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The Potential for Bioenergy Crop Production in Baden-Württemberg: An Application of EPIC and GIS to Bioenergy Modeling

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Contents

Abstract

Greenhouse gas emissions resulting from burning fossil fuels are affecting the climate of our planet. In order to abate this climate change, changes have to be made in the systems of energy production. Sustainable use of bioenergy causes no net emissions of CO_2 and can also help to reduce the emissions of NO_x. The issue has also political relevance, as the European Union has made political commitments to meet 15% of its real primary energy demand using renewable sources by 2010.

This study examines the usability of the EPIC model (Environmental Policy Integrated Climate) and Geographic Information Systems (GIS) methods to estimate the potentials of bioenergy crop production in Baden-Württemberg. The productivity estimates for different areas given by the model are distributed spatially over the study area. Productivities of different species and management options in different areas are compared. Also the use of other suitability aspects (agricultural productivity, production costs) in estimating real potentials is examined. Based on the results, the usability of this methodology on a European scale is discussed.

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About the Author

Samuli Neuvonen was assigned to IIASA's Forestry Program as a participant in the 2004 Young Scientists Summer Program (YSSP). In 2003, he graduated in Environmental Protection Science from the Department of Limnology and Environmental Protection, University of Helsinki and he is currently studying Geoinformatics at the Institute of Cartography and Geoinformatics at the Helsinki University of Technology.

Samuli's main fields of scientific interest are in combining environmental sciences and Geographic Information Systems (GIS). He has worked on different applications concerning oceanographic data and environmental accident response. He is currently employed as a researcher at the Finnish Environment Institute and working on the MARIS (Maritime Accident Response Information System for the Baltic Sea) and OILI (an operative system for oil spill detection and response) projects.

The Potential for Bioenergy Crop Production in Baden-Württemberg: An Application of EPIC and GIS to Bioenergy Modeling

Samuli Neuvonen

1 Introduction

Natural climate change occurs over long periods, but the accelerated changes now being seen are attributed to mankind's use of fossil fuels. The burning of these releases are greenhouse gases (GHG), so-called because the effect of their increased concentration in the atmosphere is to trap more of the sun's energy, thereby producing what is termed the enhanced greenhouse effect. It appears that this effect not only raises average temperatures, but also heightens extremes of climate. Climatic changes are likely to include severe environmental impacts, the most important being an anticipated rise in sea level. The conclusion that the effect of human activity on climate change is real has now been accepted, not only by scientists but also by politicians (DTI, 2003).

In order to abate this climate change, changes have to be made in our systems of energy production. Sustainable use of bioenergy causes no net emissions of CO_2 (Fischer and Schrattenholzer, 2001) and the lower combustion temperatures of biomass can also help to reduce the emissions of NO_x (Grassi and Bridgwater, 1992). The need to increase the production of crops suitable for bioenergy coincides with the measures taken in the European Community to control food production by setting aside some of the agricultural and pasture lands. This increases the opportunities for producing bioenergy crops. Bioenergy production is strongly related to issues of rural development and jobs, self-sufficiency in energy production and improved competitiveness (Fischer *et al.*, 2001a).

The issue has also strong policy relevance at the international level. The European Union (EU) and all of its member states ratified the Kyoto Protocol according to which they have to reduce (GHG) emissions by a total of 8% from the 1990 level by 2008–2012 (SYKE, 2004). One of the targets set up in order to achieve this is to double the average contribution of renewable energy from 6% to 12% by the year 2010 (EC, 1997). Biomass energy is expected to contribute significantly to this increase.

This study examines the usability of the EPIC model (Erosion Productivity Impact Calculator) and Geographic Information Systems (GIS) methods to estimate the potentials of bioenergy crop production in Baden-Württemberg. The aim is to calculate biomass production estimates for two widely used bioenergy species (poplar and miscanthus) under a few different management options. The productivity estimates for different areas given by the model are distributed spatially over the study area. Productivities of different species and management options in different areas are compared. In addition, the use of other suitability aspects (agricultural productivity, production costs) in estimating real potentials is examined. Based on the results, the usability of this methodology on a European scale is discussed.

2 Background

2.1 Previous Studies and Models Used

The potentials for bioenergy production for different areas of the world have been assessed in numerous studies (Hall *et al.*, 1993; Adams and Connors, 1995; Faaij *et al.*, 1998; Hoogwijk *et al.*, 2000; Fischer and Schrattenholzer, 2001; Fischer *et al.*, 2001a; Helynen *et al.*, 2002). Some of these have completely ignored the possibilities for the production of biomass for energy on lands previously used for agriculture or as pasture (Helynen *et al.*, 2002) as too expensive. For some areas this is certainly true, but when looking at the whole of Europe, bioenergy crops should be taken into account.

The simplest way of assessing potentials for biomass production from bioenergy crops is to estimate some average productivity per hectare for the species or method examined and then the area available for bioenergy crop production. This type of approach has been used, for example, in the World Energy Assessment (2000). The approach takes no account of the spatial variability of climate and soil conditions. As a result, the estimates acquired may not be reliable enough and do not give a good indication of where the largest potentials exist. For more precise estimates a model is needed that includes the effects of weather conditions and soil characteristics on the productivity of bioenergy crops.

There are models that have been developed for simulating the physiology and growth of tree species used for bioenergy (e.g., Rauscher *et al.*, 1990; Chen *et al.*, 1994: both referenced based on an inventory by Ceulemans, 1996). Also the Vleeshouwers (2001) model for nutrient-limited willow growth is of interest. These models meticulously take into account the different processes going on during the growth of a tree. Many of them, however, are too finely detailed for an assessment of whole stands and larger areas. Also, they are designed for modeling tree species and are not suitable for other energy crops.

There are of course many more general forest growth models — e.g., FORGRO (Mohren, 1987), BIOMASS (McMurtrie, 1985), FORSYTE and FORCYTE II (Kimmins *et al.*, 1999), FOREST-BGC (Running and Gower, 1991), HYBRID (Friend *et al.*, 1997), and many others. Their applicability for modeling short rotation woody crops (SRWC) is unclear and it was not in the scope of this study to go into details with them. Also, they have of course the same limitation of being suitable only for forest modeling.

The approach of Agro-ecological Zones (AEZ) has been used in numerous large scale studies (Fischer *et al.*, 2001a; Fischer and Schrattenholzer, 2001) for assessing the potentials for bioenergy crop production in different areas of the globe. AEZ

(FAO/IIASA, 2000) is a land evaluation method for crop productivity assessment that has been expanded with a companion model to also assess potential biomass productivity of tree species (Fischer *et al*., 2001b). Climate, soil and terrain conditions relevant to agriculture and forest species production are characterized in a standardized framework. The land use specific limitations caused by these conditions are then identified using environmental matching procedures (Fischer *et al*., 2001a).

The model operates on a GIS grid-cell database. Climatic analysis is performed for each grid-cell to get the climatic indicators relevant for matching climate conditions with thermal requirements of tree species. The requirements and characteristics of different species are defined in a Land Utilization Type (LUT) catalogue. Each LUT is checked against the climatic conditions in each cell and for those LUTs that are viable, a soil moisture balance and average annual yield in the cell is calculated. The methodology for biomass calculation is based on the eco-physiological model of Kassam (1977) and for tree species a combination of Kassam's model and the Chapman-Richard biomass increment model. The acquired production values are then adjusted based on limitations caused by soil and terrain conditions (water-stress, pests, diseases and weeds, frost, etc.) (Fischer *et al*., 2001a).

As input, the AEZ approach uses grid formed climate data (including different climate scenarios), soil data, elevation data, land cover data and certain crop parameters (length of growth cycle, length of yield formation period, leaf area index (LAI) at maximum growth rate, harvest index (HI, the ratio of yield biomass to the total cumulative biomass at harvest), crop adaptability group, sensitivity of crop growth cycle length to heat provision, etc.) (Fischer *et al*., 2001a).

2.2 The EPIC Model

The model chosen for this study is the Environmental Policy Integrated Climate model (EPIC, previously named as Erosion Productivity-Impact Calculator; Williams *et al*., 1984). It was originally developed primarily for the purposes of estimating soil erosion and its effects on soil productivity. As the changed name implies, however, the EPIC model has continuously evolved and has been used to evaluate a multitude of phenomena: crop productivity, risk of crop failure, degradation of the soil resource, impacts on water quality, response to different input levels and management practices, response to spatial variation in climate and soils, and long-term changes in climate (Mitchell *et al*., 1997). It is designed to help decision makers analyze alternative cropping systems and project their socioeconomic and environmental sustainability. The model version used in this study was EPIC3060.

EPIC seeks to simulate all the major processes related to plant growth taking, processes taking place in and between the elements of soil, hydrology, atmosphere and the plant itself. In hydrology, evapotranspiration, runoff, percolation, etc., are estimated and the effects of irrigation and drainage taken into account. The runoff is calculated using the Soil Conservation Service (SCS) Curve Number (CN) equation (USDA, 1972), the evapotranspiration by Penman-Monteith equation.

The simulated processes in the soil include carbon sequestration (plant residue, manure, leaching, etc.), nutrient balance (fertilizers, denitrification and nitrification, volatilization), mixing, trampling by grazing and erosion by wind and water. Soil loss is determined using one of five methods: USLE (Wischmeier and Smith, 1978); MUSLE (Modified USLE, Williams, 1975); AOF (Onstad and Foster, 1975); MUSS (MUSLE for small watershed); and MUST (another version of MUSLE).

Weather can be included either as actual or as simulated data. In the plant the processes of NPK uptake, stresses and N-fixation are included, as well as the effects of pests and pesticides, crop rotations, plant competition and weeding.

In order to simulate these processes well enough, the model runs on daily time steps. The major input data sets used are weather and hydrology, soil type, topography, crop species and chosen management practices (fertilization, tillage, irrigation, harvest, etc.). The used input data is organized in a relational database type file structure to avoid data duplication (see Figure 1). Each run consists of numerous sub-runs and for each sub-run certain files containing the information about the site, weather, soil, crop and management are indicated. Each file describing certain management, weather, crop, etc., can of course be used in more than one sub-run. Further documentation on EPIC can be found in Williams *et al*. (1984), Sharpley and Williams (1990) and Williams (1995).

3 Methods and Materials

3.1 The Model Setup and the Inputs Used

The area chosen for examination in this study is the state Baden-Württemberg in Southwest Germany (see Figure 2). This area was chosen based on the fact that many datasets useful for the study were easily available for this area. The species generally best suitable for bioenergy production in European conditions are willow, poplar, miscanthus and switchgrass. From these, poplar was chosen based on an estimate by Baritz (2004) and miscanthus based on promising results in previous field studies (e.g., Liebhard and Schwarz, 1994).

