Simulating agricultural decision making to project future land use

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Abstract: This paper presents an approach to predicting the impact of future agricultural policies, socio-economic change and climate change on agriculture land use. The approach is based on individual farmers' decision making as they attempt to maximise their long-term profit, given the physical attributes of their land. Soil type, climate and slope determine the limits for mechanised arable cropping, and whether and how well a crop will grow and mature. Crop simulation models predict the average crop yield and its variability. These soil water models do not include disease, so a further factor for this variability is derived from statistics on yields. The models tend to be validated on old (eg 1970s) experimental data and under-predict current crop yields. Further, break crops (eg peas/beans) tend to be under-represented in the simulated crops, so adjustments to the simulated crops are used to represent all crops. The same adjustments are then applied to future simulations. A linear programming model simulates a collection of farmers determining the cropping which maximises profit margin over labour and machinery costs given soil workability. Because of variability in yields and prices, each farmer given the same information, processes it differently due to perceptions, experiences and atittudes to risk. The model simulates this by randomly selecting yields and prices based on their variability. The outcome is thus a regional prediction of the cropping. Examples of the model are given for two contrasting regions of England. The model results are compared with observed distributions of agricultural land use. The model is very good at representing land use aggregated at the regional level and general spatial trends in land use patterns. Results for the future show that socio-economic change causes larger effects then climate change.

Keywords: *agriculture, linear programming, land use change, climate change, crop modelling*

1. INTRODUCTION

This paper presents an approach to modelling the spatial distribution of agricultural land use at the regional scale. Agriculture is the most important land use in Europe in geographic terms and the dramatic changes in agriculture over the last 50 years have had an enormous effect on the environment and landscape. Thus there is considerable interest in predicting the impact of future agricultural policies, socio-economic change and climate change on agriculture and the environment. This is particularly true at the extremes – will Southern Europe see an increase in abandonment and desertification; will northern England see pasture land use replaced by arable fields and sunflowers? Throughout Europe, the management of the agricultural land has impacts on the quality of the environment through nutrient dynamics, water resources and biological diversity. This paper presents an approach based on the physical foundations of agriculture and individuals' decision making. This was part of an integrated project also considering flood-risk, hydrology and ecology. The output of this stage provided input to the later analyses.

2. THE MODELS USED

The methodology uses a soil/crop model and a farm management model to estimate future agricultural land use under different climate and socio-economic scenarios (Figure 1).

Agricultural land use in any location is assumed to be a result of the farmer attempting to maximise long-term profit. The decisions are constrained by the physical attributes of that land, most notably soil type, climate and slope. Slope determines whether mechanised arable cropping is feasible. Climate determines which crops can be grown and will mature. Soil type, with climate, determines how well a crop will grow, with or without irrigation, and also determines limits on the time available for mechanised work in the autumn and winter period. Finally the prices and subsidies determine the profitability of each crop. Thus the steps of the agricultural analysis are to determine :

1. the viable options
2. their yields and hence profitability

3. the workability of the land
4. the crop combination which maximises profit.

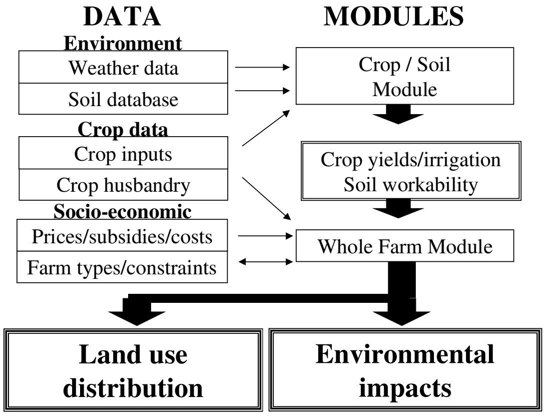


Figure.1 Schematic of the model approach

2.1 Crop yields

Crop simulation models were available which simulated a number of the major crops (Mayr et al., 1996). These are used to predict the yield over 30 years with and without irrigation if relevant, and hence the average and variability. These are soil water models and do not include disease, so a further factor for this needs to be derived from statistics on yields. Nor do they predict frost/cold damage and the possibilities of moving sowing dates due to climate change. They also tend to be validated on old (eg 1970s) experimental data and thus under-predict current crop yields. Break crops (eg peas/beans) are under-represented in the simulated crops. Adjustments are therefore made based on the simulated crops to provide an accurate representation of a wider range of current crops and these same adjustments are then applied to simulations of the future.

