# Spatial assessment of the environmental impacts of potential wheat and switchgrass bioethanol chains in Ukraine.

*Final version.*

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Ruud Gelten

# Abstract

During the previous five years, the production of bioethanol in the EU has increased from 900 to 3,700 Ml/yr (biofuels platform 2010). In order to accommodate a further increase, the European Union is searching for alternative production sites. In several scientific assessments, Ukraine has been identified as one of the most promising European countries for bioethanol production (Fischer, Prieler et al. 2010)(Wit, Faaij 2010). However, before exploiting this potential, the environmental impacts should be assessed. As the environmental impacts largely depend on local parameters, a spatially explicit assessment is essential (Hilst 2009). Currently, a spatially explicit impact assessment of Ukrainian biofuel crop production, that focuses on environmental criteria, is still lacking in scientific literature. Therefore this study aims to assess these impacts, in order to determine the areas in which the production is favourable, and the areas in which the production is less favourable. Furthermore, this study specifically focuses on ethanol production from winter wheat and switchgrass in the year 2015.

In order to prevent competition with food, it is assumed that bioethanol crops can only be cultivated on former agricultural lands, that are liberated by an increase of the agricultural efficiency. Following the study from de Wit et.al 2010, in which the potential of the Ukrainian bioenergy sector is modelled, it is assumed that in 2015 about 18-23 mln hectares are available for the production of bioenergy crops, without compromising the food availability or the food prices.

Following the guidelines of EU directive 2009/28/EC (EU Commission 2010), and the Cramer Criteria, that have been developed by the Dutch taskforce ‘energy transition’ (Cramer, Wissema et al. 2007), four criteria have been selected in order to asses the environmental impacts. The criteria include the GHG emissions, the change of the biodiversity, and the impacts on soil and water.

To asses the GHG emissions of bioethanol production, the IPCC tier 1 methodology has been applied (IPCC 2006a). Both the emissions from land use changes and the life cycle emissions have been assessed, and compared to the emissions of fossil gasoline. It can be concluded that wheat-ethanol, produced on former pasture land, leads to the highest emission. Especially on organic soils, the production of wheat should be avoided, as it leads to more GHG emissions than fossil gasoline. The main cause of the emissions is the loss of soil carbon because of the increased tillage regime. If wheat is produced on arable land, the emission will be lower, at approximately 45-60% of the emission of fossil gasoline. The production of switchgrass on formerly arable or (mineral) pastureland, leads to a net mitigation of GHGs. The main reasons are the low fertilization- and tillage regimes, and the high amount of biomass fixed carbon of switchgrass cultivation. On organic pasture land, the production will lead to an emission of approximately 20% of the emission of fossil gasoline. The main reason is the tillage in the first year of the switchgrass cycle.

To assess the biodiversity, the mean species abundance has been applied, to compare the current agrobiodiversity to the agrobiodiversity of the bioenergy crop cultivation sites. In general, the cultivation of bioenergy crops will lead to a decrease of the biodiversity. The decrease is mainly caused by the intensive management of bioenergy cropping, as compared to the currently extensive agriculture. An exception is the production of switchgrass on current arable land, which will not lead to a decrease of the biodiversity. The main reason for this, is the switchgrass’ low tillage regime and it’s long growth season, which leads to a relatively low disturbance of the current animal population.

The soil assessment is divided in three sub-criteria: soil organic matter, water erosion and wind erosion. To assess the soil organic matter, the soil organic carbon (SOC) has been used as a proxy. The SOC was calculated with the IPCC tier 1 methodology. From the analysis it can be concluded that the cultivation of wheat on arable land, leads to a modest increase of the soil organic matter. If wheat is cultivated on pasture land, the soil organic matter decreases. Especially the cultivation on pastureland with an organic soil type should be avoided, due to the large soil organic matter flux that is caused by the wheat’s tillage and fertilization regime. As switchgrass has a low-tillage regime, it can be cultivated on organic soils without a soil organic matter loss. On mineral soils, the cultivation of switchgrass, leads to an increase of the soil organic matter stock.

The water erosion has been assessed with the Universal Soil Loss Equation (USDA 2002). From the analysis it can be concluded that the general influence of water erosion in Ukraine is relatively low, because of the low precipitation. Also, the majority of the sloped areas are used for natural purposes, leaving a relatively small part for agriculture. If wheat is cultivated on sloped arable lands, the water erosion does not change, due to the similarities between wheat and the current crops types. If wheat is cultivated on pasture land, the soil erosion increases, because of the long growth season of grass, and the ability of the grass to bind the soil with it’s

extensive root system. Switchgrass cultivation on sloped arable areas leads to a decrease of the soil erosion, because of it's long growth season and large root system. If switchgrass is cultivated on pasture land, the erosion will be unaffected.

The wind erosion has been assessed by the wind erosion equation. Both the cultivation of wheat and switchgrass on arable land leads to a decrease of the wind erosion. For both crops, the decrease is highest in the South-Eastern oblasts, as the wind speeds are highest there. If pastures are used for the cultivation of wheat, the wind erosion tends to increase, as pastures are perennial crops and hence provides more shielding to wind erosion in the winter months. In the case of switchgrass cultivation on pasture land, the wind erosion remains unchanged.

The water assessment is divided into two sub-criteria: the water quantity and the water quality. The water quantity focuses on the prevention of water shortages. It has been assessed with a water balance, describing the difference between the precipitation and the evapotranspiration. In the North-Western oblasts, wheat cultivation leads to an increase of the water deficit, because of the current cultivation of many low water-consuming crop types. In the Southwest, the water shortage decreases, as the current crop mixture is more water consuming than wheat. If wheat is cultivated on pasture land, the water deficiency also tends to decrease, because of the pastures' high water consumption. Although the water use efficiency of switchgrass is considerably higher than most other crops, the high amount of biomass and the long growth season of switchgrass, leads to a high water consumption. Consequently, the cultivation of switchgrass leads to an increase of the water deficiency, on both arable and pasture land.

The water quality has been assessed by analysing the $NO_3$ concentration of the soil water, which has been modelled with the Miterra Europe model (Alterra 2010). If current agricultural land is cultivated with wheat or switchgrass, considerable differences can be seen in the $NO_3$ concentrations. The concentration change per oblast, is mainly depending on the current N application. In the oblasts with a high concentration, the $NO_3$ decreases, and in the oblast with a low concentration, it $NO_3$ increases. The concentration change of both wheat and switchgrass varies between -24 - 16 mg $NO_3$/l.

It should be noted that the results of this analysis should be interpreted with care, as they include many assumptions and estimations. Furthermore, the results of the analysis are often based on (spatial) data with large uncertainty ranges, including the uncertainty that stems from the combining of data with different spatial resolutions. Moreover, as not all parameters in this study were specifically available for Ukraine, the inclusion of non-Ukrainian data also adds to the uncertainty. To decrease the uncertainties in the study, more research is required.

From the results, it can be concluded that there are considerable spatial differences in the environmental impacts of bioethanol production in Ukraine, thereby justifying the spatial approach. There are no areas that are only positively or negatively influenced by the conversion. Furthermore, wheat cultivation leads in all cases, except for the water use criterion, to a larger environmental impacts than switchgrass. Therefore, switchgrass cultivation should be preferred above wheat cultivation, from an environmental perspective. Also, the use of current arable land should be preferred over the use of pasture land.

Finally, in order to improve the accuracy of the results, it is recommended that the spatial resolution of various parameters are improved from a NUTS2 to a local scale (> NUTS 3). Furthermore, field research is recommended to confirm the validity of the land cover map, and to improve the accuracy of several criteria, such as the water use and biodiversity.

# Table of Content

# List of abbreviations

| | |
|---|---|
| ASTER | Advanced spaceborne thermal emissions and reflection radiometer |
| CCS | Carbon capture and storage |
| CEECs | Central and Eastern European countries |
| $CO_2$-eq | $CO_2$ equivalent |
| DDGS | Dry distillers grains and solubles |
| DEM | Digital elevation model |
| DW | Dry weight |
| EEA | European environment agency |
| FAO | Food and agricultural organization of the United Nations |
| FW | Fresh weight |
| GEMIS | Global Emission Model for Integrated Systems. |
| GHG | Green house gas |
| GLC2000 | Global land cover 2000: A spatial dataset, representation of the land cover in the year 2000. |
| HAC | High activity soils |
| IEA | International energy agency |
| IIASA | International institute for applied system analysis |
| IPCC | International panel for climate change |
| IUCN | International Union for the conservation of nature |
| JEC-WTW | Joint Research Centre-EUCAR-CONCAWE collaboration |
| JRC | Joint Research Centre for environment and sustainability of the European Union |
| LAC | Low activity soils |
| LUC | Land use change |
| MAP | Mean annual precipitation |
| MAT | Mean annual temperature |
| MSA | Mean species abundance |
| NOAA | National Oceanic and Atmospheric Administration of the USA |
| NUTS | Nomenclature of Territorial Units for Statistics (a geocode standard for determining the subdivisions of countries. |
| OD(T) | Oven dry (ton) |
| PBL | Planbureau voor de leefomgeving: Netherlands environmental assessment agency |
| PET | Potential evapotranspiration |
| RUSLE | Equation to calculate water erosion |
| REFUEL | An EU funded project, with the goal to increase the market penetration of biofuels |
| SG | Switchgrass |
| SOC | Soil organic carbon |
| SOM | Soil organic matter |
| SPOT | Satellite Pour l'Observation de la Terre : A high-resolution, optical imaging satellite. |
| ULRMC | Ukrainian Land and Resources Management centre |
| USDA | United States department of agriculture |
| UU | University of Utrecht |
| WEC | Western European countries |
| WEQ | Wind erosion equation |
| WDPA | World database on protected areas |
| WH | Wheat |
| WRB | World reference base for soil resources |
| WUR | Wageningen University |

# 1. Introduction

Since the mid-20th century, the average global temperature has risen with 0.3 °C. A large part of this increase is caused by the greenhouse gas emissions from the use of fossil fuels (Hegerl, Zwiers et al. 2007). To decrease the use of fossil fuels, the EU has set targets for the use of alternative energy sources. Besides the climate related benefits, alternative energy sources also decrease the reliability on oil, thereby increasing the flexibility of the energy production system. One of the alternative sources, on which the EU is currently focussing, is biomass (EU Commission 2006). Especially in the transport sector, that is currently responsible for 24% of the $CO_2$ emissions of the EU, biofuels are expected to make a significant contribution to the renewable energy provision (EU Commission 2010). The current target for the use of renewable energy in the transport sector, has been set at 10% in 2020 (EU 2008). Bioethanol may provide a large part of this energy.

In order to accommodate the expected increase for biofuels, the European Union is searching for alternative production sites. In many scientific studies, Ukraine is identified one of the most promising European countries. An example is the study by Fischer and Hizsnyik et.al. (Refuel, IIASA, (Fischer, Hizsnyik et al. 2007), that used the AEZ methodology[1] to assess the biofuel potential of five main biofuel groups. The main reason for Ukraine's potential is its large stock of fertile agricultural land. Due to a decreasing population and an increasing agricultural efficiency, it is expected that almost 20 mln hectares of arable land can be made available for bioenergy crop production (Smeets, Faaij 2009). As half of the Ukrainian land area is covered with productive chornozem or kastanozem soils, also the potential yield levels look promising. (IUSS, ISRIC et al. 2006). Furthermore, as land and labour are relatively cheap (FAO 2010c), the costs of Ukrainian biofuels are expected to be competitive with fossil fuels in the near future (Teuling 2008).

However, before the exploitation of Ukraine's potential, the environmental effects of the biofuel production need to be assessed. Unsustainable production should be prevented, as it can lead to an increase of the net GHG emissions. Furthermore, unsustainable production can also have a negative impact on other environmental aspects (Cramer, Wissema et al. 2007). To prevent this, the Dutch taskforce 'energy transition' made a proposition in 2007, to apply several environmental criteria on the production of biofuels. The criteria are focussing on the GHG balance, the competition between biofuels and food, changes in the biodiversity, and changes to the soil, water and air (Cramer, Wissema et al. 2007). Recently, also the European Union have issued regulations that require an environmental assessment of biofuel production. Following EU directive 2009/28/EC, a minimum level of greenhouse gas savings should be achieved, and biofuel crop production is prohibited on lands with high carbon stocks, or a high biodiversity (EU 2008).

The environmental impacts of biofuel production depend largely on local parameters, such as the climate and the soil type. Depending on the location, these parameters can have a positive or negative influence. To determine the influence of biofuel production on the environment, a spatially explicit assessment is essential, as it can help to identify the areas that are favourable for biofuel production, and those that are not.

