail by Jones et al. [14].

Essentially the soil water available to plants is held at a range of suctions from wilting point (1500 kPa) to field capacity, the water content at low suction (< 35 kPa). Provided the water contents at these suctions (wilting point and field capacity) is known or can be estimated, the total amount of water in the soil that is available to plants can be calculated. The SWAP approach of Thomasson [28] is more sophisticated than traditional approaches to calculating soil available water because it takes into account the rooting depth of specific crops and partitions the available water according the suction that the plant roots have to overcome to extract the water. The SWAP approach is used in the United Kingdom [9, 20, 29], Denmark [12], and Germany [22]. However, the information to estimate SWAP at this level of sophistication does not exist on a consistent basis throughout the EU. In particular, there is a lack of adequate data on bulk density and depth of water abstraction for some regional soil and climatic landscapes.

The European Soil Bureau (ESB), based at the Joint Research Centre, Ispra (Italy) has been sponsoring the collection of soil information throughout Europe for more than ten years [19]. This has culminated in the compilation of the first version of a European Soil Database, containing spatial data at 1:1 000000 scale for the whole continent [10] and analytical data for standard profiles [17, 18] that can ultimately be linked to the spatial soil data. The process of data collection which is still going on offers the promise of the necessary soil physical data becoming available sometime in the foreseeable future. In the short term however, simplistic methods based on pedotransfer rules [3] and standardised data are all that can be used to calculate soil water available to plants on a continental scale [16].

3. Results and discussion

The European Soil Database therefore provides a starting point for delineating plant available water (SWAP) at a European level. The structure of the European Soil Database is outlined in general terms in Heineke et al. [10]. For simplicity, it is sufficient to say here that the Soil Map of Europe [2] is made up of polygons grouped into Soil Map Units (SMU). These SMUs are complex units of soils that are subdivided in semantic terms into Soil Typological Units (STU) that represent each soil type present on the map [15]. Figure 4 shows the distribution of SWAP values, in classes (mm), for a 1 m depth of soil (or shallower if there is any obstruction to rooting). Figure 5 shows the distribution of SWAP values for a short rooting crop such as potatoes using a standard rooting model [14].

The SWAP values were estimated using pedotransfer rules [16] that transform the Soil Typological Unit (STU) into a profile available water capacity or SWAP class. A detailed description of the calculation process and the distribution of SWAP values for other crops, such as grass and maize, are also described in Jones et al. [14].

The basic modelling procedures used for this study make validation difficult. However, the SWAP estimates for a 1m depth of soil in Denmark (Fig. 5) compare closely with the root zone capacity (RZC) maps for wheat produced by Jensen et al. [12, pp. 431, 432]. Results from this study show that SWAP values for a 1m depth of soil compare closely with SWAP data for cereals based on a standard crop-rooting model. Furthermore, the distributions of SWAP for cereals and SWAP in a 1m depth of soil in the UK compare well with soil available water maps produced using national soil data [20].

The ESB is currently working on extending the European Soil Database to encompass the whole of the Mediterranean Basin (including the Middle and the Near East, and North Africa) where the problems of drought are particularly acute. In future, therefore, to obtain a truly accurate assessment the risk of agricultural drought in this extended European area, the interaction between the soil water available to plants (SWAP) and the soil moisture deficit (MD) estimated from meteorological data must be examined. The following sections expand on this interaction and how it could be achieved.

3.1. SWAP and soil climate

During periods when potential transpiration exceeds rainfall, i.e. (PE > R), soil dryness can be quantified as the accumulated negative sum of (R-PE), defined by Jones and Thomasson [13] as the

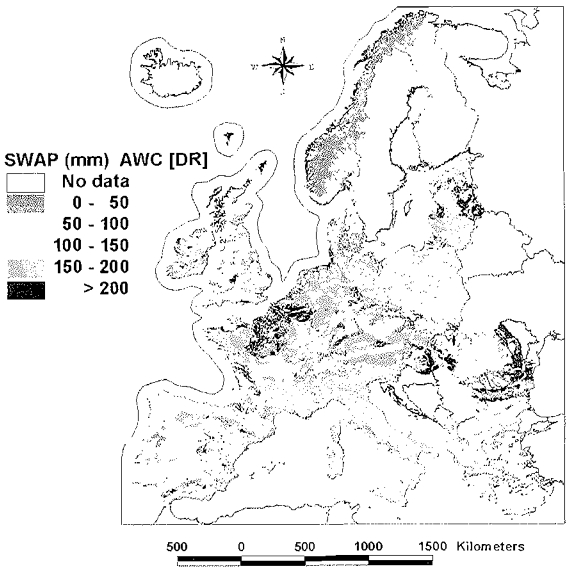


Figure 4. Soil water available to plants, SWAP (mm) to 1 m depth or to a rooting restriction.