3.1.1 Climate data

Climate data used in this study is based on the MARS meteorological database (Rijks *et al*., 1998; available at JRC Ispra), which contains daily meteorological data spatially interpolated on a 50 by 50 kilometer (km) grid-cell (Figure 3). The original weather observations dataset originate from several hundred meteorological stations across European continent, Maghreb countries and Turkey. It was compiled from data purchased from various national meteorological services, either directly or via the Global Telecommunication System of the World Meteorological Organization (WMO). The dataset used contains daily parameters of solar radiation, maximum temperature, minimum temperature and precipitation from 1992 to 2002. Based on this data the necessary statistical parameters for the EPIC weather generator were calculated.

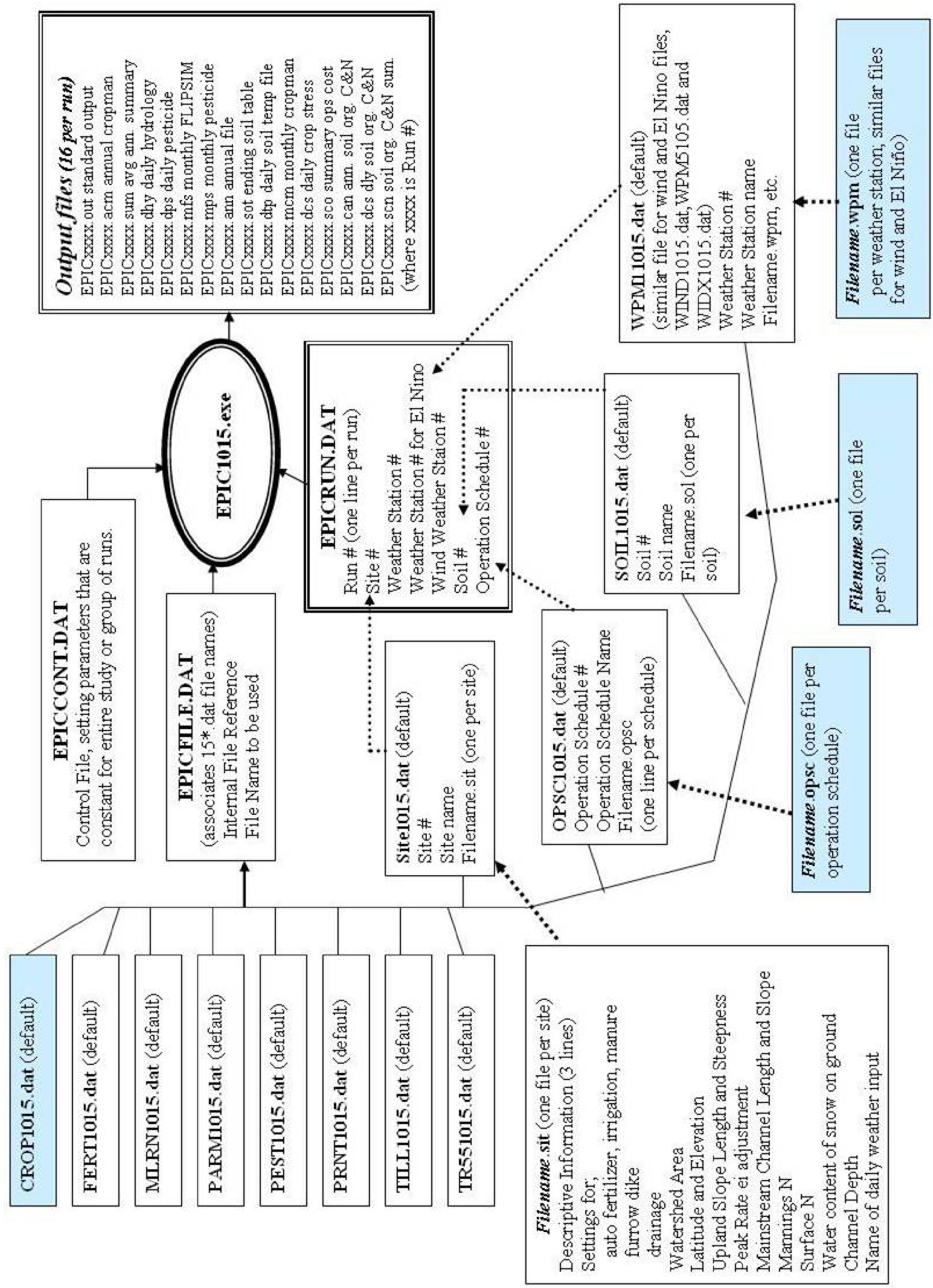

Figure 1: EPIC file structure.

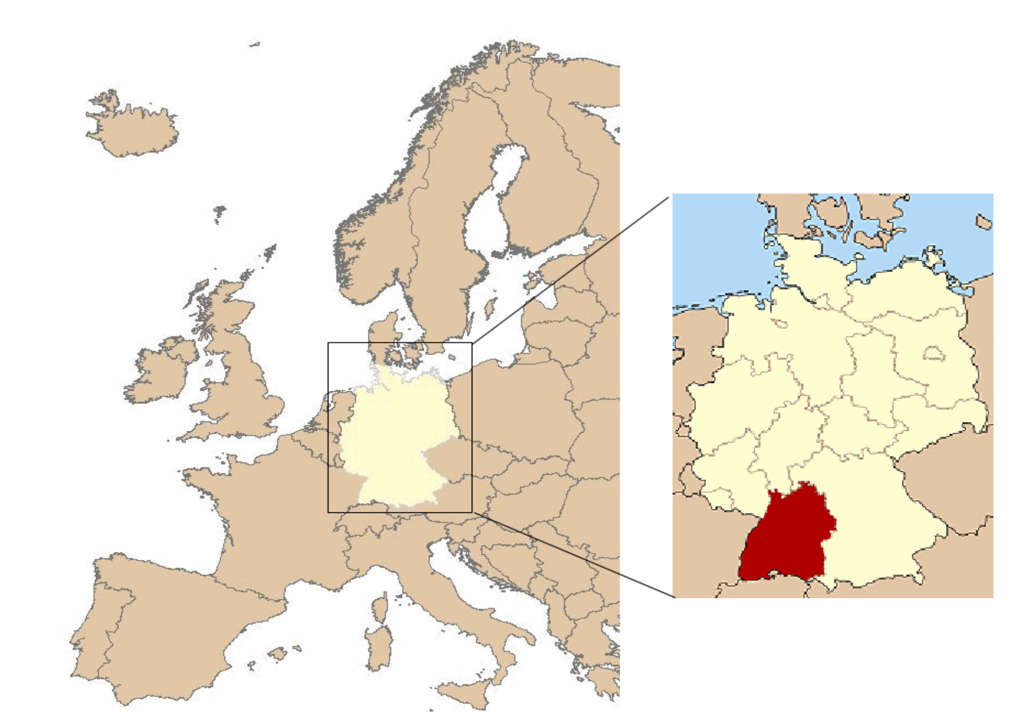

Figure 2: The state of Baden-Württemberg, area chosen for the study.

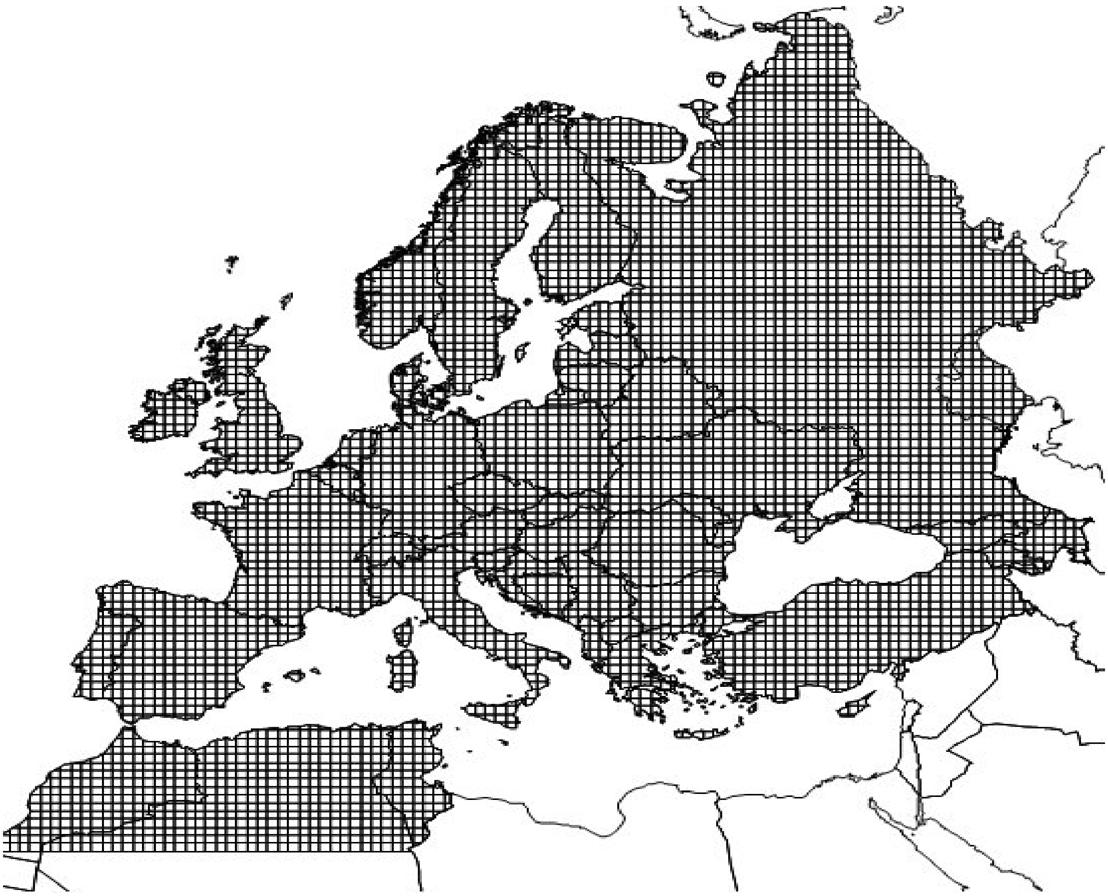

Figure 3: The grid of the meteorological data used in the model.

3.1.2 Crop parameters

Crop parameters for poplar were included with the version of the model. However, some modifications were made in order for them to better simulate the effects of coppicing (e.g., using a maximum leaf area index value of 8 instead of the normal 6, based on Kiniry (2004)).

Crop parameters for miscanthus were estimated based on parameters for switchgrass delivered with the model, expert opinions from the Universität für Bodenkultur Wien (BOKU) and from literature (Bullard *et al*., 1994; Jonkanski, 1994; Schwarz and Liebhard, 1994; Tayot *et al*., 1994; MAFF, 1999; DEFRA, 2001; de Vrije *et al*., 2002; Vargas *et al*., 2002; Li *et al*., 2003). All crop parameters used are given in the Appendix.