In the last decade, many scientists have already researched the sustainability of biofuel crop cultivation. An example are the studies by van Dam et. al. (Dam, Faaij et al. 2009) and van der Hilst et.al. (Hilst, Dornburg et al. 2010), that both have a spatially explicit character. Van dam has chosen to apply agro economic zoning (AEZ)[1], to assess the sustainability of soybeans and switchgrass in Argentina. By applying the AEZ methodology, the results are spatially explicit on a regional level. Van der Hilst takes this a step further, by conducting an environmental assessment of sugar beet and miscanthus in the North of the Netherlands, based on a GIS-based[2] methodology. The methodology that was used by van der Hilst, is also applied in this study. Where van der Hilst focuses on the Netherlands, the study by Geletukha et.al. (Geletukha 2007) focuses specifically on Ukraine. The study analyses the current and future use of Ukrainian bioethanol, and identifies the main barriers on a technical and political level, including potential-, economical-, implementation- and information barriers. An similar study was conducted by Teuling et.al. (Teuling 2008), which analysed the technical and implementation potential up to 2030 for bioenergy in Ukraine. Several scenarios were considered, to account for developments in the population and economy, and for the technical and agricultural developments. Besides the above studies, also the environmental impacts of Ukrainian biofuel production have been researched. In their work, Smeets and Faaij (Smeets, Faaij

[1] AEZ: Agro economic zoning, designed by the FAO and IASA(Dam, Faaij et al. 2009, Smeets, Faaij et al. 2005, WEO, IEA 2009). See §4.8.1 for additional information.

[2] GIS: An abbreviation of 'Geographical Information System', describing a software package that enables the user to depict and analyse detailed spatial data.

2009) assess six environmental, and seven socio-economical parameters, by a non-spatial methodology. The research focuses on poplar cultivation.

Summarising the paragraphs above, it can be concluded that there is already a solid knowledge base on biofuel production in Ukraine. The main opportunities and barriers have been identified, and the production potential is known. Furthermore, there has been research on the influence on the environment, and to the socio-economical system. However, a spatially explicit impact assessment of Ukrainian biofuel crop production, that focuses on environmental criteria, is still lacking in scientific literature. This study therefore aims to assess these environmental impacts.

Winter wheat and switchgrass have been selected as a first and second generation bioenergy crop to be researched (also see paragraph 2.4). Furthermore, the study aims for an assessment of the impacts in 2015. As the bioenergy market still has to develop, an earlier year would be improbable. Looking further into the future would be unrealistic, as the developing Ukrainian biofuel market is too volatile to make predictions beyond that year. The research aims for a maximum spatial resolution, within the constraints of data availability and time. The main research question is formulated as follows:

*"What are the spatial variations of the environmental impacts of potential winter wheat and switchgrass bio-ethanol chains, in Ukraine in 2015?"*

In order to answer the main question, several sub-questions should to be answered. Three sub-questions have been formulated:

1. *Can the variations of the environmental impacts be assessed in a spatially explicit manner, using the methodology by van der Hilst, 2009?*
2. *What are the spatial variations of the environmental impacts of potential wheat and switchgrass bio-ethanol chains in Ukraine?*
3. *What are the differences between environmental impacts of wheat and switchgrass bio-ethanol?*

To answer the research question, chapter 2 will provide additional information on the agricultural system of Ukraine. The chapter will describe the differences between the current agricultural system and two potential systems that are based on the production of winter wheat and switchgrass. Chapter 3 describes the methodology that was used to estimate the changes to the green house gas balance, the biodiversity, and the soil and water system. Subsequently, chapter 4 continues with a description of the results. In chapter 5, a discussion clarifies the main uncertainties, and the applicability of the results. Then, chapter 6 describes the main conclusions and provides the answers to the research questions.

# 2. Case study

In this report, the environmental impacts of the current agricultural system will be compared with the impacts of two potential future systems, that are based on large scale bioethanol production from winter wheat and switchgrass. First, paragraph 1 provides an introduction of Ukraine, which provides general information about the climate, soil and land use. Then, paragraph 2 continues with an overview of the current agricultural system, and an overview of the assumptions that where made to incorporate the system in this study. Subsequently, paragraph 3 estimates the amount of land that is likely to become available for bioethanol production in 2015. Then, paragraph 4 gives an overview of the wheat and swicthgrass bioethanol chains, and describes the assumptions that have been taken to incorporate the chains into this study. Paragraph 5 will provide a short overview of the assumptions.

## *2.1 Ukraine*

<u>Administrative</u>
With an area of 603,628 km$^2$, Ukraine is the largest country in Europe. It includes 24 administrative areas (oblasts), one autonomous republic (Crimea) and two city states (Kiev and Sevastopol). From North to South, Ukraine measures almost 900 km, and from East to West 1,315 km. It borders with Russia in the North and East, with Belarus and Poland in the North-West, with Slovakia and Hungary in the West and Moldova and Romania in the South-West (CIA 2009).

<u>Climate</u>
According to the IPCC classification system (classified according to the schedule in paragraph 3.1), Ukraine can be divided in four climate zones (IPCC 2006a). As can be seen in figure 2.1, Ukraine's Northern oblasts, making up 40% of the total area, are situated in the cool moist climate zone. According to climate data from NOAA (NOAA ESRL physical science division 2008), the temperatures vary from -6°C in December to 20°C in July. Precipitation varies between 30 mm/month in December and 90 mm/month in July, with a total of 600-700 mm/yr. The second region, the cool dry zone, comprises most of the central oblasts. Temperatures are similar to the first zone. The precipitation is slightly lower, with a total of 500 mm/yr. The third zone, which is the warm dry zone, is situated in the South of Ukraine, and comprises the oblasts of Odessa and Kherson. With -3-22 °C, the average temperatures are slightly higher than in the Northern and central zones. Precipitation is varying between 400-500 mm/year. The most southern climate region, which comprises the Crimean peninsula, is the warm and moist temperate zone. Temperatures range between 0-23 °C. Precipitation varies between 500-600 mm/yr.

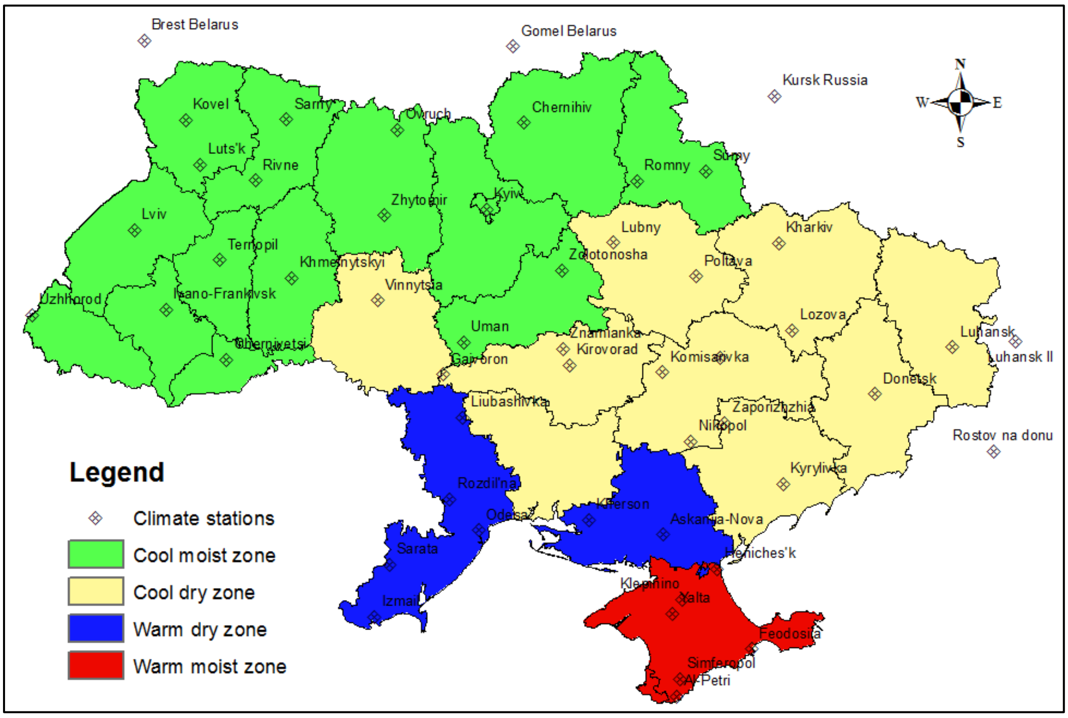


***Figure 2.1:*** *Climate map of Ukraine, according to the IPCC* (IPCC 2006a)*, including the location of the NOAA weather stations* (NOAA ESRL physical science division 2008).

Soil

To account for the various soil types in Ukraine, the European Soil Database (ESDB) has been consulted (EU Commission, European Soil Bureau Network 2004). The database displays 43 soil types, that are classified according to WRB[3] standards. The soil type distribution is displayed in figure 2.2. For reasons of readability, only the main soil types have been displayed is the figure.

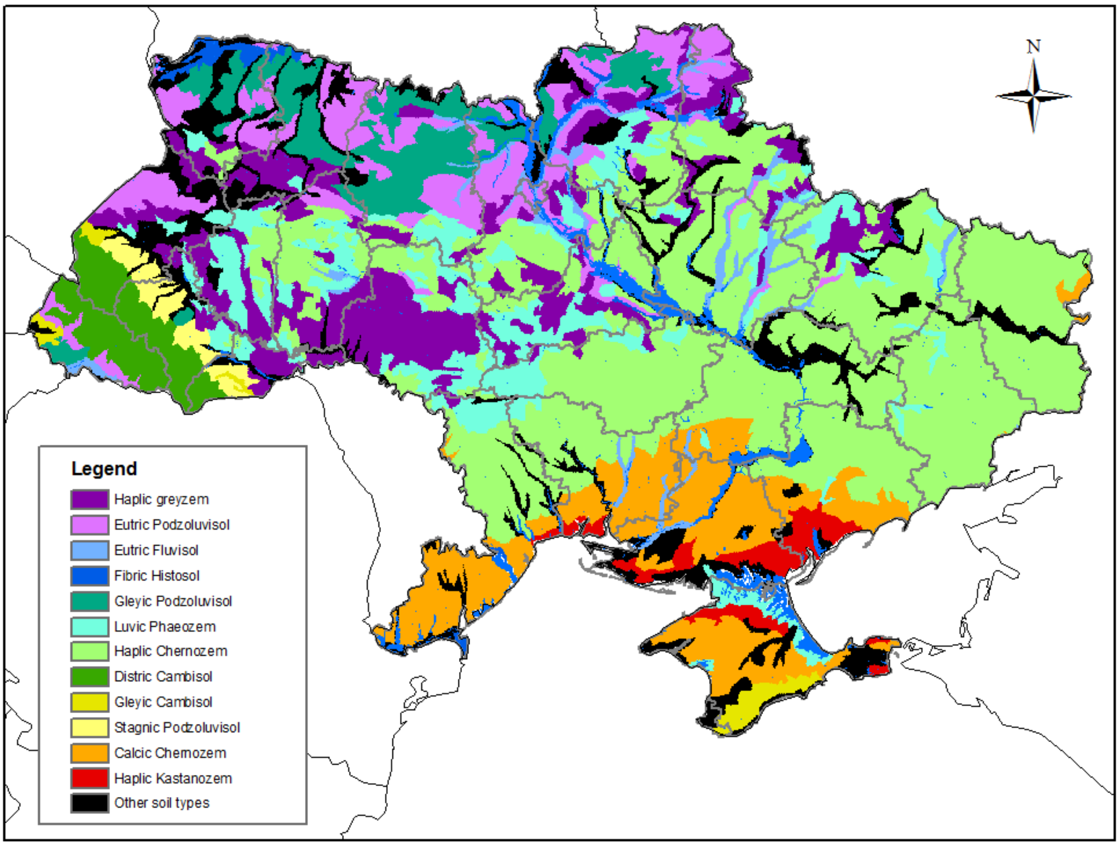


***Figure 2.2:*** *Soil classes in Ukraine according to the WRB classification. For clarity reasons, minor soil types are left out of this visualisation. Original data from the ESDB* (EU Commission, European Soil Bureau Network 2004)

From the figure, it can be seen that the majority of the Ukrainian soil types are mineral. The Northern oblasts are mainly covered in Eutric and Gleyic Podzoluvisol. According to the world reference base for soil resources, Podzoluvisol is characterised by a low nutrient content, in combination with a high acidity (IUSS, ISRIC et al. 2006). The central and Southern part of Ukraine is mainly covered in Chornozem, and the strongly related Phaeozem and Kastanozem. According to the world reference base for soil resources, the black Chernozem is counted along the most fertile soil types in the world. The soils are characterised by a high amount of organic matter, and a rich calcium content.