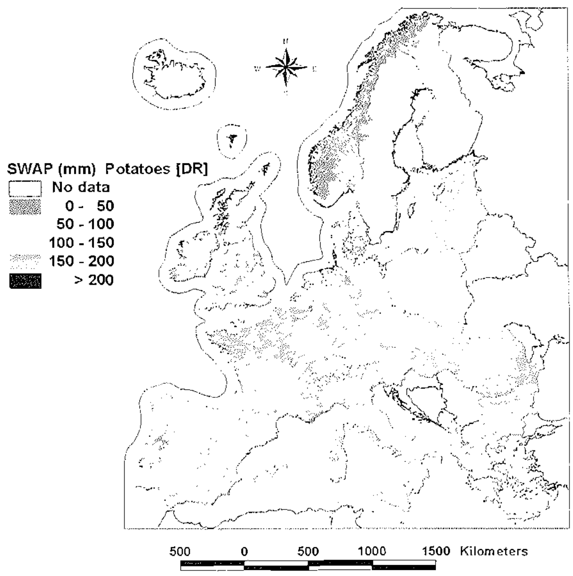


Figure 5. Soil water available to plants, SWAP (mm) for a short rooting crop e.g. potatoes.

potential soil moisture deficit (PSMD). This can be calculated from basic meteorological data and accumulated over the growing season of a crop to provide an index of climatic dryness.

The average risk of drought in an area can then be estimated using a simple "capacity model". The average potential soil moisture deficit in mm (PSMD) can be adjusted for different crops (MD-crop), also measured in mm, as described by Thomasson [27]. The resulting crop adjusted MD (mm) is then subtracted from the SWAP value (mm) calculated for the same crop according to the standard rooting models described by Jones et al. [14]. If the result is negative then the area is regarded as droughty for the crop in question but if it is positive, then the system is regarded as providing sufficient moisture for sustaining crop growth.

Currently there is a serious lack of reliable measurements of water retention properties, essential for calculating SWAP for soils in Europe. However, it is likely that during the next few years, techniques to measure or derive data that quantify the complexity of soil water relations will improve. In the meantime, simple pedotransfer rules [16, 31] and mathematically based pedotransfer functions [1, 35] offer the only alternative for estimating the soil component of drought risk.

In the UK and Denmark where there are accessible soil and climatic data sets, SWAP values are combined with climatic data to provide estimates of drought for policy making in the agricultural sector [12, 13, 29, 30]. In these north European countries, drought is not currently perceived as being of great significance yet the basic data do exist to estimate the risk. The next stage at European level will be to calculate moisture deficits, preferably on a grid basis, as has been done for UK [21], and produce distribution maps of average droughtiness based on the SWAP and average MD crop data. The meteorological data to make this possible are currently stored for the whole of Europe by the MARS Project at JRC [32].

3.2. Meteorological data

Meteorological data are crucially important for inputting to drought models. The resolution of these data is also crucially important for accurately