3.1.3 Soil data

The soil data used for the application was from the European Soil Data Base (see http://eusoils.jrc.it/). The resolution of this dataset was 10 by 10 km. Data on topography was combined within the soil data to take into account the effects of the slope of the site.

The type of land use effects the soil, which means that basically similar soils used for growing crops or as pasture have different properties. To simulate these differences the model was run prior to the actual energy crop modeling for a hundred years using a typical management of each land use (arable land, pasture or permanent crops).

3.1.4 Management parameters

3.1.4.1 Poplar plantation

To validate the model against older field data and to compare modern energy crop production to more traditional forestry, one model run was made with simulating normal Robusta poplar in an extensive plantation. The trees were planted at the density of 400 per hectare (ha) and harvested without further management after 20 years.

3.1.4.2 Poplar coppice

Earlier short rotation woody crops were planted at a density of about 3000 trees per ha and harvested on a rotation period of around seven years (e.g., Sutter *et al*., 1994). In recent years, however, the planting densities have increased and the cutting cycle has also shortened to 2–4 years (Tubby and Armstrong, 2002). This change has been supported by research results indicating increased first year yields with the increase of planting density from 4500 to 15,625 stools per ha (Armstrong and Johns, 1997). Another study investigating the effect of harvest frequency and planting densities (from 8625 to 111,000 stools per ha) on the yield of willow suggests that a figure of 15,625 stools per ha offers the best economic return over the lifetime of the crop (Bullard *et al*., 2002). This change to higher densities has also meant the change from single stem systems to short rotation coppice (SRC), where the trees are cut back after the first season to encourage coppicing.

Based on a literature review, two different short-rotation coppice approaches were chosen for poplar in this study. In both, the planting density was set at 10 000 stems per ha, cut back done after the first year and the harvesting rotation set to four years based on the results by Armstrong *et al*. (1999). The model was run for 30 years, which can be estimated to be the average lifetime of a coppice plantation (DEFRA, 2002).

In the more extensive approach no fertilization or irrigation was applied. This approach is very similar to the one used in a recent study (Laureysens *et al*., 2000) and thus gives opportunities for further validation of the model results. The more intensive approach included yearly fertilization with 1.6 t/ha of organic manure slurry or sludge. Tubby and Armstrong (2002) refer to a previous study (Heaton, 2000) showing that cattle slurry can significantly improve yields of SRC growing on low quality soils.

3.1.4.3 Miscanthus

Miscanthus was also planted at a density of 10 000 plants per ha (similar densities used by, e.g., Liebhard and Schwarz, 1994; Vargas *et al*., 2002). No irrigation was applied but two different levels of nitrogen fertilization were used: 60 kg/ha/year (similar to the base fertilization in Liebhard and Schwarz, 1994) and 100 kg/ha/year, applied in the beginning of April. Harvesting was done yearly after the winter in February. This practice reduces the yield somewhat but it also reduces the water content of the yield and is for this reason often used (DEFRA, 2001; Kilpatrick *et al*., 1994; Kristensen, 1994). The lifetime of a miscanthus plantation is estimated to be from 15 (MAFF, 1999; DEFRA, 2001) to 25 (Lewandowski *et al*., 2003) years. Here, 20 years was assumed.

3.2 Methods of Spatial Analysis on the Model Results

3.2.1 Locating the results into the real world

Before any spatial analysis was possible the data had to be imported into a GIS. The softwares used for this process were MS Excel and MS Access. The actual spatial processing was done using the Environmental Systems Research Institute's (ESRI) ArcView 3.2, ArcMap 8.3 and ArcInfo.

The model gave a result for each combination of soil class and climate area (NUTS2-regions). The values were read into Excel using a custom made VBA-macro, averaged and exported to Access. In Access, the productivity tables were joined with a table of grid addresses. The resulting dbf-files could then be imported to ArcView and linked to the actual spatial grid used. To better facilitate spatial analyses, the datasets were converted from shape grids to raster grids

Because the grid resulting from EPIC did not fully cover all of the small areas at the state border, the result grids were extrapolated using ArcMap's Spatial Analyst extension and the focalMean–function:

con(IsNull([modelOutput1]), focalmean([modelOutput1]), [modelOutput1]) .

That is, for each cell with a null value a new value was calculated based on the non-null values in its 3 by 3 environment. This extended the grid over the whole study area (Figure 4).

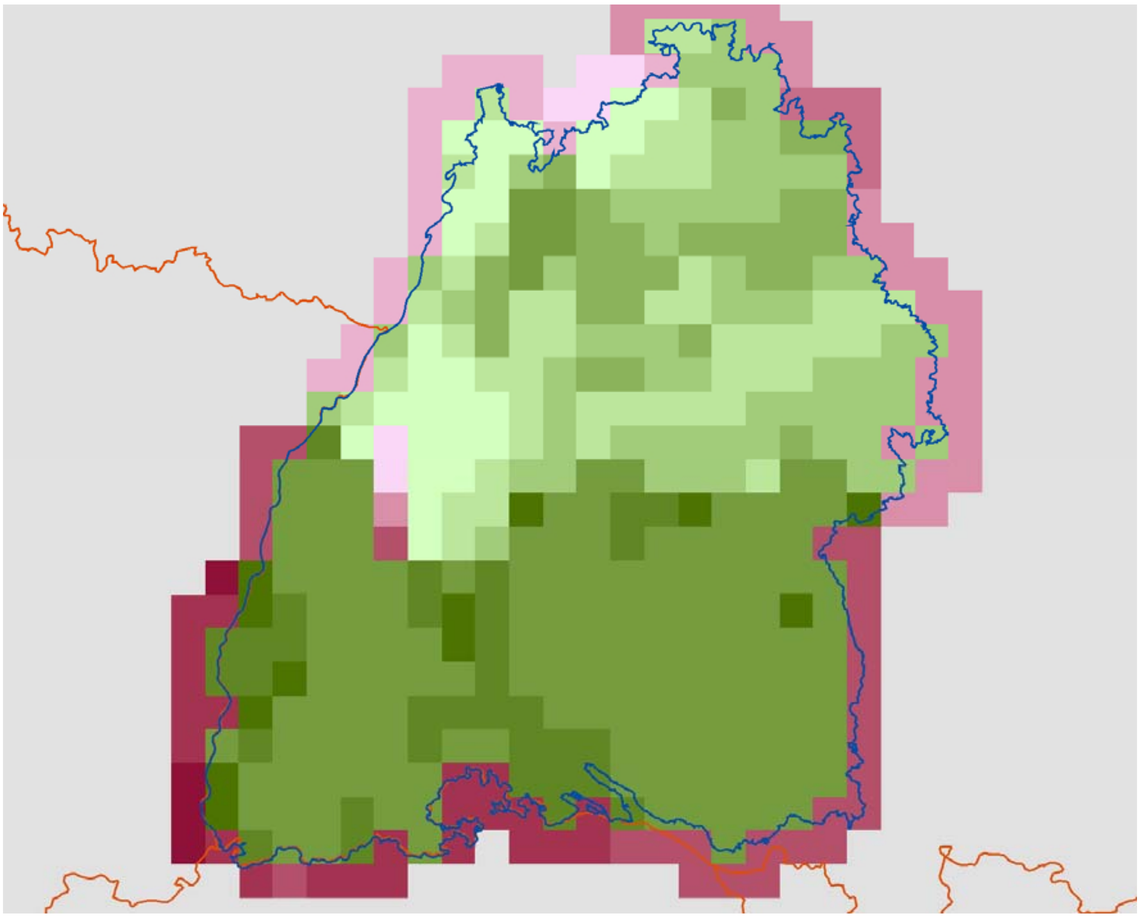

Figure 4: This image illustrates the method of extending the model results for the whole study area. Green cells are those calculated by the model and red cells result from extrapolation. The blue line shows the area of Baden-Württemberg.

To assign the achieved productivity values to actual land areas used for these purposes (arable land, pasture land and other agricultural land), the CORINE land cover dataset was used. Three different "0/1-raster masks" were produced, where the value 1 indicated the grid cell to belong into the land cover category in question. This was done using ArcMap's Spatial Analyst extension and the following map algebra commands.

For arable lands: *con(([corine] == 12 | [corine] == 13 | [corine] == 14), 1,0)* .

For pasture: *con(([corines] == 18), 1,0)* .

For other agricultural lands: *con((([corine] >= 15 and [corine] <= 17) | ([corine] >= 19 and [corine] <= 22)), 1,0)* .

The resulting raster layers could then be used to assign the model results to relevant 250 m by 250 m grid cells by multiplying them with the result raster layers (10 km by 10 km) in ArcInfo's GRID–module.

3.2.2 Comparing different species and managements

The datasets resulting from the above mentioned operations were analyzed further to examine which species and management options were most suitable for which areas. This was done using ArcMap, Spatial Analyst and map algebra. Each raster layer (e.g., productivity of miscanthus with low fertilization on arable areas) was compared with all other raster layers of the same land use (fertilized coppice, unfertilized coppice, etc., in arable lands) simply by subtracting layers from each other. Also the highest yield for each area could be calculated by comparing the layers.

3.2.3 Finding marginal areas

All of the areas indicated by CORINE as belonging to the examined land cover categories are obviously not in reality available for energy crop plantation. In most areas successful agriculture is practiced. In order to examine the feasible potentials of energy crop production a method is needed to estimate the share of areas possibly available for this purpose.

Croppi and Parrini (1994) have evaluated potential land areas available for bioenergy crop production in Italy by estimating marginalized agricultural area (land once used for agriculture but now abandoned) and set-aside. They obtained marginal area from the reduction of Agricultural Used Surface (AUS), which could be found in the agricultural censuses (1961, 1970, 1982 and 1990). Also set-asides were estimated province by province. This approach does not give a proper indication of the spatial distribution of the available areas, so that their actual production potential could be estimated using a modeling approach.

In this study, the suitability for agricultural production is used as a measure of the marginality of each area. The FAO/IIASA (2000) dataset describing the global agro-ecological zones (GAEZ) offers an estimate of the suitability for agriculture. In this dataset, the suitability of each grid cell (5 by 5 arc minutes) for cultivating different crops is estimated using eight classes: very high, high, good, medium, moderate, marginal, very marginal and unsuitable. For the purposes of this study, suitability layers for each relevant crop were combined into one layer. The crops considered relevant for Europe were cereals, pulses, sugar crops, oil crops and roots and tubers. The method chosen for combining the different suitability layers was simple: each cell in the combination layer received the highest classification present in the individual suitability layers. That is, if the cell area was very highly suitable for even one of the crops, it was considered highly suitable for agricultural use.