2.2 Weather data

The integrated project elected to use a 5x5km grid size to model spatial distributions. Climate data for 1961-90 and for future climate scenarios were available on a 10x10km grid over the UK as monthly mean data (Hulme and Jenkins, 1998). In this study we used the UKCIP98 2050s Low and 2050s High scenarios.

To generate daily weather data the following procedure was used. England and Wales have been divided into a number of agroclimatic zones (Smith, 1976). Thirty years of daily data from a weather station in each zone was used to generate 30 years of daily data for each climate scenario and for each grid. Using real data ensures that any generated sequences, correlations, extremes, etc, are plausible since they have actually happened.

For all variables:

Define x_i - daily data values for a month corrected for altitude (Smith, 1976)

μ - mean of daily values for the month = $\Sigma x_i / N$

σ - standard deviation of daily values for the month

Let $\lambda_i = (x_i - \mu) / \sigma$ Then the new daily value is $\hat{x}_i = \hat{\mu} + \lambda_i \hat{\sigma}$ where $\hat{\mu}, \hat{\sigma}$ are the scenario monthly means corrected for altitude. The annual coefficient of variation is assumed to be constant for rain, wind and sunshine hours, and, for other weather variables, the standard deviation is assumed constant across the range of altitudes. To generate rainfall, the notional water content of the air each day was calculated as:

$v = \rho / 4500 + 0.622 s / (1013.25 + s)$ where ρ is the rainfall (mm) and s is the saturated vapour pressure at the day's average temperature. v was then adjusted for the scenario monthly rainfall as above, then given s for the day's temperature, the new rainfall $\hat{\rho}$ can be calculated. This method translates dry-but-humid days to rain days, or vice-versa, thus adjusting the number of rain days in a month, both if the altitude is increased and if the temperature is increased.

2.3 Workable days

A day was defined as a workable day if the soil moisture content in the top 8cm was 99% of the field capacity level. This very simple method was found to give a better fit to farm management predictions of numbers of workable days than more sophisticated methods.

A farmer does not plan his machine capacity based on the average number of workable days as the cost of failure is much greater than the cost of extra equipment. Experience shows that they plan on about the 7th best year in 10 (Audsley, 1981), that is, significantly worse than average. Therefore the workable days in each fortnight of the year over the 30 simulated years was ordered and the average over the 15th-20th years was taken as the planning level of workable hours.

One surprising effect of the combination of the weather generator and the workable days was that there was very little change in the number of days with climate change. This results from the fact that a soil changes from workable to non-workable in the autumn due to a substantial rain event. This occurs on the same day in all scenarios. Differences tend only to occur where evaporation is sufficiently different to require an extra day or days to dry the soil surface. This in turn only matters if it is one of the 15-20th years. Thus this procedure for generating weather data eliminates any difference which might be merely due to random number generation.

2.4 Farm management model

The underlying hypothesis of the modelling approach is that farmers are 'profit maximisers'. The main differences in the crops grown by different farmers are due to the soil type, climate and their perceptions of the future profitability of crops. A linear programming model is used to simulate farmers determining the farm cropping which maximises their profit margin over labour and machinery costs taking into account the soil workability over the winter period (Annetts, 2002, Audsley, 1993).

The year is divided into fortnights in which the workable hours are calculated. Crops are defined by possible rotations and the operation sequence to produce them. Operations are defined by the time span over which they could be carried out, in the absence of restrictions due to previous and following operations, and a timeliness penalty (loss of yield or extra cost) if the operation is carried out other than at the optimum time. The management data also provide a baseline yield for all crops, and all simulated yields are scaled to these yields. The baseline harvesting times are defined in the management database for the East Anglian region under the 1995 climate and are then modified for region and climate by the maturity dates predicted by the crop simulation.

The area of operation j on crop i in period k is denoted x_{ijk}. The area of crop i is a_i. The objective is to find the values of these variables that maximise the steady state profit z and the corresponding resources n_m, the number of men and machines, m:

$$z = \sum G_i a_i - \sum C_{ijk} x_{ijk} - C_m n_m \qquad (1)$$

where

G_i is the basic gross margin of crop i

C_{ijk} is the cost of the operation, including any adjustment to the gross margin such as the reduction in yield due to carrying out the operation late.

C_m is the annual cost of resource m

and $a_i = \sum_k x_{i1k}$ (2)

The resource constraints are:

$$\sum_{i,j} R_{ijkm}\, x_{ijk} \le H_{mkn}\, n_m \qquad \forall\ m,k,n \le N (3)$$

where

R_{ijkm} is the amount of resource m of type N required to carry out $x_{ijk.}$

H_{mkn} is the amount of resource m of type n available in period k.