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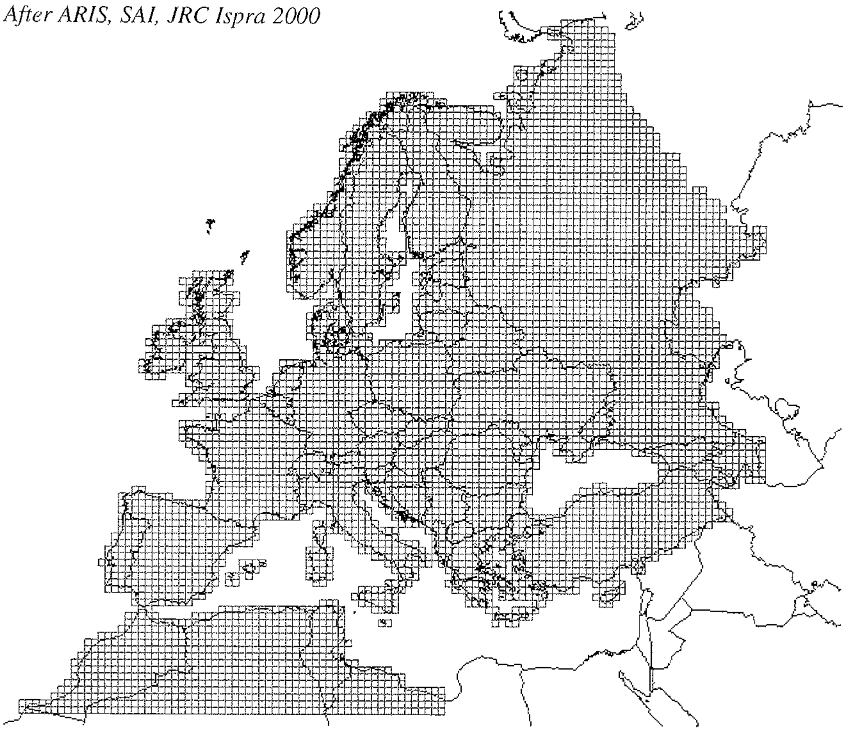

Figure 6. The 50 km × 50 km grid of the MARS meteorological database.

predicting the risk of drought. A major initiative in the MARS Project was the interpolation of European climate data on a 50 km × 50 km grid to facilitate the estimation of crop yields from the Crop Growth Monitoring System (CGMS). Figure 6 shows the distribution of the 50 km × 50 km grid squares of the MARS meteorological database. This database contains daily temperature, rainfall and evaporation for each grid square.

The data are derived from measurements, made at individual meteorological stations, which have been interpolated and subsequently corrected, for output on the 50 km grid. These data are the best currently available for the whole of Europe. However, weather and climate can change significantly over 50 km in many parts of the continent and it is clear that ultimately better data will be needed at European level to provide accurate predictions of the risk of agricultural drought. A "MARS climatology" on a 25 km × 25 km or 20 km × 20 km grid, using techniques similar to those used by Ragg et al. [21] and Hough and Jones [11], would provide a much better basis for calculating droughtiness.

For example, temperature data can be mapped more precisely than at present by using a digital terrain model (DTM). A 1 km × 1 km DTM, currently available at JRC, contains the altitude values that could be used, together with the strong relationship between temperature and altitude, to interpolate temperature parameters. Monthly mean temperatures, with standard deviation or quartile values, calculated for the individual meteorological stations, would probably be sufficient for producing interpolated data sets.

Interpolating rainfall data at finer resolution than 50 km × 50 km with the aid of a DTM is much more difficult than for temperature because the effect of altitude on rainfall amounts is complex. There is no physical standard like the adiabatic lapse rate (6 °C per 1000 m rise). For example, in sheltered situations, rainfall can decrease with increasing altitude, whereas in areas where the weather systems are dominantly cyclonic, with strong prevailing winds, orographic effects cause rainfall to increase with altitude on the windward side of any high ground. Conversely, the relationship between altitude and temperature deviates only slightly from the standard rate. Despite these complications, improving the spatial resolution of the MARS climatology database, particularly for evaporation and rainfall, has now become an urgent requirement.

4. Conclusions

It has been shown that basic soil maps can be used to identify areas where broadly agricultural drought is likely to be a problem. This approach could be useful as a "first filter" for land evaluation, i.e. whether it is possible to grow a particular crop in a specific area or the degree of risk for a cropping system. However, more precise modelling of droughtiness, based on soil-climate interactions, is needed to support policy making today. The relevance of this type of modelling, applied through a soil map at 1:1 000 000 scale, may be questioned. It is more appropriate at scales of 1:50 000 or larger, where real crop performance in specific fields, or where detailed management interventions, are being evaluated. It is clear that the basic data to run such models at scales less than 1:1 000 000 will be lacking for some parts of Europe for many years to come. In the absence of these data, however, the approach described in this paper offers the best chance of achieving results that are satisfactory enough for broad scale policy making in the immediate future.

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References

[1] Bruand A., Duval O., Wösten J.H.M., Lilly A. (Eds.), The use of pedotransfer in soil hydrology research in Europe. Workshop proceedings, INRA Orleans, France, 10–12 October 1996, European Commission: Human Capital and Mobility (DG XII) CHRX-CT94-0639 (1997), 211 p.