Combining was done with ESRI's ArcMap software with Spatial Analyst, simply using the raster calculator and the following expression of map algebra:

con((plate31= =9 or plate32= =9 or plate33= =9 or plate34= =9 or plate35= =9),0,
min(plate31,plate32,plate33,plate34,plate35)) ,

where plates 31 through 35 are the individual suitability layers and the conditional expression combines inland water with the sea areas. The acquired combination layer (Figure 5) was then used to find the marginal areas in Baden-Württemberg.

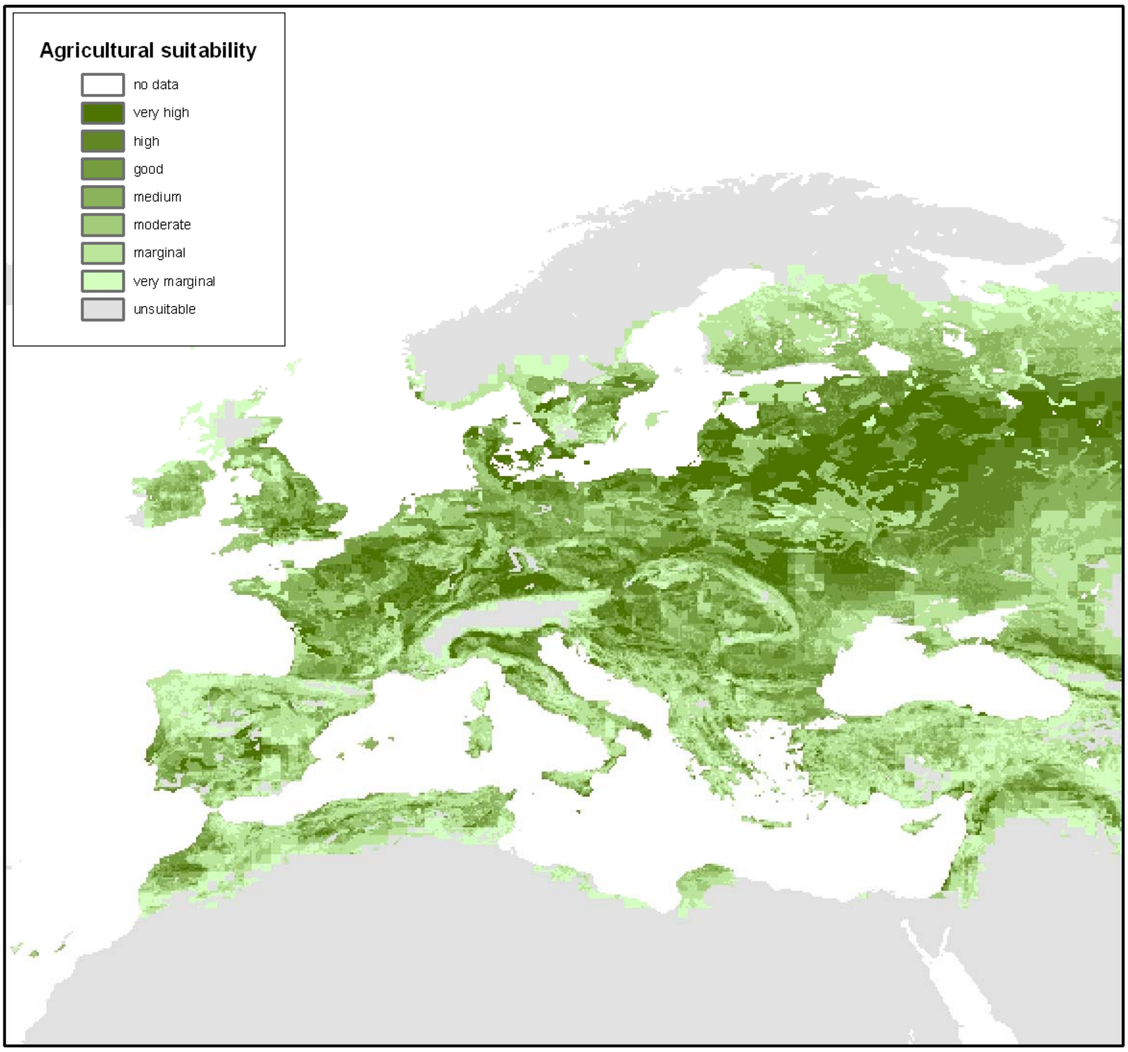

Figure 5: Overall agricultural suitability calculated from GAEZ (FAO/IIASA, 2000).

3.2.4 Economic comparisons

Another important constraint in the actual cultivation of bioenergy crops are the costs. Growing bioenergy crops is not economically reasonable in all of the areas indicated by the CORINE, or using all the management options examined in this study. The final cost of biomass for bioenergy is strongly dependent on the location, because of both the differences in establishment, production and harvesting costs and in transportation costs from the plantation to the users. Unfortunately, no spatially explicit model able to estimate these costs for the different cultivation methods examined was available for this study. Here, only very rough estimates are looked at from a more methodological point of view.

For the short rotation coppice, the establishment costs have been estimated to be around 2750 €/ha (including weed control before planting, fencing, ploughing, cultivations, planting, herbicide application, cutting back, filling in) (also REFA, 2004) and the management costs around 75 €/ha/year (including vegetation control and fertilization). For the harvesting, chipping and transporting within the farm, the cost estimate is around 24 € per ton (the costs will of course depend on the scale of plantation and the methods used) (DARD, 2002).

According to MAFF (1999) the costs for establishing a miscanthus plantation (with 10,000 plants per ha) are about 1220 € per ha. Yearly management costs are 102 € per ha with a fertilization level of 60 kg N per ha per year and about 102 € with 100 kg N per ha per year. Harvesting is estimated to cost around 250 € per ha using a cut and bale technique (MAFF, 1999).

As mentioned above, the establishment of SRC is estimated to cost 2750 € per ha. On the other hand, the price of seedlings is about 1500 € per 10,000 (e.g., Itasca Greenhouse, 2004). Based on this, it can be estimated that when establishing an extensive poplar plantation, which does not need as much preparation and where the density is only 400 trees per ha, the cost will be in the order of 700 € per ha. Harvesting costs are estimated to be roughly 20 € per m^3, based on Lundmark (2004), which means about 50 € per ton.

Based on Suurs *et al.* (2002), the costs of transportation are estimated to be about 1.24 €/km for an EU truck with a capacity of 120 m^3 or 25 tons. The density of baled miscanthus varies from 140 to 170 kg/m^3, depending on moisture content (Kristensen, 2004). For poplar chips the density is about 150 kg/m^3 (McLaughlin *et al.*, 1996). When put together the above figures mean that on an EU truck about 20 tons of miscanthus or poplar chips can be transported at one time (both have about equal density). The cost of transportation would thus be 0.062 €/km/ton. To account for suboptimal logistics, the cost is assumed here to be 0.07 €/km/ton. The effects of varying land value and storage costs are excluded in all of the above cases.

The average transportation distance for each location was approximated using the data about settlements provided by ESRI (AND Data Solutions, 2002) and assuming that the real distance traveled from plantation to user is twice the Euclidean distance. Based on this assumption and all of the above figures, the following equations were used to calculate the cost per ton for each of the examined cases and each grid cell.

Robusta poplar extensive plantation:

The establishment cost:	700€ / (20*productivity)
Yearly costs:	-
Harvesting cost:	50€
Transportation costs:	0.07€ * 2* distance .

SRC without fertilization:

The establishment cost:	2750€ / (30*productivity)
Yearly costs:	-
Harvesting cost:	24€
Transportation costs:	0.07€ * 2*distance .

SRC with fertilization:

The establishment cost:	2750€ / (30*productivity)
Yearly costs:	75€ /productivity
Harvesting cost:	24€
Transportation costs:	0.07€ * 2*distance .

Miscanthus with high fertilization:

The establishment cost:	1220€ / (20*productivity)
Yearly costs:	170€ / productivity
Harvesting cost:	250€ / productivity
Transportation costs:	0.07€ * 2*distance .

Miscanthus with low fertilization:

The establishment cost:	1220€ / (20*productivity)
Yearly costs:	102€ / productivity
Harvesting cost:	250€ / productivity
Transportation costs:	0.07€ * 2*distance .

4 Results and Discussion

4.1 Comparison of Model Results to Previous Studies

Model results for Robusta poplar with the mentioned management (section 3.1.4) varied from 113 to 185 tons/ha over the 20 year period. These figures are fairly compatible with field data from the corresponding location (Schober, 1975). At a yearly basis this corresponds to a productivity of 5.65–9.25 tons/ha.

Also the model results for poplar coppice favorably followed the results from field studies. Galinski *et al.* (1991) refers to field studies in the North Pacific with yields of 27.6 tons/ha/year; Heilman and Stettler (1985) and Pontailler *et al.* (1999) have achieved yields as high as 30 tons/ha/year in France. However, yields of this scope have always been achieved in plantations of very intensive management (high fertilization and optimal irrigation). Karacic *et al.* (2003) refers to a study by Ericsson (1994) stating that yields higher than 10 tons/ha/year are rare without any irrigation or fertilization. The results from the EPIC model obtained in this study favorably follow the results from comparative field studies (e.g., Sutter *et al.*, 1994; Laureysens *et al.*, 2000; Karacic *et al.*, 2003). A summary of the results is given in Table 1.

EPIC was also able to simulate miscanthus well. The model results corresponded with the yields achieved in the numerous European field tests (Schwarz, 1993; Dalianis *et al.*, 1994; Jonkanski, 1994; McCarthy and Mooney, 1994; Lewandowski *et al.*, 2000; Price *et al.*, 2004). Values above (Lewandowski *et al.*, 2003) and below (Jørgensen, 1997) the ones given by the model have been witnessed, but they have been due to extraordinary weather conditions or use of irrigation. A summary of the values is presented in Table 2.

Table 1: Summary of the productivity values for poplar coppice estimated by EPIC.

	No Fertilization			Fertilization		
	Arable	**Pasture**	**Other**	**Arable**	**Pasture**	**Other**
Average	6.965698	8.795461	7.373827	11.11698	11.86619	11.27216
Minimum	4.840429	6.637357	5.303357	9.320071	8.99275	9.132929
Maximum	9.728	11.39136	9.557679	13.60543	14.15064	13.10086

Table 2: Summary of the productivity values for miscanthus estimated by EPIC.