Types are successively more restrictive workable hours such as for ploughing, harvesting (must be dry), spraying (must be dry and not windy) which are assumed to be subsets.

Sequencing constraints ensure that a sequential operation (for example drilling after cultivations after ploughing) is not carried out before its preceding operation:

$$\sum_{k \le K} x_{ijk} \le \sum_{k \le K} x_{i(j-1)k} \qquad \forall\ i, j > 1, k (4)$$

where

K ε $(P_{ij} \cap P_{ij-1})$

P_{ij} is the set of periods in which operation j on crop i can be carried out. If the intersection K is null, the constraint is simply the sum over all periods.

For non-sequential operations $a_i = \sum_k x_{ijk}$ (5)

When j = 1, the above sequence constraints refer to the previous crops in the rotation. Define r_{ick} to be the area of crop i following crop c in period k.

$$\sum r_{ick} = x_{cJk} \qquad (6)$$

$$\sum_{k \le K} xi1k \le \sum_c r_{ick} \qquad (7)$$

Each crop is a member of a disease class, P^d, which affects the rotation possibilities. There is a loss of yield for crops following particular disease class crops. The annual build-up of a disease is reduced by growing crops not encouraging that disease. The build-up value B_d is the minimum number of years between crops of that disease class. The constraint for disease d is:

$$\sum_{i \in P^d} a_i B_d - \sum_{i \notin P^d} a_i \le 0 \forall d \qquad (8)$$

Rotational penalties are also subtracted from the objective z (eqn 1).

In simple terms, the sum of the crops must be less than the land available, T. However this constraint must allow more than one crop per year and more than one year per crop. Thus the area of land occupied by a crop or between crops, at any time, must be less than or equal to the area of land available for crops. Crops include permanent crops such as grazing, perennial crops such as forage, annual crops such as wheat, rape and set-aside, and catch crops.

Let t_{ic} be the total area of land transferring from crop i to crop c. Let N_i be the number of year ends an annual, perennial or catch crop i crosses, P be the set of permanent crops and Δ_{ic} have value one if the transfer from crop i to c crosses the year end, otherwise zero. Then

$$\sum_{i\in P} a_i + \sum_{i\notin P} N_i a_i + \sum_{ic} \Delta_{ic} t_{ic} \leq T \qquad (9)$$

Additional constraints represent features such as sugar beet quotas and feeding dairy cows from forage crops. This is a linear programme, which can be rapidly solved on modern computers.

For crops that would be potentially irrigated in the UK, three levels of irrigation are simulated by the crop model. Three versions of the crop are then provided to the management model with the gross margin adjusted for the cost of providing the required amount of water. The model can then select any version of the crop and the appropriate labour and machinery for irrigation. In this study no limit was placed on the amount of irrigation.

In addition to the gross margin, each crop has a nitrate leaching value associated with it which is a function of the yield, nitrogen applied, soil type and rainfall. Thus in addition to total profit, each farm has a total nitrate leaching (Annetts, 2002).

Farmer perception of yield and price

Because of the variability in yields and prices the next year's crop margin is unknown. Given the same information each farmer and adviser will process it differently due to different perceptions, experiences and attitudes to risk. The different perceptions of the relative profitability mean that farmers in the same physical situation make different decisions. The model simulates this by randomly selecting yields and prices based on their variability and thus simulating a collection of farmers. Aggregated at the regional level, the cumulative decisions show how agriculture will adapt to accommodate changes in climate or economics.

On an individual farm a farmer would select a sub-set of the large number of possible crops. Over a region however the average farm can include a small percentage of a crop. Thus, when calculating the distribution of crops over a grid, it is important to take all the crops into account. However, many crops are grown in very small areas for very specific customers. Thus, the following choices were considered: wheat, winter and spring barley, spring oats, winter and spring oilseed rape, linseed, winter and spring beans, dried peas, potatoes (with 0mm, 100 mm and 200 mm irrigation), sugar beet (with 0mm, 100 mm and 200 mm irrigation), maize, sunflower, soybean, grass, permanent grass and forage maize. Dairy cows consume the latter three crops.