The main areas with organic soils, can be found in the North-East, and around the river Dnipro, in the centre of the country. The majority of the organic soils is fibric histosol (peat).

Land use

To indentify the different land uses in Ukraine, the Corine land cover database has been consulted (EEA 2009). The database distinguishes between 23 different land use types, at a resolution of 860x860m. As shown in figure 2.3, 16 land use types can be identified within the borders of Ukraine.

[3] WRB is an acronym for the World Reference Base for soil resources. This soil classification system is the successor to the International Reference Base for Soil Classification (IRB), an initiative of FAO, supported by the United Nations Environment Programme (UNEP) and the International Society of Soil Science (FAO 1998).

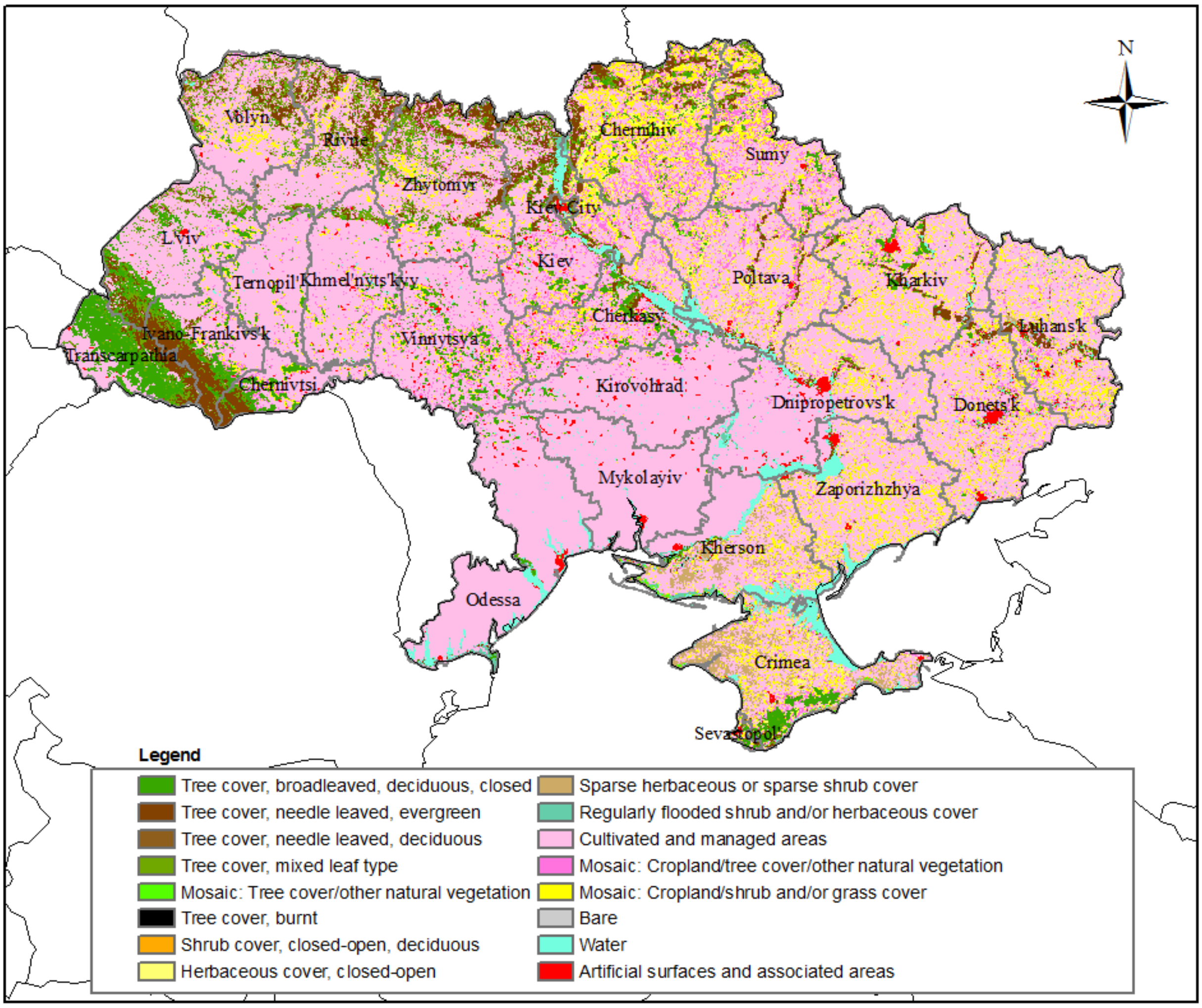


***Figure 2.3:*** *Land use, as given by the Corine database* (EEA 2009) .

As can be seen from the figure, most of the Ukrainian land is used for agricultural purposes. Ukraine's agricultural land comprises approximately 41.8 Mln hectares (USDA, Lindeman 2004), which corresponds to 70% of it's land surface (CIA 2009, FAO 2002). 7.9 Million hectares of the agricultural area is pasture land (FAOSTAT ). The other 34 mln hectares is arable land, although only 27.1 mln hectares is actually sown (State Statistics Committee of Ukraine, Ostapchuk et al. 2009), due to a lack of investment funds (Gebuis 2010).

According to the National Statistics from the State Statistical Committee of Ukraine, 57% of the arable land is used for the cultivation of cereals (State Statistics Committee of Ukraine, Ostapchuk et al. 2009). Of this area, 46% is used for wheat cultivation, 27% for barley, 16% for maize, and 11% for other cereals. Furthermore, significant amounts of land are used for the cultivation of sunflowers (16%), potatoes (5%) and rapeseed (5%). The remaining land is used for 'other crops' (7%) and for the production of feed (10%).

Approximately 7,9 mln hectares are used as pasture land. It is mainly concentrated in the North-Eastern and South-Eastern oblasts. According to the FAO, the majority of the village pastures are serious degraded, because of overgrazing (Bogovin 2001). The state of the natural pastures is unknown.

## 2.2 Current agricultural practices

To analyse the impacts of bioethanol production, the environmental effects of the current agricultural system will be compared to the wheat and switchgrass bioethanol chains. This paragraph will give an overview of the current agricultural system of Ukraine.

Land cover

Four of the land use types in the Corine database are described as agricultural. The database distinguishes between '*cultivated land*, '*mosaic cropland/tree cover'*, '*mosaic pasture land/cropland'* and '*temporarily flooded cropland'*. In this study, only the first three types are assumed to be available for bioenergy crop cultivation. To determine the relative amounts of pasture and arable land in the three categories, the data has been compared with data from the Globcover database (ESA 2008), that gives an approximation of the fractions arable land and pasture land on a spatial basis. According to Globcover, the *agricultural land* and *mixed cropland* categories, comprise approximately 65-85% arable, and 15-35% other land. The category *mixed pasture land/cropland* includes approximately 20-50% arable land and 50-80% pasture land.

Although the mixing of different land-use types per gridcell may be more accurate, it also has several disadvantages. The range of the land use fractions is fairly large, which prevents making accurate assumption on the actual land use of a location. Furthermore, the mixing of land use types implies that also the environmental impacts will be mixed, as the impacts differ per land use type. This will increase the complexity of the research, and decrease the clarity of it's results. Therefore, the *cultivated areas*, and *mixed cropland* categories, have been reclassified as 100% arable land, and the *mixed pasture land/cropland* category has been reclassified as 100% pasture land. Although this underestimates the total amount of pasture land in Ukraine (FAOSTAT ), it will improve the clarity of the report, and prevents the mixing of the effects that occur on arable and pasture land. The new land use classification can be seen in figure 2.4.

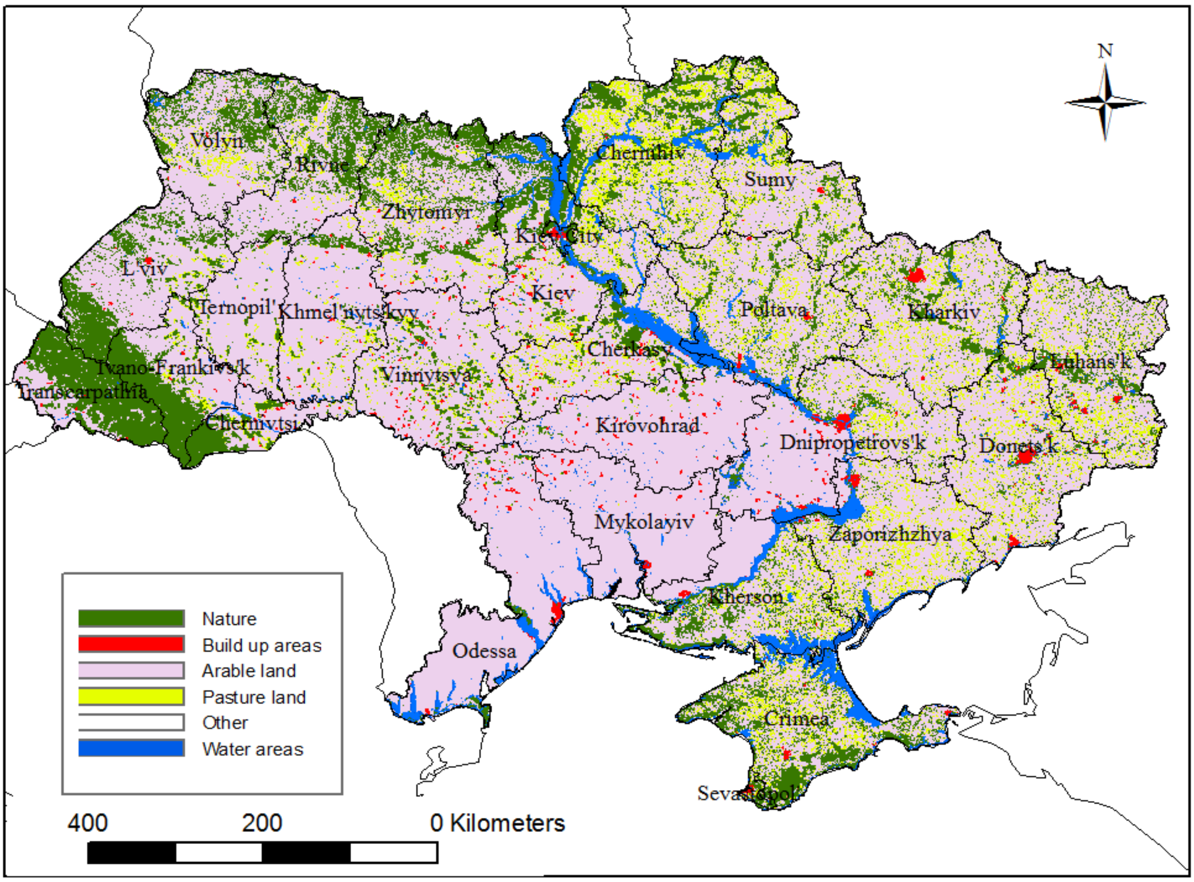


***Figure 2.4:*** *Map of Ukraine, 1:6,700,000, after a reclassification of the Corine database* (EEA 2009). *Please note that all forested areas are aggregated into the 'nature'-class*

Besides the location of the agricultural land, also the distribution of the crop types per oblast is relevant for the spatial analysis. The crop fraction per oblast are provided by the State Statistics Committee of Ukraine. A comprehensive overview of the currently cultivated crops per oblast can be found in table 1 of appendix 1.1. A summary of this table is given in figure 2.5.