	Low Fertilization			High Fertilization		
	Arable	**Pasture**	**Other**	**Arable**	**Pasture**	**Other**
Average	11.89531	14.41655	11.89638	14.2882	16.21802	14.16155
Minimum	8.3174	10.2036	8.085	10.01275	11.2027	9.79535
Maximum	16.8568	19.52595	16.81635	19.72525	21.8219	19.21285

4.2 The Spatial Distribution and Comparisons of Model Results

The spatial distribution of productivity for the species and management options studied is presented in Figures 6–8. The calorific values of poplar and miscanthus can be used to relate the model values to energy production. The calorific value (lower heating value) of poplar used in the literature varies from 16.7 GJ/ODT (Buitelaar *et al*., 1994) to 19.5 (Centre for Biomass Technology, 1999; Richardson, 2003). The values at the higher end tend to concern more the actual stem wood, while the value for branches is usually a bit lower. Thus, a value of 17.9 GJ/ODT, used also by Foster and Matthews (1994) for short rotation coppice, is assumed here.

Based on Schwarz (1993) the calorific value of miscanthus is as high as that of firewood (18 to 19 MJ kg^{-1}). McCarthy and Mooney (1994) estimated the value to be 18.2 MJ/kg for the harvested material. Dalianis *et al*. (1994) arrived at a bit lower value of 17.2 MJ/kg. Thus, an intermediate value similar to poplar can be assumed here for miscanthus. Based on this calorific value the productivity range presented in the figures (5-21 ODT/ha/year) corresponds to a range of about 90–380 GJ/ha/year.

Based on the model, the productivity was highest in all areas using miscanthus and the management option with more intensive fertilization. Also, miscanthus with lower fertilization gave generally higher yields than any other practice. In some areas, however, poplar coppice fertilized with slurry produced more than miscanthus with the low N-fertilization. Similarly, the productivity of traditional Robusta poplar plantation was in general lower than with any of the other examined managements, but did exceed the productivity of unfertilized poplar coppice in some areas. The comparisons between these management practices are shown in Figure 9.

ArcMap was used to compare the effects of fertilization on poplar coppice and miscanthus. Figure10 shows the increase of the yield when poplar coppice is fertilized using slurry and when the yearly amount of fertilization for miscanthus is increased from 60 to 100 kg N per ha.

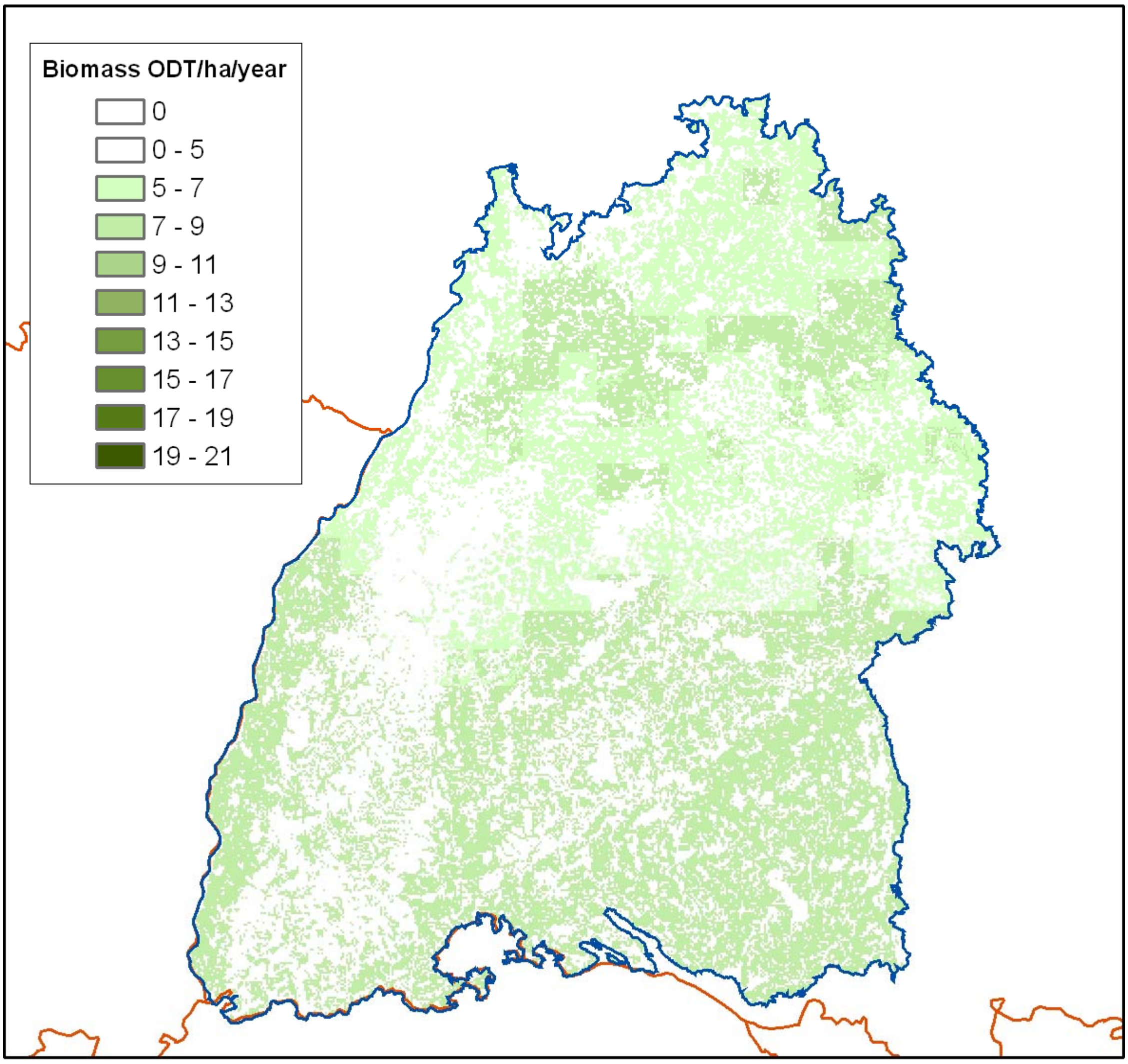

Figure 6: The spatial distribution of productivity for Robusta poplar in an extensive plantation (400 trees per ha) and 20 year rotation.

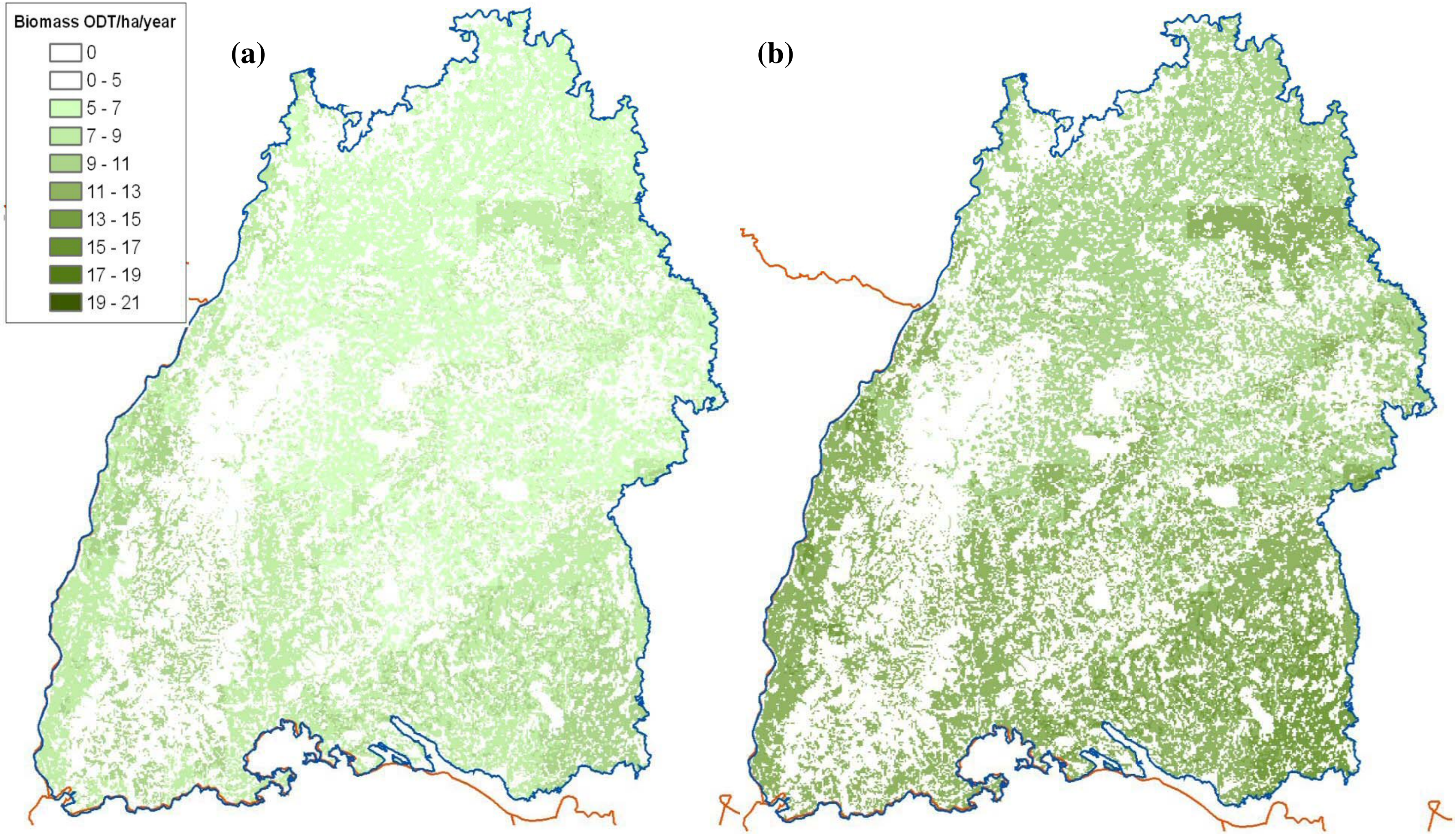

Figure 7: The spatial distribution of productivity for (a) unfertilized and (b) fertilized poplar coppice.