[2] CEC, Soil Map of the European Communities, 1:1 000000, CEC Luxembourg, 1985, 124 p.

[3] Daroussin J., King D., A pedotransfer rules database to interpret the Soil Geographical Database of Europe for environmental purposes, in: Bruand A., Duval O., Wosten H., Lilly A. (Eds.), The use of pedotransfer in soil hydrology research in Europe, Proceedings of the second workshop of the project "Using exisitng soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning", EUR 17307 EN, 1997, INRA, Orleans, France, pp. 25–40.

[4] Dracup J.A., Kil Seong Lee, Paulson E.G. Jr., On the Definition of Droughts, Water Res. Resour. 16 (1980) 297–302.

[5] Eswaran H., Reich P., van den Berg E., Zdruli P., Global distribution of soils with xeric soil moisture regime, Third International Meeting on Red Mediterranean Soils. Chalkidiki, Greece. Summary Papers, 1995, p. 85.

[6] FAO, ISRIC and ISSS, World Reference Base for Soil Resources, World Soil Resources Report 84, Rome, 1998, 88 p.

[7] FAO-UNESCO (1974), FAO-UNESCO Soil Map of the World: Vol. 1, Legend, UNESCO, Paris, 1998.

[8] FAO-UNESCO-ISRIC, FAO-UNESCO Soil Map of the World: Revised Legend, World Soil Resources Report 60, Rome, 1990, 119 p.

[9] Hall D.G.M., Reeve M.J., Thomasson A.J., Wright V.F., Water retention, porosity and density of field soils, Soil Survey Technical Monograph No. 9, Harpenden, UK, 1977, 75 p.

[10] Heineke H.J., Eckelmann W., Thomasson A.J., Jones R.J.A., Montanarella L., Buckley B. (Eds.), Land Information Systems – Developments for planning the sustainable use of land resources, European Soil Bureau Research Report No. 4. EUR 17729 EN, 1998, Office of the Official Publications of the European Communities, Luxembourg, 546 p.

[11] Hough M.N., Jones R.J.A., The United Kingdom Meteorological Rainfall and Evaporation Calculation

System: MORECS Version 2.0 - An overview, Eur. J. Hydrol. 1 (1997) 227–239.

[12] Jensen N.H., Balstroem T., Madsen H.B., Root zone capacity maps for Denmark based on the EU soil profile analytical database, in: Heineke H.J., Eckelmann W., Thomasson A.J., Jones R.J.A., Montanarella L., Buckley B. (Eds.), Land Information Systems: Developments for planning the sustainable use of land resources, EUR 17729 EN, 1998, Office for Official Publications of the European Communities, Luxembourg, pp. 421–434.

[13] Jones R.J.A., Thomasson A.J., An agroclimatic databank for England and Wales, Soil Survey Technical Monograph No. 16, Harpenden, UK, 1985, 45 p.

[14] Jones R.J.A., Zdruli P., Montanarella L., The estimation of drought risk in Europe from soil and climatic data, in: Vogt J.V., Somma F. (Eds.), Drought and Drought Mitigation in Europe, 2000, Kluwer Academic Publishers, The Netherlands.

[15] King D., Jones R.J.A., Thomasson A.J. (Eds.), European Land Information Systems for Agro-environmental Monitoring, EUR 16232 EN, 1995, Office for Official Publications of the European Communities, Luxembourg, 285 p.

[16] King D., Le Bas C., Daroussin J., Thomasson A.J., Jones R.J.A., The EU map of soil water available for plants, in: King D., Jones R.J.A., Thomasson A.J. (Eds.), European Land Information Systems for Agro-environmental Monitoring, EUR 16232 EN, 1995, Office for Official Publications of the European Communities, Luxembourg, pp. 131–142.

[17] Madsen H.B., Jones R.J.A., Soil Profile Analytical Database for the European Union, Danish J. Geogr. 95 (1995) 49–57.

[18] Madsen H.B., Jones R.J.A., Towards a European Soil Profile Analytical Database, in: Heineke H.J., Eckelmann W., Thomasson A.J., Jones R.J.A., Montanarella L., Buckley B. (Eds.), Land Information Systems: Developments for planning the sustainable use of land resources, EUR 17729 EN, 1998, Office for Official Publications of the European Communities, Luxembourg, pp. 43–50.