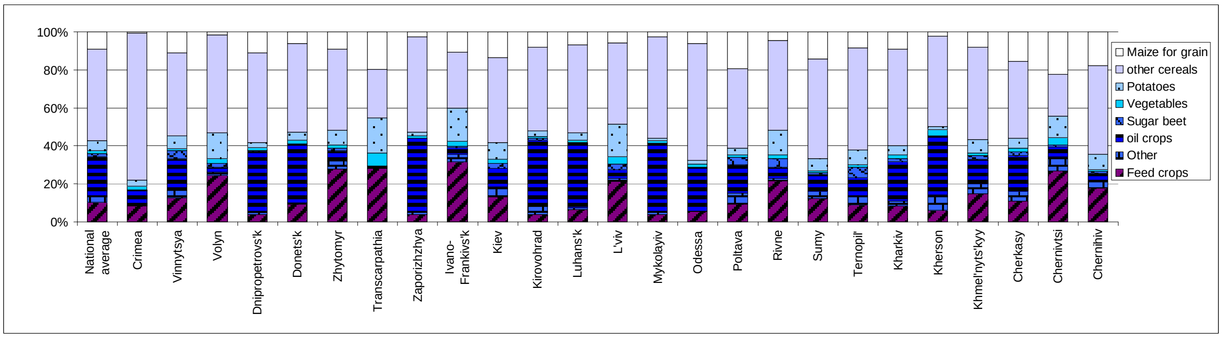


***Figure 2.5:*** *Fraction of the harvested areas of crops in Ukraine per oblast* (State Statistics Committee of Ukraine, Ostapchuk et al. 2009).
* Note: The category 'other cereals includes wheat, barley, rye, and other cereals. The category *'vegetables'* includes cabbages, tomatoes, onion, table beet, carrots, pumpkins, and other vegetables. The category oil crops includes rape and sunflowers. Perennial crops, such as vine yards, olive trees and fruit plantations are excluded from this figure.

In the calculations of this report, 'other crops' and 'feed crops' were not taken into account, as it is uncertain what crop types are included in these categories.

Land preparation
Before the arable land can be sown, the soil needs to be tilled. In Ukraine, approximately 75% of the arable land is under a full tillage regime, 25% under a reduced tillage regime, and 0.1% under a no tillage regime (Lahmar 2006). Since it is unclear where the reduced tillage areas are situated, or what crop types are under the regimes, all arable land is assigned a full tillage regime in this study. Pasture land is assumed to be tilled only once per 20-year cycle (Hilst 2009).

Seeding and harvesting dates
The seeding and harvesting timetable of agricultural land, strongly depends on the crop type. Most crops types are sown during the early spring period. Other crops, such as winter wheat, winter barley and rapeseed are sown during the end of fall. More detailed information about the seeding and harvesting dates can be found in figure 1 of appendix 1.1.

Fertilization
After the independence of 1991, the fertilizer use of Ukraine has decreased with approximately 90%, due to a lack of financial means (FAO 2005). Although the application of fertilizers has been slowly increasing again since 1999, it is still relatively low compared to Western European countries (FAO 2005). In 2005, mineral fertilizers were used on approximately 46% of the arable land (FAO 2005). The use of organic fertilizers is even lower, due to the disintegration of the large cattle farms that existed under the Soviet regime. In 2005, only 3.6% of the arable area was fertilized with organic fertilizers (FAO 2005). The spatial variations of the organic fertilizer gift are unknown. Also the composition of the manure can vary significantly, based on the animal stock and the fodder composition. As the nutrient gift from organic fertilizers could not be spatially estimated, and is only seldom used, it has been excluded from this research.

The fertilization regime of pastures is very different from the fertilization of arable land. Although pastures are rarely fertilized with mineral fertilizers, most village pastures do host a population of grazing livestock (Bogovin 2001). However, as the location and size and of the livestock herds are unknown, the manure application on pasture land could not be taken into account.

Water management
According to the ESDB, 1.2% of the Ukrainian soils are organic (EU Commission, European Soil Bureau Network 2004). The majority of the organic soils in Ukraine are peat soils, that have been developed in wetland bogs or (historic) river beds. As organic soils have a large water holding capacity, they need to be drained, before they can be cultivated (IPCC 2006a). It is therefore assumed, that all cultivated organic soils are currently under a drainage regime.

Irrigation takes place on 5.2% of the arable land (State Statistics Committee of Ukraine, Ostapchuk et al. 2009). Traditionally, irrigation is mostly applied on, potatoes, forage crops and vegetables (vegetables: 10% of the areal). To a lesser extend, grains are also irrigated (5% of the wheat areal) (NOAA ESRL physical science division 2008). It is assumed that the irrigated areas are mainly located in the Southern oblasts. However, as the exact distribution of the irrigated land is unknown, and the irrigated areal is relatively small, it is assumed that all agricultural land is rain-fed.

Current yield levels
The current crop yields per hectare are provided for each oblast by the State Statistical Committee of Ukraine (table 2, appendix 1.1). To convert the yield levels from fresh to dry weight, the moisture content of each crop was estimated on the basis of various sources, as can be seen in table 3 of appendix 1.1. The current average yield levels per crop type are depicted in figure 2.6, including the variability per oblast. It should be noted that not all crop types are cultivated in all oblasts.

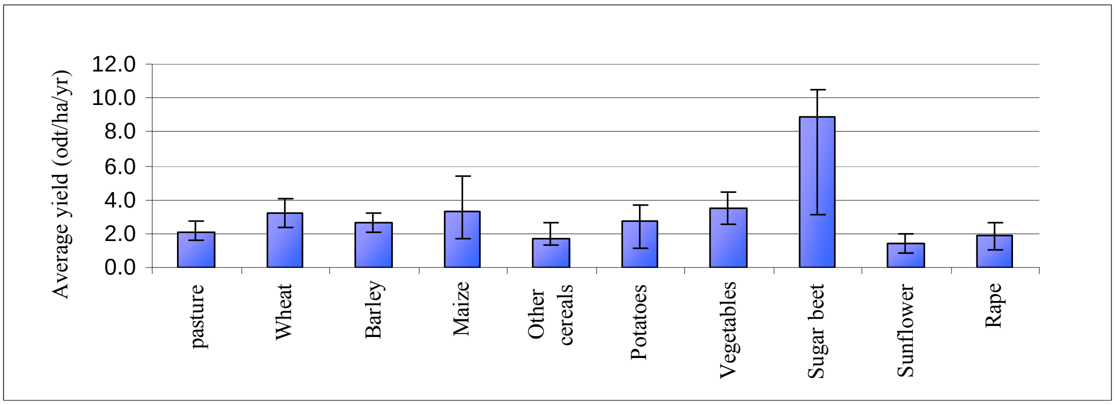


***Figure 2.6:*** *The average yield levels of crops that are cultivated on arable land (odt/ha/yr), including the variability per oblast.*

Residual biomass of harvested crops
Besides the harvested biomass, the above crops also produce residual biomass, that is not used in the food sector. An example is the cultivation of wheat, that can be divided in the production of wheat grains, and straw. While the grains are harvested, the straw is often left on the land (Gebuis 2010). It is assumed that this is also valid for the other cereals. For the other crops, such as sugar beets, vegetables, sunflowers and potatoes, it is assumed that the leaves are left on the land, as they contain a very high moisture content (Hilst 2010). Except the root-crops, also the root system is assumed to remain in the soil after harvesting.

## 2.3 Bioethanol potential

In this study, it is assumed that only the current arable and pasture land types are available for the production of bioenergy crops. However, also within these categories there are restrictions to the availability of land. Within the arable land category, it is unlikely that perennial crops such as olive yards, vine yards and other fruit plantations will be converted to bioenergy crops, because of their economical value. Furthermore, there are also restrictions to the conversion of pastures and arable land in general. In directive 2009/28/EC, the European commission states that the production of biofuels should not endanger the food security (EU Commission 2010). Consequentially, the cultivation of bioethanol crops is restricted to land that is not used for food or feed production.

In a recent study by REFUEL, an estimation is made of the land availability for bioenergy crops. As the land availability is directly related to the amount of land that is required by the food/feed sector, REFUEL models the land requirements of that sector up to 2030 (Wit, Faaij 2008). The projection of the required land is mainly dependent on the development of the land productivity. However, also the population growth, and the dietary changes are taken into account. To account for uncertainties, the land requirement is based on three scenarios, that are following three potential development paths of the agricultural system. In the' low estimate scenario', it is assumed that the current productivity trend of Ukraine will be linearly continued into the future. Because of the improved productivity, less land is required to realize the demand for food and feed. About 17.6 Mha may become available for bioethanol production. However, although a linear extrapolation of the trend could be accurate for Western Europe, several arguments underline an upward deviation of this trend in Ukraine. In recent history, the transition towards a market economy, and the collapse of the intensive large scale agricultural companies, led to a significant decrease of the yield levels (Wit, Faaij 2008). As the Ukrainian agriculture is still recovering from this decrease, an extrapolation of past trends would lead to an underestimation of the actual developments. Furthermore, the eastern European countries are increasingly influenced by the European Union. Consequentially, also the policy and the agricultural practices converge towards the practices in WEC countries. Consequently, the 'baseline scenario' assumes that Ukraine's yields will attain the $WEC_{2004}$ level in 2030. The more progressive 'high estimate scenario' assumes an even faster convergence. The drivers for this rational are improved pest management, fertilizer optimization, farmer education and breeding optimization.

Besides the freed up land in the food sector, REFUEL also accounts for agricultural land that is converted to built-up area, or used for nature conservation. The results of the scenarios for the year 2015 can be found in Table 2.1.

***Table 2.1:*** *Projections of available land (mln hectares) for biofuel crop production in Ukraine for the year 2015* (Wit, Faaij 2008) .

| Mha biofuel crops on: | Low | Baseline | High |
|---|---|---|---|
| Arable land | 15.3 | 16.8 | 20.2 |
| Pasture land | 2.3 | 2.3 | 2.3 |
| Total land | 17.6 | 19.1 | 22.5 |

From table 2.1, it can be seen that even in the low estimate scenario, almost 40% of the agricultural land may become available for the conversion to bioenergy crops. It is however unknown which lands will convert to bioenergy crops, and which lands will remain under food/feed crops. Because of this uncertainty, the results section will visualise the conversion of all agricultural grid cells.

## *2.4 Bioethanol production chains*

As stated before, this study will focus on the cultivation of wheat and switchgrass for the production of bioethanol. The ethanol production from both crops has a similar production chain, although the sub-processes within the chain may be different. The general chain is shown in figure 2.7. The following paragraphs will provide more insight in the sub-processes and assumptions within each block.

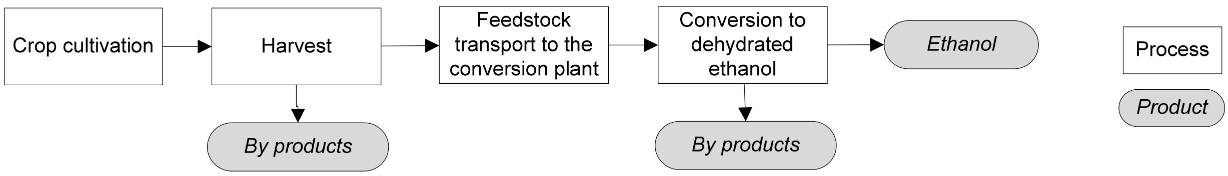


***Figure 2.7:*** *The wheat and switchgrass bioethanol chains.*

### *2.4.1 The winter wheat bioethanol chain*

Crop description

Wheat (*Triticum hybernum*) is amongst the most cultivated crops in the world ((FAO 2002). In Ukraine, about 22% of the arable land is used for wheat production (State Statistics Committee of Ukraine, Ostapchuk et al. 2009). Of this area, about 91% is winter wheat. Wheat is considered as an attractive crop type for ethanol production, as it has a relatively high energy content, which is approximately 17 GJ LVH/odt (Kaltschmitt, Hartmann 2001) {{227 Kaltschmitt, M 2001}}. Winter wheat is a first generation bioenergy crop.

Maximum attainable yield levels

After the collapse of the agricultural productivity in the 1990s, Ukraine's agriculture has been intensifying again during the last decade (Wit, Faaij 2010, State Statistics Committee of Ukraine, Ostapchuk et al. 2009, Gebuis 2010). Machines and fertilizers are used by more companies than a decade before, and average yield levels have been increasing. Based on the scenario's from REFUEL, it is assumed that the agricultural enterprises of 2015 will continue to adopt these new regimes, leading to high yield levels per hectare (Wit, Faaij 2010).

According to REFUEL suitability data, the potential wheat yield levels per hectare have been calculated for each oblast (Refuel 2008)[4]. In Refuel, the land area of each oblast was divided into six agricultural suitability classes.

[4] This data is not available on the internet, but has been produced my Refuel as input for their report on the bioethanol potential in Europe.