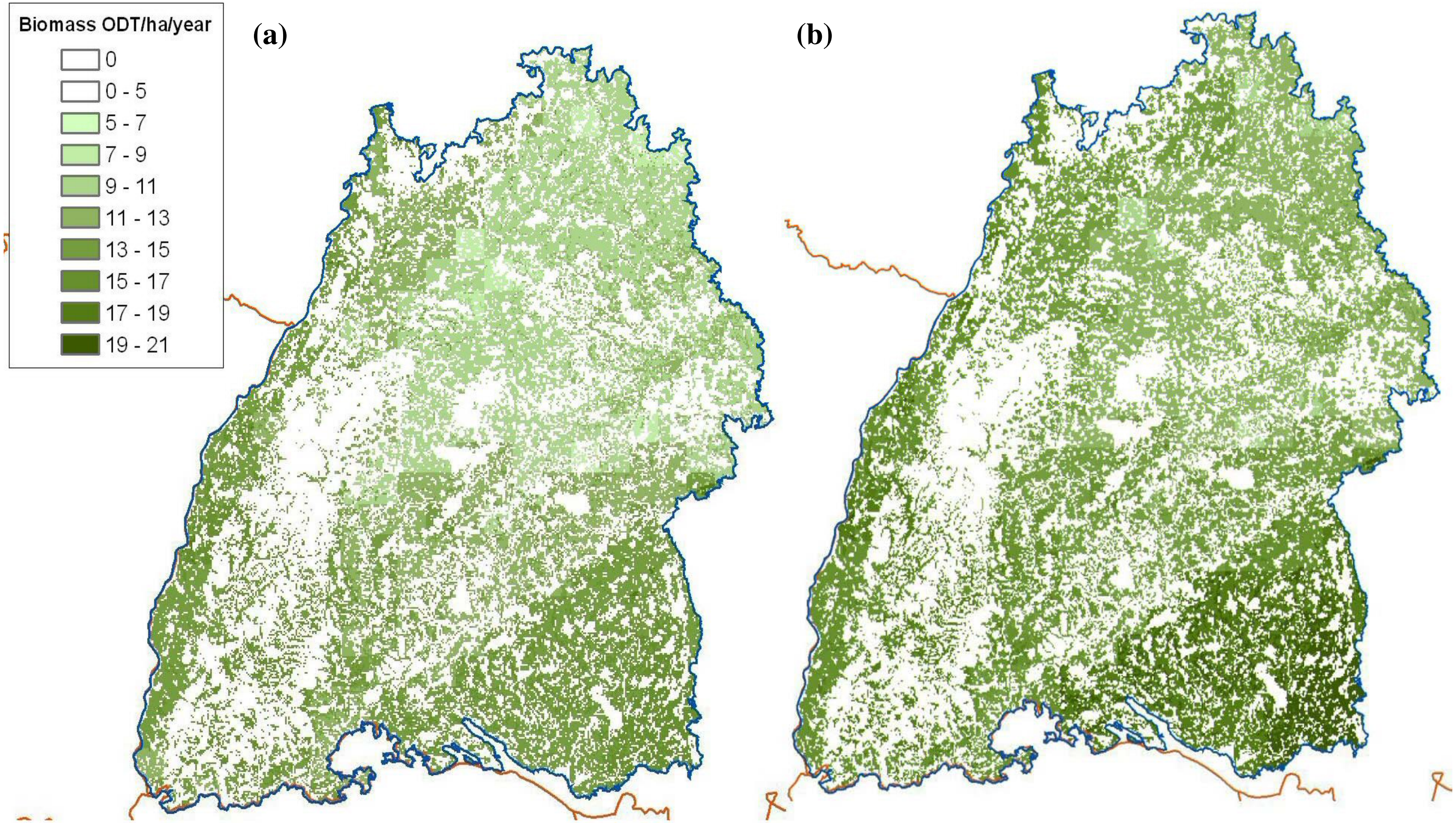

Figure 8: The spatial distribution of productivity for (a) miscanthus with low fertilization (60 kg N yearly) and (b) miscanthus with higher fertilization (100 kg N yearly).

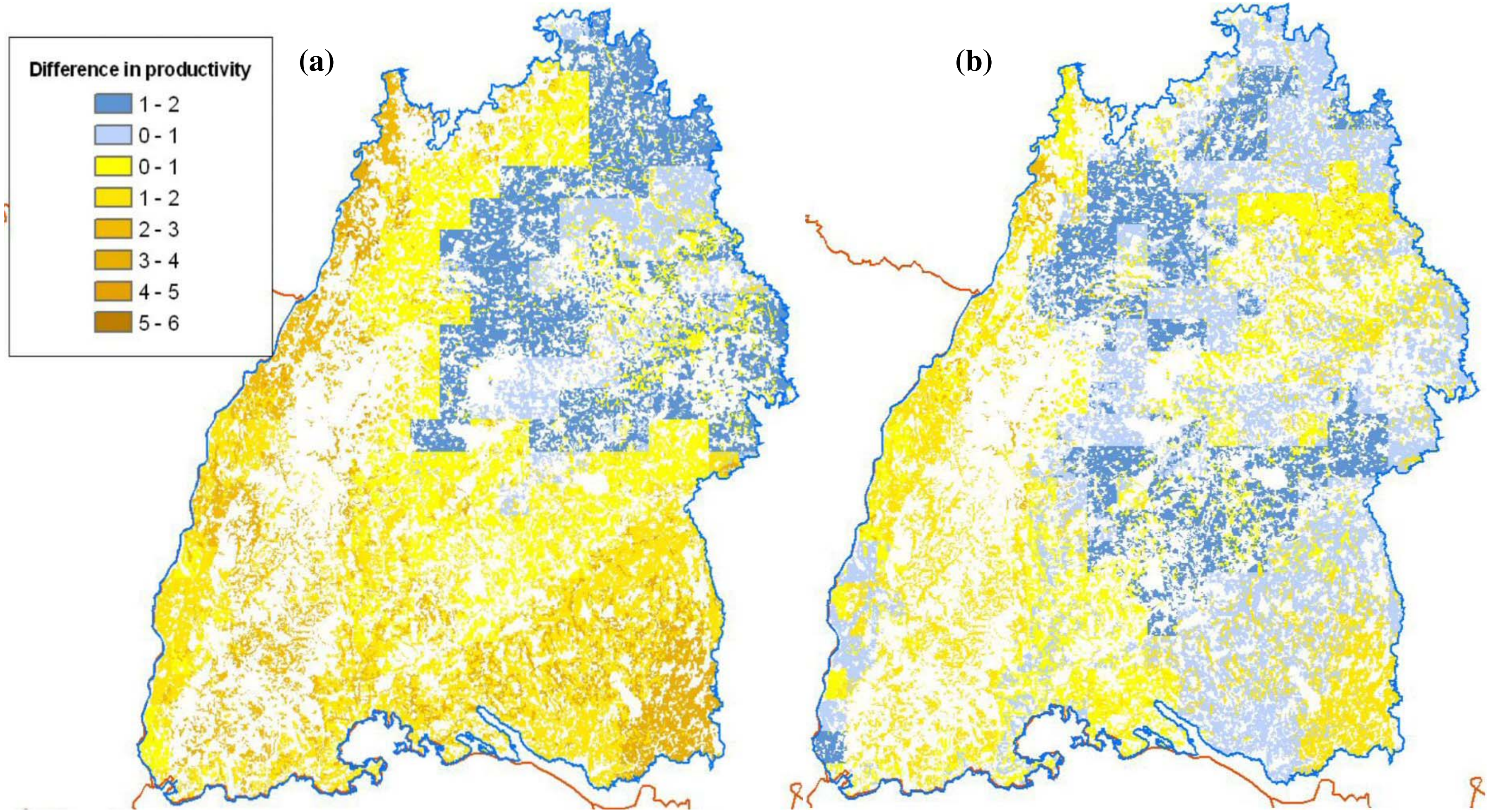

Figure 9: Comparison of the productivity (a) between miscanthus (low level of fertilization) and fertilized poplar coppice and (b) between extensive Robusta poplar and unfertilized poplar coppice. In (a) coppice is more productive in the blue areas and miscanthus in the yellow-brown areas. In (b) Robusta poplar is more productive in the blue areas and coppice in the yellow-brown areas. In both figures, the numbers show the difference in tons/ha/year.

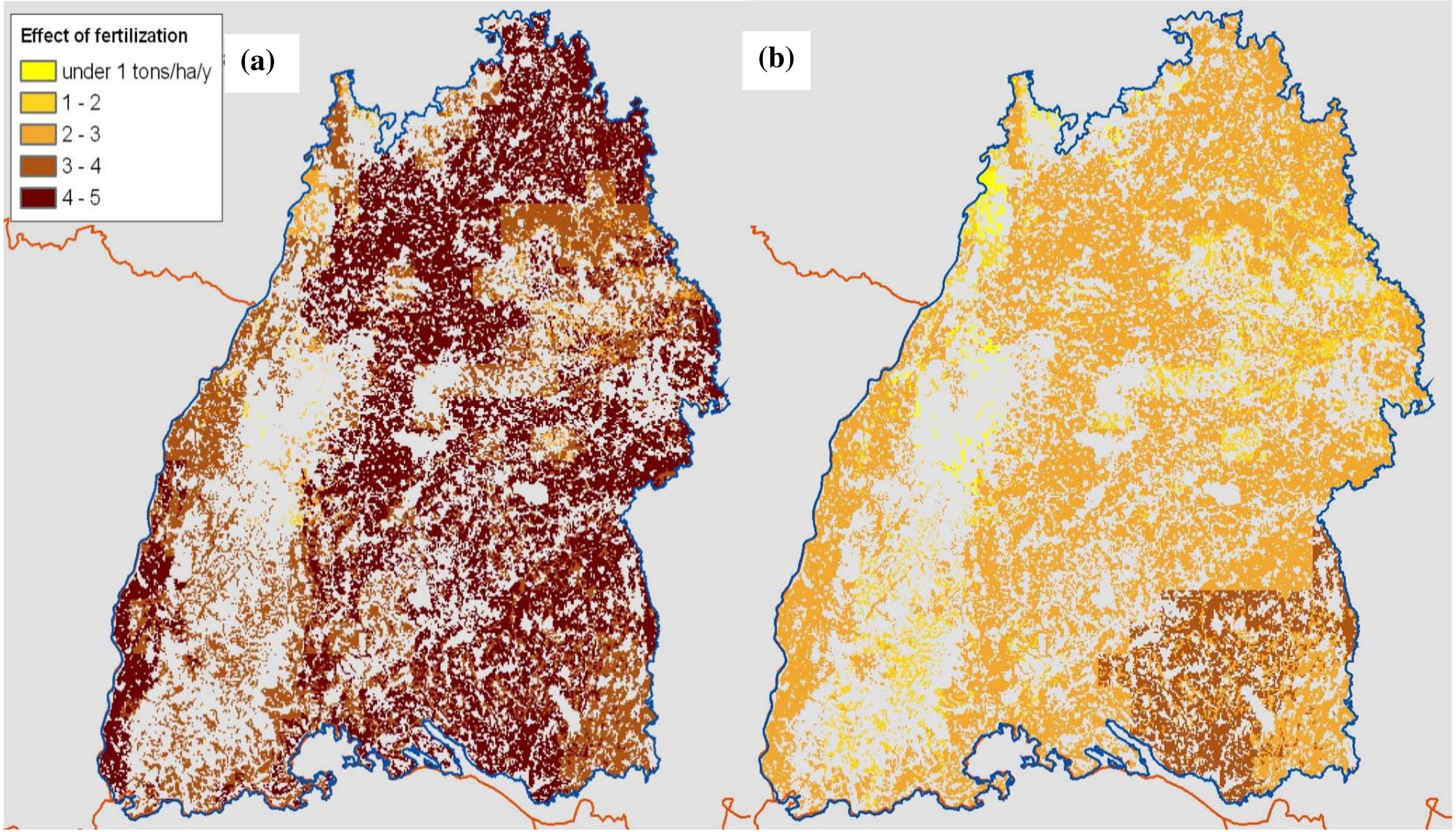

Figure 10: Effects of fertilization (a) on poplar coppice and (b) miscanthus. Colors show the increase of annual production in different areas if slurry (for poplar) or higher N-fertilization (for miscanthus) is used.