In addition to the climate scenarios, two socio-economic scenarios were used to study the impact of alternative price and subsidy schemes and the effect of improved technologies. The chosen contrasting futures for the modelling were (IPCC, 1996):

- Regional Enterprise (equivalent to IPCC A2) linked with the High climate scenario
- Global Sustainability (equivalent to IPCC B1) linked with the Low climate scenario

The baseline socio-economic scenario is taken as 1995, which, with the current climate, is used to validate the initial predictions of agricultural land use. The impacts on agricultural land use are first calculated using the UKCIP98 2050s Low and 2050s High climate scenarios with no socio-economic changes to determine the effect of climate change alone. Then the combined impacts are calculated using the linked socio-economic and climates scenarios.

3. APPLICATION

The method was applied to two agriculturally distinct regions in England - an East Anglian region which is mainly arable but with sugar beet in Norfolk and the North West which has some arable and horticulture, but is mainly managed grassland (Cheshire) and rough grazing (upland areas and the Lake District).

Each region is divided into 5 km x 5 km grids, for which data are required concerning the weather, soils, use of the land, flooding risk, altitude and slope. Crop management and economic data on all the possible crops are required for each region. Areas within each grid are first classified by elevation and slope - *Lowland* areas (lower than 200 m and slopes of ≤ 11 %) are suitable for arable farming and grazing livestock; *Upland* areas (between 200 m and 300 m and slopes of ≤ 11 %) are considered unsuitable for arable farming, but suitable for managed grassland and *Hill* areas (higher than 300 m or with a slope of > 11 %) are only suitable for rough grazing. In addition some areas are classified as Nitrate Vulnerable Zones (NVZs) where only reduced level of inputs are permitted by government legislation. *Upland* areas are simulated as Lowland with the expectation that the result will be grassland. Overall 5 farm types are modelled: East Anglia Lowland with normal input levels occur in 516 grid squares; East Anglia Lowland with reduced NVZ input levels occur in 34 grid squares; North West Lowland with normal input levels occur in 479 grid squares; North West Upland with normal input levels occur in 63 grid squares; and North West Hills occur in 86 grid squares.

Each 5 km x 5 km grid square is divided into a number of cells, each of the same soil type. Typically a grid will have 3 or 4 soil types. In total there were 124 different soils. Each cell is treated as if it were one farm, for which the crop model predicts the crop dry matter yield and maturity dates for each of the 30 years. The farm management model uses these to calculate the crop gross margins. Generic farms are set up to represent the farms within the area, for which the optimal farm cropping plan is calculated.

In order to determine how much of the land in each grid square was available for agricultural use, data were obtained from the ITE Land Cover Map of GB. Data on flooding are provided for each grid and scenario as the area unsuitable for arable agriculture but suitable for grazing livestock, or unsuitable for any agricultural use.

3.1 Results

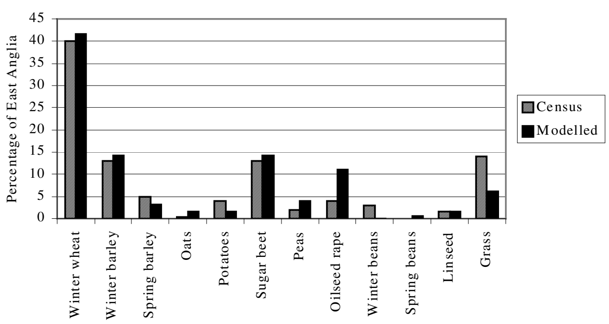


Figure 2. Comparison of model and census data

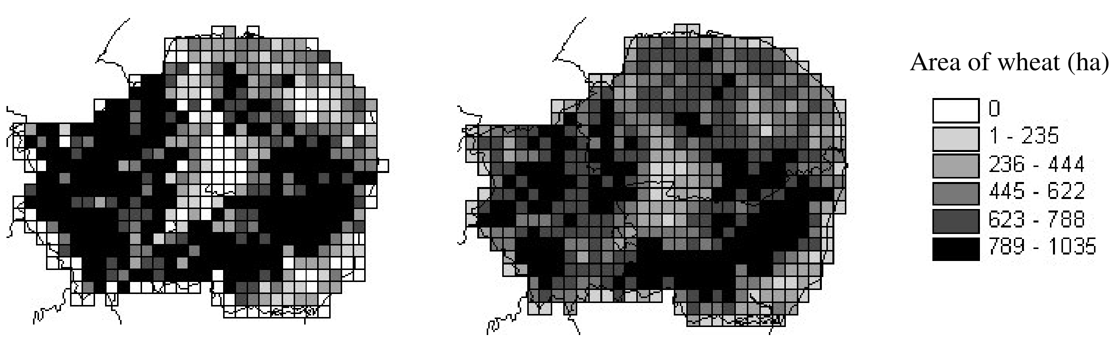
The East Anglian region cropping comparisons of actual census data against modelled land use in 1995 are good (Figure 2). A slight underestimate in the areas of grass, potatoes and beans and the slight overestimate in the areas of oilseed rape and oats are probably due to average farmer perceptions being above or below the 1995 price and yield status of the crops. There will always be a time lag between a change in the profitability of the crop and the farmer reacting. This will be greater if there is a substantial investment involved such as with grass and dairy cows. Potatoes also have a very large variation making it difficult to estimate a long-term mean. However if the model predicts a change in the crop area with a new scenario, one should expect a pro-rata change in the actual area of that crop