Furthermore, a differentiation was made between five land use classes[5]. The total potential yields per land use class were calculated by multiplying the area per suitability class with the class-specific yield level, and summing the results for all suitability classes. Then the average oblast-specific yield levels per hectare could be calculated, by multiplying the yield levels per land use class by the area of that specific class, and dividing the sum of those classes by the total agricultural area per oblast. The average yield levels per hectare vary per oblast from 4.0 to 8,7 odt/ha/yr, as can be seen in figure 2.8. The areas with the largest potential can be found in the Northwest of Ukraine. The South-eastern oblast are have the least potential. As the attainable yield describes the total harvested biomass, it can be separated into the yield of straw, and the yield of wheat grains. Approximately 0.425 kg of straw is produced per kg of harvested wheat grains (JEC-WTW 2007). Only the wheat grains will be used for the conversion to ethanol.

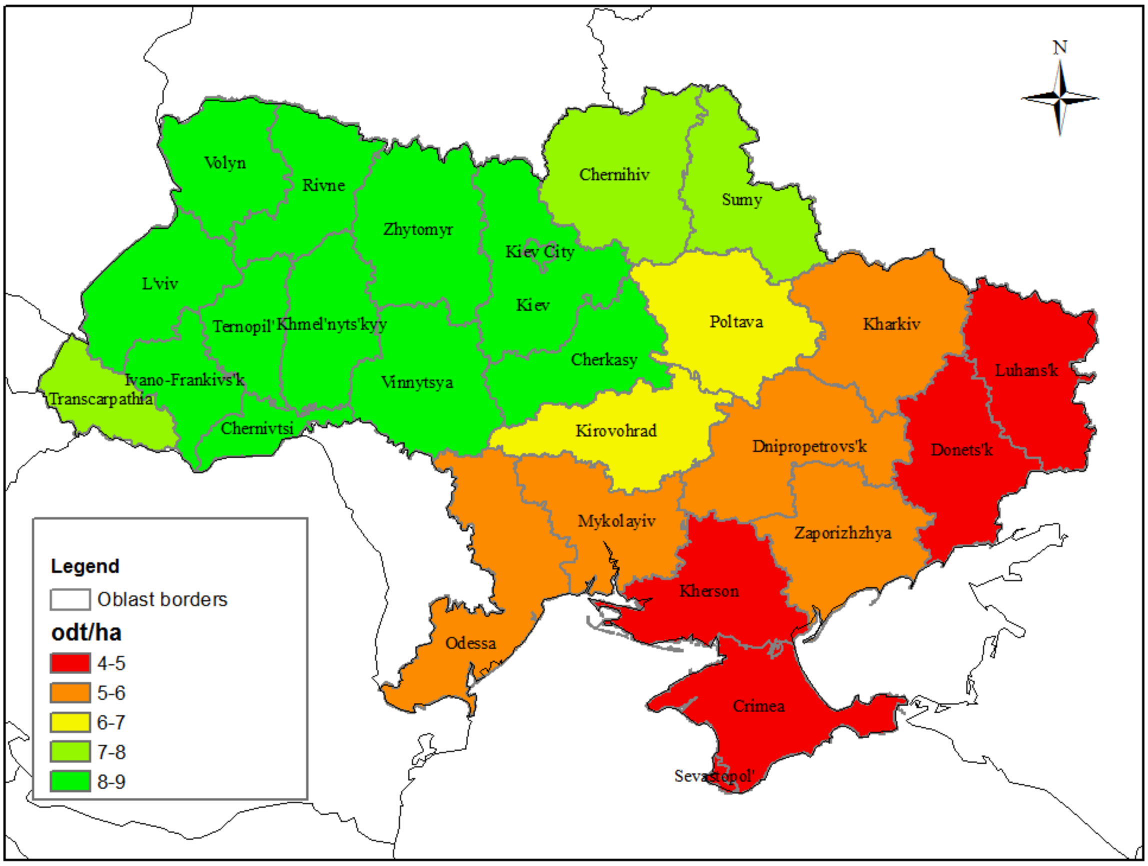


***Figure 2.8:*** *Attainable yield levels of winter wheat per hectare on agricultural land, averaged per oblast, based on refuel data* (Refuel 2008).

<u>Cultivation</u>

To achieve the maximum attainable yield levels, it is assumed that optimal fertilization levels are applied. In this study, the fertilization levels are based on estimations by the North Dakota State University (2010). For the application of nutrients, it is assumed that there is currently a minimum nutrient concentration in the soil. This assumption can be justified, as a large quantity of the Ukrainian soils is currently under-fertilized (FAO 2005). The following nutrients are applied:

[5] REFUEL suitability classes: *very suitable, suitable, moderately suitable, marginally suitable, very marginally suitable, very marginally suitable* and *not suitable*. REFUEL land use classes: *natural grassland, arable land, permanent crops, heterogeneous agriculture* and *pastures*.

***Table 2.2:*** *the fertilization of winter wheat*

| Fertilizer | Nutrient application |
|---|---|
| Nitrogen | 224 kg N/ha |
| Phosphorous | 41.5 kg P/ha |
| Potassium | 125 kg K/ha |

*Source:* (NDSU 2010a)

Besides nutrients, some crops also require the application of lime, because of soil acidity. However, as the yield levels of winter wheat are only affected on lands with a pH lower than 4.5 (Baer 2007), lime fertilization is only required on 1.8% of the Ukrainian land (FAO 2005). As the location of these areas are unknown, and only a small percentage of the land requires lime, it is assumed that wheat is not limed.

Besides fertilization, also the application of pesticides should be optimized. Optimal pesticide levels have been estimated by JRC, at an annual rate of 2.3 kg glysophate per hectare (JRC: 2008).

Just as in the current agricultural system case, a full tillage regime is assumed for wheat. Also the water management system is similar, implying that organic soils are drained, and there is no irrigation.

During the seeding process, that commonly takes place in the end of September, about 90 kg of seeds are mechanically inserted on every hectare (NDSU 2010b). In the beginning of August the wheat is ready for harvesting (Nasa earth observatory, world data centre for Geoinformatics and Sustainable Development et al. 2010). When wheat is harvested, it will yield both wheat grains and straw. Every ton of wheat grains leads to the co-production of 1 ton of straw (JRC: 2008). In the wheat chain, it is assumed that the straw will be harvested, and taken off the field. By using the straw, farmers will improve the carbon balance of the ethanol, as the cultivation related emissions can be partly allocated to the co-product. All input data that is applicable to the cultivation of wheat, can be found in tables 12-14, appendix 1.3.

Transport

Subsequent to the harvesting, the wheat grains are transported to the conversion plant. By road, the average travel distance will be approximately 35 km (see also *chapter 3: methodology*) (Scientific Engineering Bureau Biomass 2010); (Russian Biofuels association, Reuters limited 2007). Following the methodology of JEC-WTW, the transport will be facilitated by 40t trucks, that return empty. Besides the emissions from the transfer, there are also emissions from the loading/unloading of the feedstock (Smeets, Lewandowski et al. 2009). It is assumed that 1% of the feedstock is lost in transport (Kaltschmitt, Reinhardt 1997). All transport related input data and emission factors can be found in table 15, appendix 1.3.

Conversion to ethanol

The conversion process starts with hydrolysis, to release the fermentable sugars (Pandey 2009). The hydrolysis can be facilitated by enzymes, or acid-treatment. In this study, enzymatic hydrolysis is applied, following the method of Punter et.al. (Punter, Rickeard et al. 2004). The next step is the fermentation, that is facilitated by yeasts. Besides ethanol, dry distillers grains with solubles (DDGS) are also produced. As DDGS has a high protein and fiber content, it is often used as an animal feed (University of Minnesota 2007). All in- and outputs of the conversion process are given in table 2.3.

***Table 2.3****: In- and outputs of the wheat to ethanol conversion process.*

| | I/O | Amount | Unit |
|---|---|---|---|
| Wheat grains | Input*[1,2] | 1.864 | $MJ/MJ_{ethanol}$ |
| Electricity for steam | Input*[2] | 0.007 | $MJ/MJ_{ethanol}$ |
| Natural gas for steam | Input*[2] | 0.404 | $MJ/MJ_{ethanol}$ |
| Electricity other | Input*[2] | 0.054 | $MJ/MJ_{ethanol}$ |
| DDGS | Output*[3] | 0.688 | $MJ/MJ_{ethanol}$ |
| Ethanol | Output | 1 | MJ |

*Source:*
*[1] (Kaltschmitt, Hartmann 2001)
*[2](Punter, Rickeard et al. 2004).
*[3]The amount of DDGS was derived by multiplying it's energy content: 16 MJ LHV/ kg fw (Kaltschmitt, Reinhardt 1997), with the produced amount: 0.043 kg $fw/MJ_{ethanol}$ (Punter, Rickeard et al. 2004).

### *2.4.2 The switchgrass bioethanol chain*

Crop description

Switchgrass (*Panicum Virgatum*) is the second energy crop that will be taken into account. Although switchgrass is native to plains of North-America, it has proven to grow also well in Europe (Brickell, Zuk 1997). Switchgrass is a perennial pant, with an assumed cycle of 20 years. With 17.8 GJ LHV/odt, it’s energy content is slightly higher than that of wheat (ECN ). An advantage of Switchgrass is that it can be cultivated on degraded lands (McLaughlin, Kszos 2005, Applewood seed company 2009, Miller, Brewer et al. 2007-2009). Furthermore, Switchgrass is suitable for Ukraine as it can be grown in a large range of temperatures and precipitation (McLaughlin, Kszos 2005, Applewood seed company 2009, Miller, Brewer et al. 2007-2009). Switchgrass is a second generation bioenergy crop.

Attainable yield levels

Following the same methodology as with the winter wheat, the potential switchgrass yield per hectare has been estimated for each oblast on the bases of Refuel suitability data (Refuel 2008). The average oblast-specific yields vary from 8.9 to 19.2 odt/ha/yr, as can be seen in figure 2.9. The most productive areas can be found in central Ukraine.

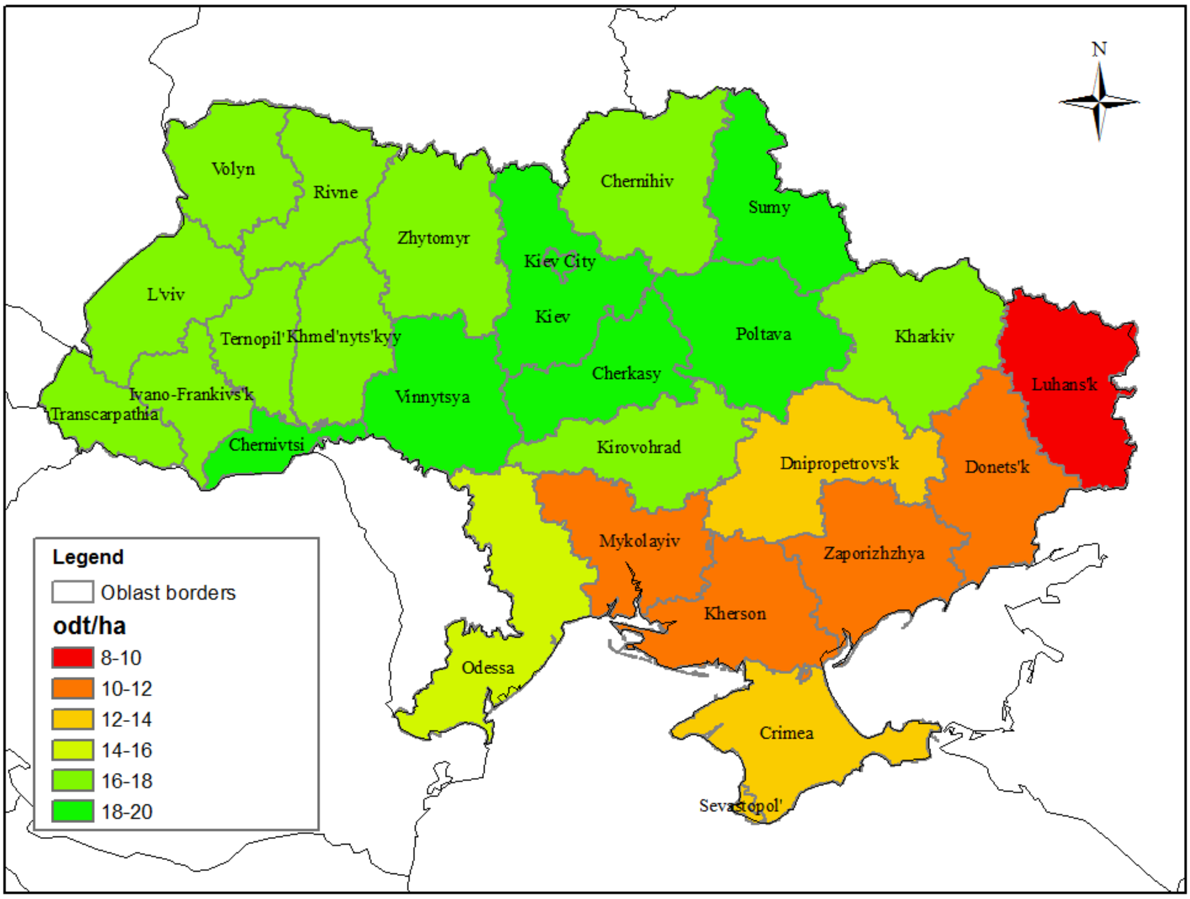


***Figure 2.9:*** *Attainable yield levels of switchgrass per hectare on agricultural land, averaged per oblast, based on refuel data* (Refuel 2008).