4.3 Productivity in Marginal Areas

Even though the GAEZ-data of agricultural suitability is quite detailed on the global and even European scale, it is rather coarse on the scale of Baden-Württemberg (see Figure 10). A more detailed dataset of suitability was not available for this study, so this dataset was used. Figure 11 illustrates how the results look. After using ArcMap to choose the grid cells located on marginal areas, the total productivities for marginal areas were calculated. These totals for each management are given in Table 3.

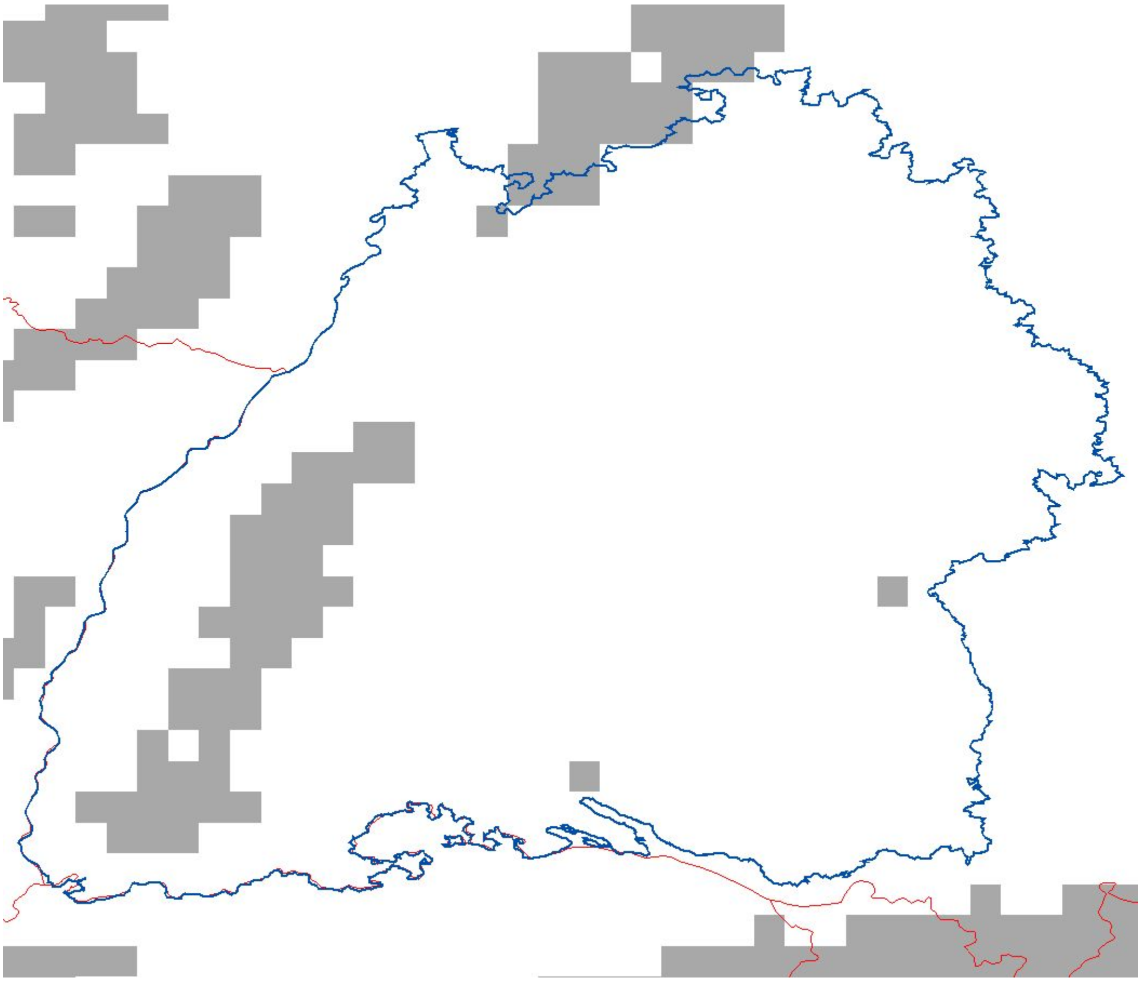

Figure 10: Marginal agricultural areas in Baden-Württemberg (marked with grey) based on GAEZ.

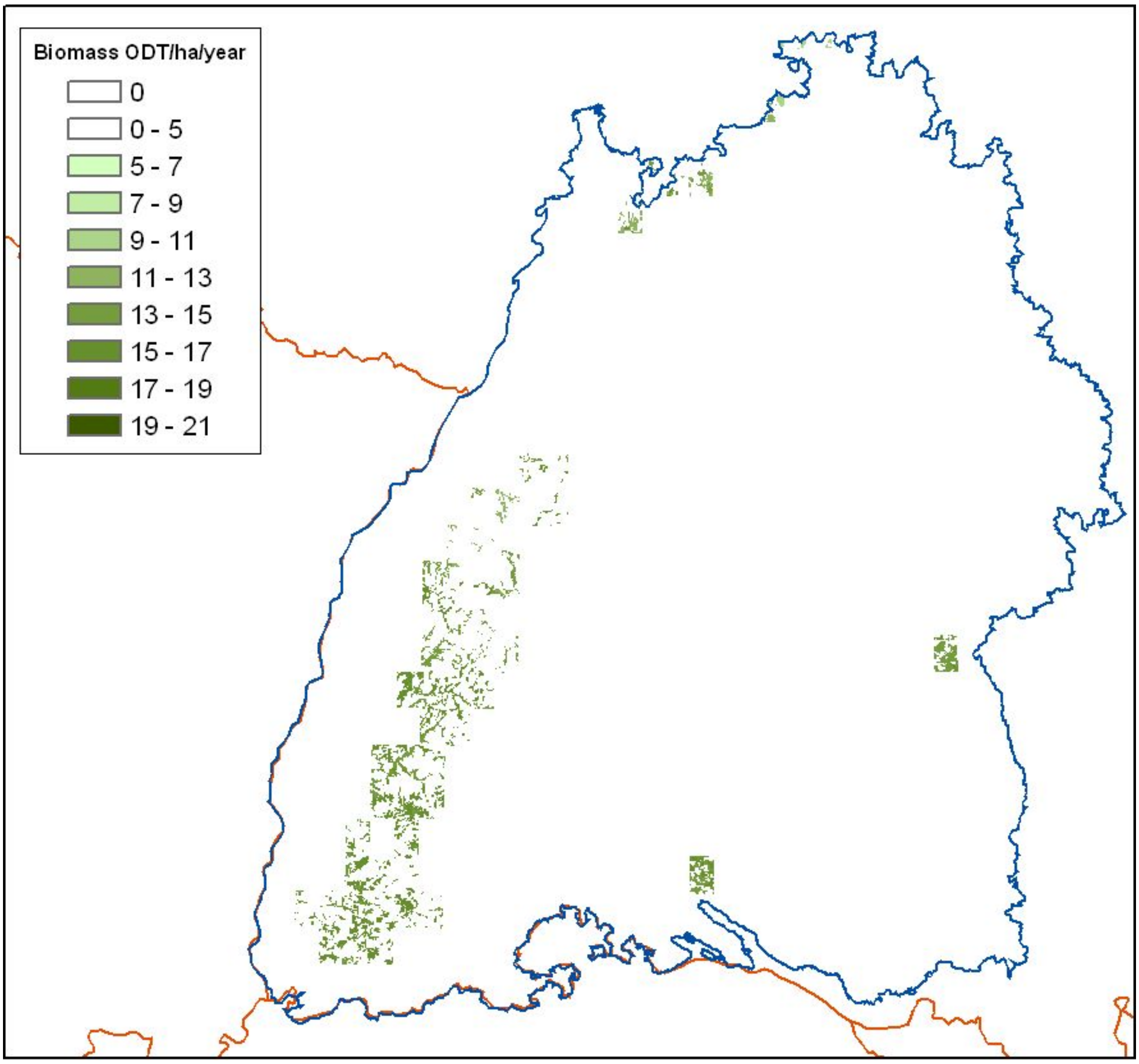

Figure 11: Biomass productivity on marginal areas of Baden-Wurttemberg using miscanthus and high fertilization (100 kg N/ha/year).

Table 3: Total productivity potential for each management option on the marginal areas of Baden-Württemberg.

Management	ODT	PJ
Extensive Robusta poplar	465551.29	8.38
Poplar coppice (unfertilized)	543365.55	9.78
Poplar coppice (fertilized)	744928.64	13.41
Miscanthus (low fertilization)	855454.41	15.40
Miscanthus (high fertilization)	976364.16	17.57

4.4 Costs in Different Areas

The costs per ton biomass were calculated as described in section 3.2.4. Table 4 gives a summary of their variation according to the management option. As can be seen from the table, the costs of biomass from extensive Robusta poplar plantation were above all of the other options examined in all areas. For this reason it is excluded from the visual comparison given in Figure 12.