[19] Montanarella L., Jones R.J.A., The European Soil Bureau, in: Bullock P., Jones R.J.A., Montanarella L. (Eds.), Soil Resources of Europe, European Soil Bureau Research Report No. 6, EUR 18991 EN, 1999, Office for Official Publications of the European Communities, Luxembourg, pp. 3–14.

[20] Proctor M.E., Jones R.J.A., Thomasson A.J., Interpretations of the digital EC soil map for agricultural and environmental applications in the UK, in: Feyen J. (Ed.), Agriculture: Application of computerized EC soil map and climate data, EUR 12039 EN, 1989, pp. 107–118.

[21] Ragg J.M., Jones R.J.A., Proctor M.E., The refinement and representation of spatial data in an information system using statistical and DBMS procedures, and trend surface analysis, Geol. Jb. A104 (1988) 295–308.

[22] Renger M., Strebel O., Beregnungsbedarf landwirtschaftlicher Kulturen, in: Abhängigkeit vom Bodenwasser und Boden 32 (1980) 572–576.

[23] Schoeneberger P.J., Wysocki D.A., Benham E.C., Broderson W.D., Field book for describing and sampling soils, Natural Resources Conservation Service, USDA, National Soil Survey Center, Lincoln, NE, 1998.

[24] Soil Survey Staff. Soil Taxonomy, USDA Handbook No. 438, Government Printing Office, Washington DC, 1975, 754 p.

[25] Soil Survey Staff. Keys to Soil Taxonomy, 8th ed., USDA Natural Resource Conservation Service, Washington DC, 1998, 326 p.

[26] Soil Survey Staff. Soil Taxonomy, 2nd ed., USDA Handbook No. 436, Government Printing Office, Washington DC, 1999, 869 p.

[27] Thomasson A.J., Assessment of average soil droughtiness, in: Jarvis M.G., Mackney D. (Eds.), Soil Survey Applications, Soil Survey Technical Monograph No. 13, 1979, Harpenden, UK, pp. 43–50.

[28] Thomasson A.J., Assessment of soil water reserves available for plants (SWAP): a review, in: King D., Jones R.J.A., Thomasson A.J. (Eds.), European Land Information Systems for Agro-environmental Monitoring, EUR 16232 EN, 1995, Office for Official Publications of the European Communities, Luxembourg, pp. 115–130.

[29] Thomasson A.J., Jones R.J.A., Land evaluation at regional scale, in: Bouma J., Bregt A.K. (Eds.), Land qualities in space and time, 1989, Pudoc, Wageningen, The Netherlands, pp. 231–240.

[30] Thomasson A.J., Jones R.J.A., An empirical approach to crop modelling and the assessment of land productivity, Agric. Syst. 34 (1991) 351–367.

[31] Van Ranst E., Thomasson A.J., Daroussin J., Hollis J.M., Jones R.J.A., Jamagne M., King D., Vanmechelen L., Elaboration of an extended knowledge database to interpret the 1:1 000 000 EU Soil Map for environmental purposes, in: King D., Jones R.J.A., Thomasson A.J. (Eds.), European Land Information Systems for Agro-environmental Monitoring, EUR

16232 EN, 1995, Office for Official Publications of the European Communities, Luxembourg, pp. 71–84.

[32] Vossen P., Meyer-Roux J., Crop monitoring and yield forecasting activities of the MARS Project, in: King D., Jones R.J.A., Thomasson A.J. (Eds.), European Land Information Systems for Agro-environmental Monitoring, EUR 16232 EN, 1995, Office for Official Publications of the European Communities, Luxembourg, pp. 11–29.

[33] Wilhite D.A., (Ed.), Drought Assessment, Management and Planning: Theory and Case Studies, Kluwer Academic Publishers, 1995.

[34] Wilhite D.A., Glantz M.H., Understanding the drought phenomenon: The role of definitions, Water Int. 10 (1985) 111–120.

[35] Wösten J.H.M., Lilly A., Nemes A., Le Bas C., Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and land use planning, SC-DLO Report 156, 1998, Wageningen, The Netherlands, 106 p.

[36] Zdruli P., Luli F., Cara K., Kimble J., Almaraz R., Eswaran H., Soils with xeric soil moisture regime in Albania, Third International Meeting on Red Mediterranean Soils, Chalkidiki, Greece, Summary Papers, 1995, p. 184.

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