Cultivation

The fertilization of switchgrass has been based on the optimal application level. However, as information on the optimal fertilization is unavailable, a balanced fertilization regime has been assumed in stead, to describe the optimal rate. In the balanced regime, the annual fertilization rate is equal to the loss of nutrients from the soil. According to the methodology of Alterra (Alterra 2010), a 100% nutrient uptake efficiency was assumed, because of the switchgrass’s large root system, that reduces most losses (Lesschen 2010). Using the nutrient content, the annual fertilization rate was estimated at 7.5 kg N/ odt yield., 0.9 kg P/ odt yield., and 2.5 kg K/ odt yield (Fixen

2010, Elbersen, Christian et al. ). Besides the fertilizers that are applied during the production phase, also the establishment requires fertilizers. As switchgrass is currently not cultivated in Ukraine, the establishment regime has been estimated with US data. During the establishment, the land is fertilized with 80 kg ammonium nitrate (28 kg N/ha), 40 kg $P_2O_5$ (17.5 kg P/ha) and 60 kg $K_2O$ (49.8 kg K/ha) (Bullard, Metcalfe 2001). Switchgrass does not require additional liming if the soil acidity is larger than pH 5 (Bates, Keyser et al. 2008).

Optimal pesticide levels are estimated at an annual application of 2.5 kg glyphosphate per hectare (Bullard, Metcalfe 2001). In the establishment phase, extra herbicides are required. It is assumed that 2 kg Advance/ha, 7.7kg MCPA/ha, and 2kg IPU/ha are applied (Bullard, Metcalfe 2001).

As switchgrass has a 20 year cycle, land preparation will only take place in the first year. For this year, a full tillage regime is assumed. The other years are assigned a no-tillage regime. Organic soils are assumed to be drained, and there is no irrigation. As switchgrass seeds will germinate at soil temperatures of 10 °C (Blade energy crops 2009), seeding in Ukraine will be likely around the end of April. About 10 kg of seeds will be mechanically inserted on every hectare (Bullard, Metcalfe 2001). Harvesting takes place in November (Garland 2005), during the first days of winter frost. Following the production methods of Bullard and Metcalfe, the switchgrass will be baled after the mowing, and loaded on a truck for the transport to the conversion plant. The harvesting does not generate co-products. The input data that is applicable to the cultivation of switchgrass, can be found in tables 12-14, appendix 1.3.

Transport

Subsequent to the harvesting process, the bailed switchgrass is transported to the conversion plant. As data on switchgrass transportation was unavailable, the data for this process has been based on the transportation of straw, as described by JEC-WTW in 2008. By road, the travel distance is on average 20 km, and will be facilitated by 40t trucks, that return empty. Emissions from the loading/unloading process are included. Kaltschmitt estimates that there are no switchgrass losses during transport. All transport related data can be found in table 15, appendix 1.3.

Conversion

At the conversion plant, the switchgrass will be converted to ethanol. As switchgrass is a ligno-cellulosic plant, a hydrolysis step is required to ferment the crops cellulose and hemi-cellulose fractions. The hydrolysis can be done by enzymes, acid catalysed steam explosion, or dilute acid pre-treatment. Following JEC-WTW, the hydrolysis will in this study be facilitated by dilute acid pre-treatment (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). Concentrated sulphuric acid dissolves and decomposes the cellulose, leaving only small sugars (Pandey 2009). After the hydrolysis, the sulphuric acid has to be neutralized, which is done by the addition of calciumoxide. Once the neutralisation is complete, the yeasts are added, to start the fermentation process. As data for switchgrass was unavailable, the data for straw fermentation was used in stead, following the methodology of Hoefnagels et.al.

The lignin fraction typically makes up 15-20% of the switchgrass' biomass (McLaughlin, Somson et al. 1996). Unlike the (hemi)cellulose, the fraction cannot be converted to ethanol (McLaughlin, Somson et al. 1996). Following the methodology of (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008), it will be combusted for the production of steam and electricity that is required for the conversion. All remaining electricity is considered a by-product. For every GJ of switchgrass-ethanol, 0.052 GJ of electricity is produced (Kaltschmitt, Hartmann 2001). All in- and outputs of the conversion process are given in table 2.4.

***Table 2.4****: In- and outputs of the switchgrass to ethanol conversion process.*

| Conversion process*[1] | I/O | Amount | Unit |
|---|---|---|---|
| Switchgrass | Input*[2,3] | 2.377 | $MJ/MJ_{ethanol}$ |
| CaO | Input*[2,3] | 0.0024 | $kg/MJ_{ethanol}$ |
| $H_2SO_4$ | Input*[2,3] | 0.0041 | $kg/MJ_{ethanol}$ |
| Electricity (lignin) | Output*[2] | 0.052 | $MJ_e/MJ_{ethanol}$ |
| Ethanol | Output | 1 | MJ |

*Source:*
*1 Based on the conversion of straw, following the methodology from (Hoefnagels, Smeets et al. 2008).
*2(Kaltschmitt, Hartmann 2001)
*3(CONCAWE, European Council for Automotive R&D (EUCAR) et al. 2006)

## 2.5 Overview

In the following table, a short summary is provided that states the assumptions and characteristics of the bioethanol production chain.

***Table 2.5:*** *Characteristics of the current situation and the wheat and switchgrass bioethanol chains.*

| Item | Current | Wheat chain | Switchgrass chain |
|---|---|---|---|
| Reference land[1] | Based on current land cover: 7.9 mln ha pasture land, 33.9 mln ha arable land, of which. 27 mln hectares is currently cultivated. Both grassland and arable land are treated as pure categories. | All arable and pasture land is converted to wheat | All arable and pasture land is converted to switchgrass. |
| Crop types[1] | Current crop mixture varies per oblast. More information in appendix 1.1. | All annual crops are converted to wheat. Perennial crops will not be converted. | All annual crops are converted to switchgrass. Perennial crops will not be converted. |
| Available land for conversion | N/A. | Pasture land and arable land, holding annual crops. | Pasture land and arable land, holding annual crops. |
| Water management[3] | - Drainage on organic soils, if cultivated<br>- No irrigation | - Drainage of organic soils, if cultivated<br>- No irrigation | - Drainage of organic soils, if cultivated<br>- No irrigation |
| Soil management[3] | - Arable land: 100% full tillage[6]<br>- Pastures: Once per cycle full tillage. Other years no tillage. | 100% full tillage | Once per cycle: full tillage. Other years: no tillage. |
| Cycle[4] | Arable land: 1 year cycle<br>Pasture land: 20 year cycle | Wheat is an annual crop: 1 year cycle | Switchgrass is a perennial crop: 20 year cycle. |
| Fertilizer use | Arable land: Current mineral fertilization regime (medium input), varying per crop type. Without manure.<br>Pasture land: no fertilization.[1,5] | Optimal fertilization, without manure[6] | Establishment phase: USA level fertilization.<br>Production phase: balanced fertilization, without manure.[7] |
| Pesticide use | Current Ukrainian pesticide application. | European level pesticide use.[8] | European level pesticide use, which varies, depending on the time in the cycle.[7] |
| Diesel use for agri. machinery | N/A | 162 l /ha/yr | Depending on the year in the cycle. On average 60 l/ha/yr. |
| Yields | Current average yields on arable land, depending on the crop mixture and climate and soil conditions: 5.5-7 odt/ha[1] | Depends on the location: 4-8,5 odt/ha, excluding co-products.[11] | Depends on the location: 9-19 odt/ha[11] |
| Co-products of cultivation | Rest products will not be removed from the field. | Straw: 4-9 odt/ha. Will be removed from the field.[12] | None |
| Transport to conversion plant | Not applicable. | Transported by 40t trucks. Including empty return trip. | Transported by 40t trucks. Including empty return trip. |
| Co-product of the conversion | Not applicable. | Dried Distillers Grain with Solubles (DDGS) | Lignin fraction |

*1 (Ostapchuk, et.al. 2009)*
*2 (Wit, Faaij 2010)*
*3 (Lahmar 2006)*
*4 (Hilst 2010)*
*5 (FAO 2005)*
*6 (Davis, Westfall 2009)*
*7 (Bullard, Metcalfe 2001)*
*8 (JRC: 2008)*
*9 (Schreuder, Dijk et al. 2008);(Hilst, Dornburg et al. 2009)*
*11(Refuel )(PBL 2009)*
*12 (Bolinder, Angers et al. 1997)*

[6] According to (Lahmar 2006) 24% of the arable area of Ukraine is under a reduced tillage regime.

# 3. Methodology

In this study, four environmental criteria will be assessed. The criteria have been selected, based on guidelines by EU directive 2009/28/EC (*article 17*: Sustainability criteria for biofuels and bioliquids) and on the criteria that were proposed by the project group Sustainable production of biomass of the Taskforce energy transition (Cramer Criteria, 2007). One of the criteria is the Green house gas balance, which will be discussed in paragraph 3.1. In accordance to EU regulations, the GHG emission saving from the use of biofuels shall in 2015 be at least 35 % (EU 2008). To this end, the emissions from the land use change and the ethanol life cycle will be assessed. Another criteria is the biodiversity (§3.2). Directive 2009/28/EC prohibits the production of biofuels in areas with a high biodiversity. The mean species abundance will be used as an indicator to assess the biodiversity. Another criterion assesses the impact of biofuel production on the soil (§3.3). Biofuels should not lead to the degradation of the soil. Therefore, the soil organic matter content, water erosion and wind erosion have been used as indicators of the soil criterion. Another criterion assesses changes in the water system (§3.4). Both the water quality and quantity have been taken into account. The methodologies in this study are based on the methodologies from van der Hilst et.al. 2010. Additional information on the comparison of different methods and indicators can be found in her research (Hilst, Dornburg et al. 2010). In this chapter the methodology of the assessments will be described. The input data can be found in appendix 1.

## *3.1 Green house gas balance*

One of the criteria for the production of bioethanol, is the emission reduction of 35% as compared to fossil ethanol. To this end, the GHG emissions related to land use changes, are discussed in paragraph 3.1.1. The paragraph includes the changes in the above and below ground biomass, the changes in the soil organic carbon and the change of the carbon flux (IPCC 2006a). Another part of the GHG balance is the life cycle, which includes the emissions from the cultivation, transport, and conversion (paragraph 3.1.2). Following the IPCC methodology, the GHG-gasses $CO_2$, $CH_4$ and $N_2O$ have been taken into account (IPCC 2006a).

### *3.1.1 Land use change emissions*

Land use changes (LUC) are one of the main contributors to the global green house gas emissions (WRI 2008). Depending on the amount of biomass before and after the conversion, and on the change of the soil organic carbon, a land use change can lead to an emission or capture of green house gasses. To describe the effects of land use changes, the following equation has been applied:

$$\Delta E_{LUC} = \frac{\left(\Delta C_{biomass} + \Delta C_{so\,c} + \Delta C_{N_2O}\right) * F_1}{T}$$

| | |
|---|---|
| $E_{LUC}$ | = total land use change emissions caused by the change from current crops to respectively wheat and switchgrass (g. $CO_2$-eq ha $yr^{-1}$) |
| $\Delta C_{biomass}$ | = Change of the carbon, stored in the above and below ground biomass [$gCO_2$-eq $ha^{-1}$] |
| $\Delta C_{soc}$ | = Change of the soil organic carbon [$gCO_2$-eq $ha^{-1}$] |
| $\Delta C_{N2O}$ | = The change in the land use change related $N_2O$ emissions [$gCO_2$-eq $ha^{-1}$] |
| $F_1$ | = 1- the fraction that is allocated to the co-products |
| T | = Required time to reach a new equilibrium (in this report 20 years) [yr] |

Based on: (IPCC 2006a)*

* In line with the tier 1 approach of the IPCC, the dead wood and litter category has been excluded from the assessment (IPCC page 5.13).