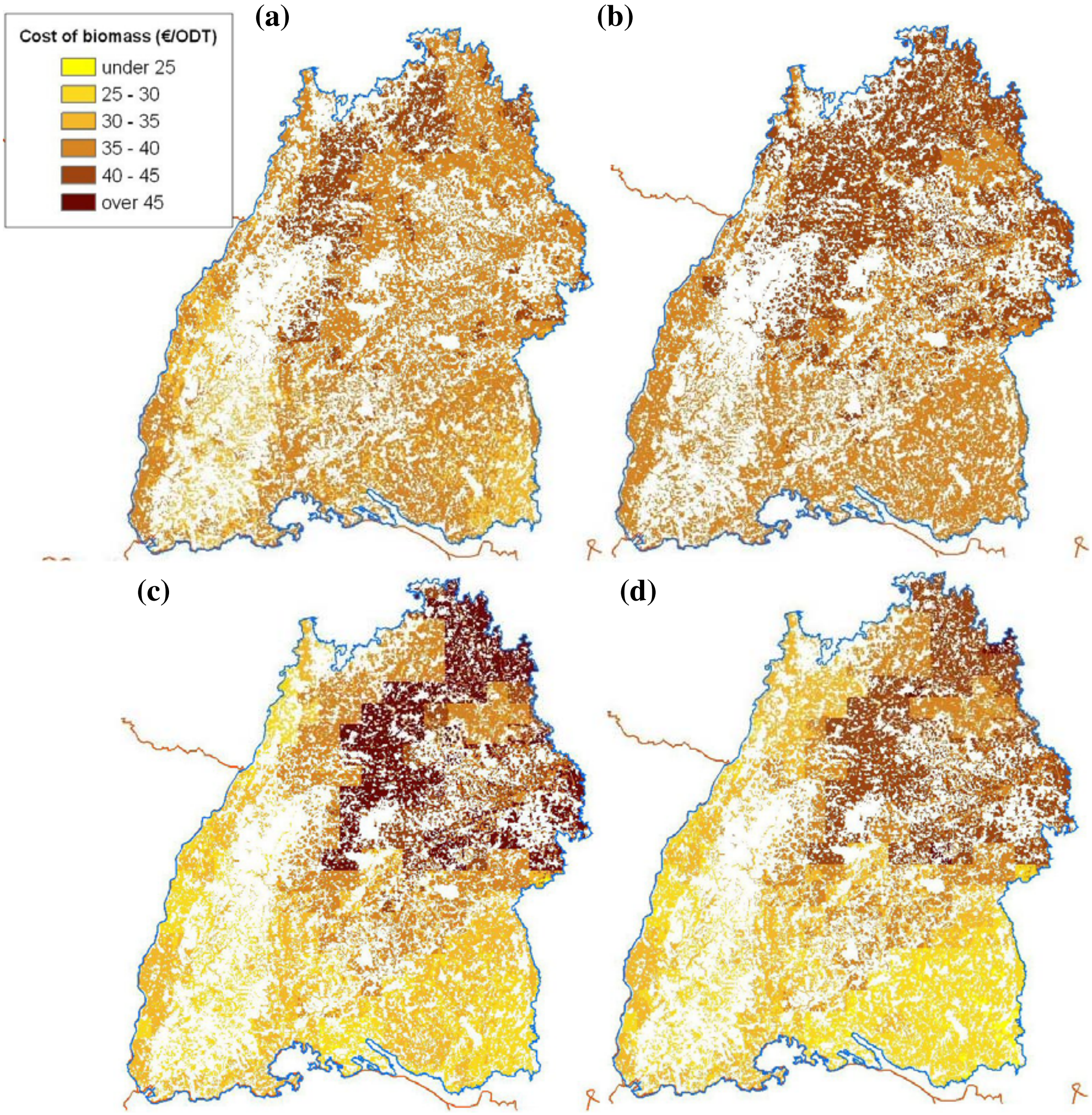

Figure 12: A comparison of estimated costs for biomass in different areas using different management options: (a) unfertilized poplar coppice,(b) poplar coppice fertilized with slurry, (c) miscanthus with lower fertilization, and (d) miscanthus with higher fertilization.

Table 4: A summary of the variation of estimated costs for biomass with different management.

Management	Minimum	Maximum	Average
Extensive Robusta poplar	56. 674	60.317	58.040
Poplar coppice (unfertilized)	32.676	42.401	37.391
Poplar coppice (fertilized)	36.060	43.508	39.334
Miscanthus (low fertilization)	23.481	50.772	35.745
Miscanthus (high fertilization)	23.892	48.564	34.617

5 Discussion and Conclusions

5.1 Limitations of the Approach

In principle, the approach applied in this study results in a spatially explicit estimate on the potentials of bioenergy crop production and their costs in the study area for the different management options. This kind of results can be used to guide decision making concerning both the higher level political commitments as well as the actual implementation of these commitments on a local level. In practice, however, there are many factors that increase the uncertainty of the acquired results.

The results from the model put the different management options into a rather clear order in terms of productivity (Tables 1 and 2, Figures 6–8): miscanthus had the highest productivity, poplar coppice was second and extensive poplar the last. Management with higher fertilization always gave higher yields than with lower fertilization. The only ones to break this clear order were the pairs: miscanthus with low fertilization vs. coppice with fertilization and nonfertilized coppice vs. extensive Robusta poplar. Even in these cases, however, the order was maintained in the majority of areas and the scale of reverse order was rather small (Figure 9).

The question arises whether EPIC can really be sensitive enough to variations caused by differences in soil properties and weather conditions. Based on literature, it could be expected that at least in some areas of Baden-Württemberg poplar coppice would be more successful than miscanthus. More work is needed to validate the use of EPIC for bioenergy crops and especially for coppiced woody crops.

Another factor affecting the sensitivity of the model and the variations given by the model is of course the input data. The soil data was averaged over 10 km by 10 km grid cells and the weather data over 50 km by 50 km. With this level of generalization in the input data, many of the small features and microclimates are missed. Of course this is a question of what datasets are available and what the end purpose of the study is. In future, use of the available 1 km by 1 km soil data could alleviate these problems.

The issue of resolution had an obvious effect also on the analysis of marginal areas. As illustrated in Figure 10, the suitability data used in this study was not detailed enough for studies of this scale. Although, inside the GAEZ grid cells of 5 by 5 arc minutes both marginal and suitable fields definitely exist. Thus, many marginal areas are neglected when choosing only the areas inside the cells classified as marginal by GAEZ. On the other hand, many of the fields considered in this study as marginal are definitely very suitable for and probably continuously in agricultural use. Whether these two cancel each other out, could not be estimated within the scope of this study. In order to more precisely estimate the amount of marginal areas and thus get an estimate for the actual potential for biomass production, either more detailed data about the marginal areas or a completely different approach is needed.

Finally, it should be noted, that the cost estimations made in this study are very rough. The far greater costs of biomass from extensive poplar plantation is mainly due to higher harvesting costs (20 €/m^3). In the case of a plantation with easy topography, even tree density and low percentage of "trouble trees", these costs could well be lower than the estimate used here. On the other hand, the cost estimates given in this study might be too low in general. When converted to euros per GJ (based on an average caloric value of 18 GJ/ODT), the range of costs is 1.3–3.4 €/GJ. As explained in section 3.2.4 many actual costs (land value, storage, etc.) have been excluded, based on the limitations set by the small scope of this study. Also, the assumption made for the transportation distance is very much on the lower end (only to the closest urban settlement). In future studies, more work needs to be done to include spatially explicit cost modeling.

5.2 Suitability of the Approach for the European Scale

The purpose of this study was to examine the usability of EPIC for bioenergy crop modeling and the use of GIS in estimating bioenergy potentials in a spatially explicit way. This was also a feasibility study in the sense that the ultimate aim was to examine one possible approach for a bioenergy assessment on a European scale. The quantitative results acquired in this study are not as important as the methodology used.

Regarding EPIC, the conclusion is that it is capable of modeling bioenergy crops. Some work is maybe needed to adjust EPIC and the parameters it uses to simulate more precisely the character of some processes of bioenergy farming, but there is no reason why the model would not be suitable for this purpose.

Regarding the overall approach, it is concluded that the approach is suitable for assessing the bioenergy potentials of Europe or any sub region of Europe. It is important to note, that many stages of the analysis process presented in this study are not yet adequate. Better input datasets are needed and the cost modeling to be developed. Also, when applied on a European scale, special consideration should be given to the trade-off between the spatial detail of the data and the computer time needed for processing. In this study only a small portion of one country was examined and, although no difficulties were encountered, on the European level the size of the datasets might grow beyond the capacity of a normal desktop PC. However, the approach in itself is feasible and once the different parts of the process are refined, the process described here can give valuable results.

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Appendix: Crop Parameters Used

CR #	OP NAME	**1 WA**	2 HI	**3 TOP**	**4 TBS**	**5 DMLA**
90	POPL	**30**	0.05	**25**	**6**	**4**
123	POPC	**30**	0.05	**25**	**6**	**6**
124	MISC	**45**	0.02	**25**	**8**	**8**

CR #	OP NAME	6 DLAI	7 DLAP1	8 DLAP2	9 RLAD	10 RBMD
90	POPL	0.99	15.1	40.95	1	1
123	POPC	0.99	10.4	30.95	1	1
124	MISC	0.8	15.25	40.95	0.1	10

CR #	OP NAME	11 ALT	12 GSI	13 CAF	14 SDW	15 HMX
90	POPL	5	0.007	0.85	80	7.5
123	POPC	5	0.007	0.85	80	7.5
124	MISC	3	0.0074	0.85	80	2.5

CR #	OP NAME	16 RDMX	17 WAC2	18 CNY	19 CPY	20 CKY
90	POPL	3.5	660.41	0.0015	0.0003	0.002
123	POPC	3.5	660.41	0.0015	0.0003	0.002
124	MISC	2.2	660.52	0.007	0.0009	0.006

CR #	OP NAME	21 WSYF	22 PST	23 COSD	24 PRYG	25 PRYF
90	POPL	0.05	0.6	6.72	1000	5
123	POPC	0.05	0.6	6.72	1000	5
124	MISC	0.01	0.6	2.2	0	0

CR #	OP NAME	26 WCY	27 BN1	28 BN2	29 BN3	30 BP1
90	POPL	0.01	0.006	0.002	0.0015	0.0007
123	POPC	0.01	0.006	0.002	0.0015	0.0007
124	MISC	0.55	0.03	0.008	0.002	0.0019

CR #	OP NAME	31 BP2	32 BP3	33 BK1	34 BK2	35 BK3
90	POPL	0.0004	0.0003	0.006	0.003	0.002
123	POPC	0.0004	0.0003	0.006	0.003	0.002
124	MISC	0.0012	0.0009	0.011	0.0071	0.006

CR #	OP NAME	36 BW1	37 BW2	38 BW3	39 IDC	40 FRST1
90	POPL	3.39	3.39	3.39	8	5.1
123	POPC	3.39	3.39	3.39	8	5.1
124	MISC	3.39	3.39	3.39	6	5.15

CR #	OP NAME	41 FRST2	42 WAVP	43 VPTH	44 VPD2	45 RWPC1
90	POPL	15.5	8	1	4.75	0.4
123	POPC	15.5	8	1	4.75	0.4
124	MISC	15.95	10	0.8	4.75	0.7

CR #	OP NAME	46 RWPC2	47 GMHU	48 PPLP1	49 PPLP2	50 STX1
90	POPL	0.2	100	500.95	20.15	0.05
123	POPC	0.2	100	1000.95	400.15	0.05
124	MISC	0.3	100	4.47	7.77	0

CR #	OP NAME	51 STX2	52 BLG1	53 BLG2	54 WUB	55 FTO
90	POPL	1	0.01	0.1	0	0
123	POPC	1	0.01	0.1	0	0
124	MISC	0	0.01	0.11	0	0

CR #	OP NAME	56 FLT	
90	POPL	0	POPLAR ROBUSTA
123	POPC	0	POPLAR COPPICE
124	MISC	0	MISCANTHUS