Spatially (Figure 3 for wheat) the results are encouraging but show less concentration than appears to occur in practice. Thus the model allows farms with a small area of wheat which in practice would be not viable. For example these would be very small areas of a soil type highly suitable for arable farming surrounded by an unsuitable area. However it should be born in mind that the census data is based on the location of the holding and the farm may actually be spread over several grids.

3.2 Future scenarios

Winter wheat yields increase in most areas in the 2050s Low climate scenario, but in the higher temperatures of the 2050s High climate scenario, yield increases are generally lower. Conversely grass yields do not increase by as large an amount in 2050s Low, but increase by 30% in nearly all areas in 2050s High. Potato and sugar beet yields also increase, but show the same trend as wheat.

In the East Anglian region, the *distribution of cropping* shows that when the socio-economic scenario is unchanged, the major cropping is also little changed. Irrigated potatoes, however, which are not currently extensive, double in area. The area of sugar beet using 200mm irrigation also increases, particularly in the 2050s Low scenario. The two new socio-economic scenarios show substantial changes. In the East Anglian region, the proportion of the area in winter crops reduces in all the 2050s scenarios, due to corresponding increases in the spring crops, sugar beet and potatoes. The yields of sugar beet and potatoes are the ones that increase most in the crop simulation. The largest increase in potatoes is in the south of the region.



Wheat distribution for the MAFF data　　Wheat distribution for 1995

Figure 3. Comparison of spatial distribution of wheat from model and census

The results can be aggregated to the effect on the environment (Figure 4). The overall level of irrigation required in the East Anglian region increases from 23 to 30 mm/ha/yr in the RE scenario. The increased cost of water in the socio-economic scenarios has little effect on reducing the amount of water used for irrigation. In the GS scenario it was assumed that only 75% of the water was required for the same level of irrigation, otherwise this also indicated an increase in irrigation level.

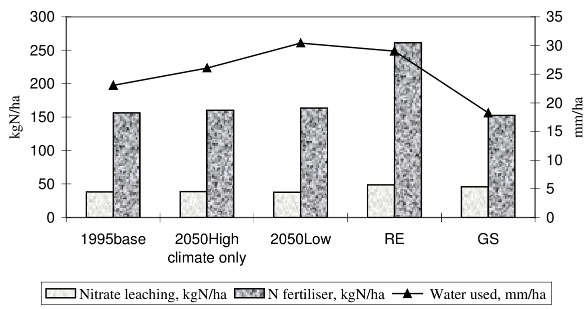


Figure 4. Irrigation and nitrate leaching from different scenarios

Nitrogen use was very little changed between most scenarios in spite of the different cropping. The one difference was the RE scenario in which wheat yields are assumed to increase by 50% so that nitrogen required is increased by 50%. However nitrate leaching does not increase by the same amount.

The *distribution of cropping* in the North West region also shows little change in cropping type with climate change and the current socio-economic scenario, but both the RE and GS scenarios generate a large increase in arable cropping, due to the reduced competitiveness of dairy farming. The *distribution of arable cropping* shows changes that largely mirror those in the East Anglian region. The increase in temperature means that most of the area is now suitable in terms of maturity for winter wheat, sugar beet and potatoes. The proportion of the area in sugar beet shows a large increase throughout the lowland areas and penetration northwards, though in this region most of it is unirrigated. This is the potential for sugar beet as there are currently no factories in this area. The increase suggests that by the 2050s there may be a case for a factory in this region, although the crop is still too sparse to justify a factory in the extreme north. The irrigation required in the North West region is, in the highest scenario, only about 6 mm/ha/yr. In the Upland areas, the area of farmed grass only reduces from 95 % to 93 % of the area when there are no economic changes, but in the RE case this reduces to 83 % of the upland area. There is a very large reduction in farmed grass in the lowland areas in this scenario.

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