Depending on the climate and soil characteristics, it can takes several decades before a new land use equilibrium is reached. Following the IPCC, a period of on average 20 years is assumed to reach a new equilibrium (IPCC 2006a). The GHG emissions of the LUC are evenly spread over this timeframe.

Land use changes can be direct or indirect. Direct changes involve the changes in the land cover to accommodate the biofuel feedstock production. Indirect changes refer to the changes in land use that take place elsewhere as a consequence of the bioenergy project (Berndes, Bird et al. 2010). In this study only direct land use changes are included, as it is assumed that only surplus land can be used for bioenergy production.

The following sub-paragraphs will elaborate on the calculation of the various parameters in the LUC-equation. The sub-equations that are used during the calculations were directly taken from the IPCC 2006, and can be reviewed in appendix 1.2.

Biomass change

To estimate the change in the carbon that is contained in the above and below ground biomass of plants, the currently cultivated biomass is compared with the biomass of wheat and switchgrass cultivations.

To calculate the current biomass, a differentiation was made between arable land and pasture land, depending on the land cover at the location of the land use change. To calculate the current biomass on arable land, oblast specific yield levels per hectare of nine different crop groups[7] have been taken from the State Statistics Committee of Ukraine (table 2, appendix 1.1). By using the moisture content of each crop type (table 3, appendix 1.1), the yields were converted to dry weight. Then, to include the total above and below ground biomass, the yields were multiplied with the corresponding harvest ratio's[8] per crop (table 4, appendix 1.1). To determine the average biomass per hectare for each oblast, the oblast specific biomass of each crop type per hectare was multiplied with the corresponding crop fractions per oblast, and summed for all crops. Finally, the total biomass per hectare was multiplied with it's carbon fraction, to determine the total carbon per hectare. The carbon fraction was determined on the basis of carbon factors from the IPCC (IPCC 2006a). Annual crops were assigned a carbon factor of 0.47 ton C/odt.

To estimate the above and below ground biomass of pasture land, data was provided by the IPCC (IPCC 2006b). According to the tier 1 methodology, the amount of biomass is directly dependant on the climate zone.

The IPCC climate zones were determined according to the mean annual precipitation, temperature, potential evapotranspiration, and the number of frost days. The classification scheme can be found in figure 1 of appendix 2 (IPCC 2006a). The variables that were required to determine the climate zones, were provided by 45 Ukrainian weather stations (NOAA ESRL physical science division 2008). Also 4 non-Ukrainian weather stations were used, to provide accurate data on border areas. The climate data per station can be found in table 1-ab of appendix 2. To estimate the temperature and precipitation in the areas between the stations, the data has been interpolated with the Spline method. This method estimates the values by fitting a minimum curvature surface to the data (Priyakant, Rao et al. ). Because of the minimum curvation, the Spline method is specifically suitable to interpolate climate data from weather stations (Childs, ESRI education services. 2004). The Spline interpolation can be done by two methodologies, namely the *regularized* and the *tension* method. In order to prevent values outside the sample data range, the tension method has been applied.

The potential evapotranspiration was not measured by the weather stations. Therefore, the annual water balance (paragraph 3.5) was used as a substitute. According to the IPCC, a positive water balance indicates a moist climate, and a negative balance indicates a dry climate.

Although the original climate zones are not hindered by administrative borders, in this study they are applied per oblast. This has been done to prevent climate zones from creating artificial borders in the results. The oblasts borders are regarded as the most appropriate perimeter, as many other parameters are also defined per oblast.

According to the climate zone, the pasture land was assigned an indication of the total biomass per hectare (table 5, appendix 1.1). Finally, the total biomass per hectare was multiplied with it's carbon fraction, to determine the total carbon per hectare. Grassland was assigned a carbon factor of 0.5 ton C/odt (IPCC 2006a).

To estimate the total biomass of the wheat bioenergy chain, the potential oblast-specific wheat yield per ha was calculated from the Refuel model, according to the method that has been described in paragraph 2.4.1 (attainable yield levels).The below ground biomass of wheat was then calculated according to the harvest index estimated by Bolinder (Bolinder, Angers et al. 1997). Finally, the total biomass per hectare was multiplied with it's carbon fraction, to determine the total carbon per hectare. Wheat was assigned a carbon factor of 0.47 ton C/odt (IPCC 2006a).

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[7] Wheat, barley, grain maize, other cereals, potatoes, vegetables, sugar beat, sunflower and rape. The category vegetables comprises: 21% cabbage, 19% tomatoes, 13% onions, 9% table beets, 9% cucumbers, 9% carrots and 15% others.

[8] Harvest ratio: Defined as the ratio between annual yields and total above and below ground biomass.

To estimate the total biomass of the switchgrass bioenergy chain, the potential oblast-specific switchgrass yield per hectare was also calculated from the Refuel model. The yield is equal to the above ground biomass. To estimate the below ground biomass, IPCC standards have been followed, that prescribe a root-to-shoot ratio of 3.0 (IPCC 2006a). Finally, the total biomass per hectare was multiplied with it's carbon fraction, to determine the total carbon per hectare. Switchgrass was assigned a carbon factor of 0.5 ton C/odt (IPCC 2006a).

Soil organic carbon change on mineral soils

The following paragraph describes the calculation for the changes in the soil organic carbon (SOC). For the assessment of the SOC, a differentiation was made between organic and mineral soils.

In mineral soils, the SOC is dependant on the reference SOC, the land use type, the tillage regime and the fertilization regime. The IPCC provides factors for all parameters, which are multiplied to provide the SOC.

The reference SOC is determined by the climate zone and the soil type. Following the IPCC classification, four climate zones were distinguished. To include the soil characteristics, the spatial soil database ESDB has been consulted (EU Commission, European Soil Bureau Network 2004). In order to use the data from this database, the soil map had to be reclassified according to IPCC guidelines. The reclassification has been done on a basis of a WRB-to-IPCC reclassification scheme, that can be found in figure 2 of appendix 1.5. In the scheme, the 42 soil types of the original WRB classification are reclassified into the classes '*high activity soil*', '*low activity soil*', '*wetlands*', '*spodic soils*', '*organic soils*' and '*volcanic soils*'. Each climate-soil combination was assigned a reference SOC, according to IPCC methodology. The reference SOCs can be found in table 7 of appendix 1.2.

Another factor that was taken into account, is the land use. For both the current arable land and the land in the wheat bioethanol chain, a land use factor has been used that is applicable to annual, long-term cultivated crops (IPCC 2006a). For the current pasture land, a factor has been used that is applicable to permanent grassland. Switchgrass shows similarities to both grassland and cropland. The first year in the cycle is similar to annual crops, because of the tillage, seeding, fertilization and harvesting regimes. Other years in the cycle are similar to permanent grassland, because of the no-tillage and low-fertilization regimes. Therefore, the first year of the cycle is assigned a land use factor that is applicable to annual crops, and other 19 years are assigned a factor that is applicable to permanent grassland. The total is averaged to provide an annual factor.

The other parameters, which describe the tillage and fertilization regimes, where also assigned IPCC factors. The factors correspond with the tillage and fertilization regimes that are already described in the case study. An overview of all factors can be found in table 8 of appendix 1.2.

The driver of the SOC change in organic soils is the change of the carbon flux. Carbon fluxes are influenced by the climate and the land use type. Based on these parameters, the IPCC has estimated various carbon fluxes, that have been applied in this study (IPCC 2006a). Because of the similarities in the management regimes, the carbon flux of wheat is assumed to be the same as the carbon flux of current arable land. In the first cycle year, switchgrass shows a close resemblance to annual crops. In the other years, it shows a resemblance to pasture land. Hence, the carbon flux of switchgrass is assigned $^{1}/_{20}$ of the carbon flux of arable land, and $^{19}/_{20}$ of the flux that is applicable to grassland. By subtracting the carbon flux of the current arable- and pasture land, with the carbon flux of wheat and switchgrass, the organic SOC change can be determined. The carbon fluxes can be found in table 9, appendix 1.2.

LUC related $N_2O$

Besides the $CO_2$ emissions, land use changes can also lead to the emission or mitigation of nitrogenous oxide. Following the IPCC methodology (IPCC 2006a), land use changes lead to two sources of $N_2O$ emissions. The first source is the loss of nitrogen that is mineralised in the soil. The direct emissions from this source were determined by combining the annual loss of soil organic matter (SOM) with the C:N ratio. Besides the direct emission, there is also an indirect emission, that occurs during the leaching/runoff of mineralised nitrogen. The indirect emission could be calculated with a leaching factor from the IPCC (IPCC 2006a).

The second $N_2O$ source, is the emission that occurs on drained organic soils, through the denitrification of organic matter. As the denitrification rate is dependant on the temperature, climate specific denitrification rates where proposed by the IPCC. To calculate the emissions, the rates were multiplied with corresponding emission factors (IPCC 2006a). By subtracting the $N_2O$ emissions of the current agricultural system from the emissions of the bioenergy chains, the change could be calculated. As the climate zone does not change, and the denitrification rate is not influenced by other parameters, the net emission change is zero. Consequentially, only the change in SOM determines the LUC related $N_2O$ emissions. The $N_2O$ is converted to $CO_2$-equivalent according to the IPCC conversion standards, that indicate a $CO_2$-eq of 298g/g $N_2O$ (IPCC 2006a). The input data for the calculations in this paragraph can be found in tables 10 - 11 of appendix 1.2.

Allocation
As the production of bioenergy crops also leads to the production of co-products, only a part of the LUC emissions was allocated to the ethanol. In line with EU directive 2009/28/EC, GHG emissions have been allocated on a basis of the energy content.

As 1 GJ of wheat grains also leads to the production of 0.354 GJ of straw, only 73.9% of the LUC emissions is allocated to the wheat grains (JRC: 2008). Further onwards in the chain, the conversion process leads to the production of 0.688 GJ of DDGS animal feed, per GJ of ethanol (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). Consequentially, 44% of the LUC emissions will be allocated to ethanol.

Switchgrass does not produce co-products during the production phase. However, during the conversion process, electricity is produced from the excess lignin fraction. Every GJ of ethanol leads to the production of approximately 0.052 GJ of lignin electricity (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). Consequentially 95.1% of the LUC emissions will be allocated to the ethanol.

### *3.1.2 Life cycle emissions*

Next to the effects of the land use change, also the processes of the bio-ethanol life cycle can lead to GHG emissions. The life cycle emissions were calculated according to the formula below, that is based on EU directive 2009/28/EC (EU Commission 2010). The main input data for the calculations can be found in tables 12-17 of appendix 1.3.

$$E_{TOT} = E_{LUC} + E_{LCE}$$
$$E_{LCE} = e_{cult} * F_1 + (e_{td} + e_{con}) * F_2$$

$E_{TOT}$ = Total emissions of the bioethanol production (g. $CO_2$-eq $MJ^{-1}$)
$E_{LUC}$ = Total annual emissions, caused by land use changes (g. $CO_2$-eq $MJ^{-1}$)
$E_{LCE}$ = Total emissions from the cultivation, conversion, and transport of wheat or switchgrass(g. $CO_2$-eq $MJ^{-1}$)
$e_{cult}$ = Emissions from the cultivation of wheat or switchgrass (g. $CO_2$-eq $MJ^{-1}$)
$e_{td}$ = Emissions from the transport of feedstock to the conversion plant (g. $CO_2$-eq $MJ^{-1}$)
$e_{con}$ = Emissions from the conversion of wheat or switchgrass (g. $CO_2$-eq $MJ^{-1}$)
$F_1$ = 1- the fraction that is allocated to the co-products of cultivation and conversion [-]
$F_2$ = 1- the fraction that is allocated to the co-products of conversion [-]

Most of the emissions in the life cycle analysis are initially calculated in g $CO_2$-eq per hectare. Therefore, they need to be divided by the energy density ($MJ_{ethanol}$/ha), to determine the emissions per MJ. To determine the energy density, the energy content of wheat and switchgrass was multiplied with the potential yield levels. The energy content of wheat has been taken from Kaltschmitt et.al., as 9.12 $GJ_{ethanol}$/odt grains (Kaltschmitt, Hartmann 2001). On the basis of JRC-WTW, the potential grain yield levels are taken as 70% of the total yield level, to account for the straw yields. The energy content of switchgrass has been calculated as 9.29 $GJ_{ethanol}$/odt (2.63 kg fw. Switchgrass per ethanol; (University of California 2007). There are no co-products from harvesting.

In the original methodology from directive 2009/28/EC, also carbon capture and storage has been taken into account. However, as Ukraine does currently not use this technology (Scientific Engineering Bureau Biomass 2010), carbon capture and storage has been excluded.

Emissions from cultivation
The emissions from the cultivation can be separated in the emissions from the use of seeds, fertilizers, pesticides and the use of diesel. Furthermore, also crop residues can lead to emissions. A spatial analysis is unnecessary, as the emissions are assumed to be homogeneous for Ukraine. The input data and the emission factors can be found in tables 12-14 of appendix 1.3.

The emissions from seeds occur only during the production. The emission factor for wheat seed is taken from West et.al. (West, Marland 2002) and the factor for switchgrass from Bullard and Metcalfe (Bullard, Metcalfe 2001). In the case of switchgrass, the seeding emissions are divided by the crops life cycle.

Also pesticides cause emissions during their production. Pesticides are added every year. The emission factors have been taken from Wood and Kaltschmitt (Kaltschmitt, Reinhardt 1997, Wood, Cowie 2004).

Mineral fertilizers also generate emissions during their production. The emission factors for each nutrient are given by Smeets et.al. (Smeets, Lewandowski et al. 2009). Besides the greenhouse gasses that are emitted during the production, the use of fertilizers also leads to the emission of nitrous oxides. The direct $N_2O$ emissions are calculated by multiplying the applied nitrogen per hectare with an IPCC emission factor (IPCC 2006a). Besides the direct $N_2O$ emissions, there are also indirect emissions caused by the leaching/runoff of mineral N, and the deposition of volatilised N from managed soils. The emissions from leaching/runoff are calculated by multiplying the applied nitrogen with an IPCC-leaching factor and an IPCC-emission factor (IPCC 2006a). The emissions from N-deposition can be calculated by multiplying the applied nitrogen with a volatilisation fraction, and an emission factor that estimates the emissions from depositioned nitrogen. Both factors are given by the IPCC (IPCC 2006a), and can be reviewed in tables 10-11 of appendix 1.2.

Also the use of machinery leads to an emission of $CO_2$, related to the use of diesel. Diesel is used during field preparation, seeding, the application of additives, harvesting and yield storage. The diesel use during the cultivation of wheat, was estimated by JRC (JRC: 2008). The diesel use of switchgrass cultivation was estimated by Bullard (Bullard, Metcalfe 2001). The emissions from the use of diesel can be found in table 14 of appendix 1.3.

Finally, another emission is caused by the nitrogen fraction of the residues that remain after the harvest. As it is assumed that al above ground biomass is removed after harvesting, only the below ground biomass contributes to the residue $N_2O$. Below ground residues only occur if the crop area is renewed and tilled. As wheat is an annual crop, it is renewed every year. Switchgrass is a perennial crop, which is only renewed once in 20 years. The $N_2O$ emissions from residues are calculated by combining the average yield level with a crop specific residue ratio from the IPCC, and the residues N-content (IPCC 2006a). The emissions are divided by the crops life cycle, to account for the land renewal. Besides the direct $N_2O$ emissions, residues also produce indirect emissions, through leaching and runoff. The indirect $N_2O$ is calculated by multiplying the nitrogen of the residues with an IPCC-leaching factor and an IPCC-emission factor (IPCC 2006a). The applied data can be found in tables 10-11 of appendix 1.2.

Emissions from transport

Subsequent to the harvesting, the wheat grains are transported to the conversion plant. It is assumed that Ukraine will install large scale conversion plants, that can produce approximately 350 mln litres of ethanol per year[9].

In the wheat chain, every hectare produces on average 4.7 odt grains/ha/yr (Refuel 2008), corresponding with a production of 2,045 litres of ethanol (JEC-WTW 2007). Therefore, one plant can serve a maximum of 170,000 hectares. Following the baseline scenario of de Wit. Et.al., about 19.6 mln hectares may convert to wheat. Therefore, 115 conversion plants are required to convert the feedstock. Assuming a circular catchment area, the average distance from a farm to each plant will be 29 km in a strait line. By road, it is assumed the route will be approximately 20% longer, leading to a travel distance of on average 35 km.

In the switchgrass chain, every litre of ethanol requires on average 2.6 kg of feedstock (University of California 2007). With a production of on average 15,4 odt/ha/yr, every conversion plant can serve a maximum of 59,100 hectares. Therefore 332 plants are required to convert the feedstock. The average transport distance to each plant will be 17 km in a strait line, and 20 km by road.

To calculate the GHG emissions, the distances are combined with emission factors (Kaltschmitt, Reinhardt 1997). Based on WTW 2008, it is assumed that the trucks return empty (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). Additional emission occur during the loading/unloading of the feedstock (Smeets, Lewandowski et al. 2009). All transport related input data and emission factors can be found in table 15, appendix 1.3.

Emissions from conversion

The conversion process of wheat to ethanol requires steam, that is produced from natural gas and electricity. The GHG emission that is related to the use of electricity, is mainly depending on the Ukrainian electricity mixture in

[9] Comparable to 90% of the capacity of the largest ethanol plant in Europe, that has been running in Germany since 2005 (Crop energies AG 2010). In the US, there are several comparable plants that are used for bioethanol production (RFA, Nebraska Energy Office, Lincoln, NE. 2010).

2015. In the GEMIS model[10], the mixture is estimated, including the corresponding emission factors (Oeko institut 2010). For the natural gas, the present emission factor of Russian natural gas has been used (Biograce, Harmonised calculations of Biofuel Green house gas emissions in Europe 2010). Total emissions were calculated by multiplying the emission factors with the application rates of electricity and natural gas. The emission factors, and emissions are included in table 16, appendix 1.3.

The conversion of switchgrass to ethanol requires steam, sulphuric acid and calcium oxide. The heat that is required for the steam production is attained by partly combusting the lignin fraction. The combustion of lignin is considered carbon neutral, as an equal amount of carbon was taken out of the atmosphere during the growth of the switchgrass. The emission factors from calcium oxide and sulphuric acid have been taken from JRC 2007 (JEC-WTW 2007), and can be found in table 17, appendix 1.3.

<u>Allocation</u>
Similarly as with the LUC emissions, only a part of the life cycle emissions will be allocated to the ethanol. As 1 GJ of wheat grains also leads to the production of 0.354 GJ of straw, only 73.9% of the wheat cultivation emissions are allocated to the wheat grains (JRC: 2008). Further onwards in the chain, the conversion process of the wheat grains leads to the production of 0.688 GJ DDGS per GJ of ethanol (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). This influences the emissions of the cultivation, the transport and the conversion. Consequentially, a total of 44% of the wheat cultivation emissions and 59.5% of the transport and conversion emissions are allocated to the ethanol.

Switchgrass does not produce co-products during the production phase. However, during the conversion process, electricity is produced from the excess lignin. Every GJ of ethanol leads to the production of approximately 0.052 GJ of lignin electricity (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). Consequentially 95.1% of the cultivation, transport and conversion emissions will be allocated to the ethanol.

## *3.3 Biodiversity*

The production of bioenergy crops can affect the biodiversity in several ways. According to Dornburg et.al., the effects of land use change are dominant on the short term, while on the long term the contribution to reduced climate change becomes important (Dornburg, Faaij et al. 2008). As the long term effects of climate change are not applicable to 2015, this study will only look into the effects of the short-term biodiversity change. Many indicators have been developed to describe the state of the agro-biodiversity. Examples are the high nature value on farmland (EEA 2004), the cumulative distribution of bird species (Hagemeijer, E.JM. and Blair M.J. 2002), the mean species abundance (MSA) (Alkemade, Oorschot et al. 2009) and the land cover class density (LCCD) (Prydatko 2010). Based on the data availability, the accuracy of the results and the achievable spatial resolution, the MSA has been selected as the most suitable indicator for agro-biodiversity in Ukraine.

The MSA can be described as an index, that calculates the mean trend in the population size, of a representative cross section of original species. The cross section is focused on mammals, insects, vascular plants and bird species (Alkemade, Oorschot et al. 2009). One of the advantages of the MSA is that many species can be incorporated in the analysis, in stead of only measuring a single indicator species. A second advantage is the relatively low data requirement. The MSA also has several disadvantages, that are discussed in the discussion section of this report.

The MSA is dependant on the land use, the infrastructure, the land fragmentation, the atmospheric nitrogen deposition and the influence of climate change. In the wheat and switchgrass bioethanol chains, it is assumed that only the land use factor will change. The relative impact on the MSA can therefore be calculated as follows:

$$\Delta MSAlu = \mathrm{MSA}_{\mathrm{Lu,\,bioenergy\_crop}} - \mathrm{MSA}_{\mathrm{Lu,\,current}}$$

$\Delta \mathrm{MSA}^{lu}$ = Difference in the Mean Species Abundance between the future and current situation. (-)
$\mathrm{MSA}_{lu}$ = The influence of land use classes on the MSA. (-)

To indicate the current biodiversity, the Netherlands environmental assessment agency has applied $\mathrm{MSA}_{lu}$ factors to all land use classes of the Corine database (Alkemade, Oorschot et al. 2009). As the Ukrainian Land and Resources Management Centre (ULRMC) apply the same factors in their research, the values are assumed to be

[10] Global Emission Model for Integrated Systems. Developed by the German Institute for applied ecology.

valid for Ukraine (Prydatko, Kolomytsev et al. 2008). As the inclusion of mosaic land use classes is relevant for the biodiversity assessment, the land use mosaics from the Corine database have not been reclassified for the calculations in this paragraph. Hence there are three agricultural classes that are taken into account: *cultivated and managed areas*, *mosaic forest/cropland* and *mosaic cropland/grassland*. Based on descriptions by Alkenmade et.al., these classes have been respectively assigned the $MSA_{lu}$ factors for *low impact agriculture*, *bio-forestry* and *livestock grazing* (Alkemade, Oorschot et al. 2009).

In the wheat bioenergy chain, it is assumed that the agriculture will intensify. Consequentially, all agricultural land was assigned the $MSA_{lu}$ factor that is applicable to *intensive agriculture*. To determine the $MSA_{lu}$ for switchgrass, a specific factor for perennial bioenergy crops has been developed by van Rooij et.al (van Rooij 2008). All $MSA_{lu}$ factors can be found in table 18 of appendix 1.4.

## 3.4 Soil

Currently, 1 mln hectares of former agricultural land is left uncultivated because of soil related infertility (Exergia 2003-2004). Two reasons that contribute to this problem are a lack of soil organic matter/nutrients, and erosion. The erosion can be related to both wind and water runoff. For a bioenergy chain to be sustainable, the soil should be preserved without losing nutrients to erosion or over-harvesting. The this end the changes to the soil will be assessed.

### 3.4.1 Soil organic matter

A healthy soil is essential to achieve high yields (Bot, Benites 2005). Apart from the mineral fertilizers, all nutrients are naturally provided by the decomposition of soil organic matter (SOM). Where the soil is exploited for crop production without restoring the organic matter, the nutrient cycles are broken, soil fertility declines and the equilibrium in the agro-ecosystem is disturbed (Bot, Benites 2005). A declining organic matter stock should therefore be prevented. Furthermore, a high SOM can provide habitat for many soil organisms and improves the water holding capacity of the soil (Bot, Benites 2005).

To estimate the change of the SOM, detailed data is required on the current stocks, and the in- and outflows of organic material. As the required data cannot be gathered within the timeframe of this project, a different approach has been selected. According to Dias-Zorita et. al. (Diaz-Zonita, Duarte et al. 2002) the soil organic carbon and the soil organic matter are highly interlinked. The change in soil organic carbon is therefore used as a proxy, to approach the differences in the SOM. The calculation method of the SOC change is explained in paragraph 3.1.1.

### 3.4.2 Water erosion

Besides the SOM change, also water erosion is used as a criterion to describe the environmental impact on the soil. Water erosion mainly occurs in sloped or mountainous regions, when the water from a rain shower flows downhill, partly removing the topsoil (sheet erosion). As the topsoil contains the majority of the soil minerals, water erosion leads to a soil impoverishment (USDA 2002). On steep slopes, this may be a natural process. It can however be accelerated or decreased by human intervention (USDA 2002). A second type of water erosion is caused by the impact of raindrops, and the forming of rills and gullies, when the water flows downhill (USDA 2002). Other types of water erosion include ephemeral gully, classical gully, stream channel, or geologic erosion. As there is no methodology to estimate the impact of these types, only the sheet and rill erosion are taken into account (USDA 2002).

In order to assess the water erosion, the Universal Soil Loss Equation (RUSLE) has been be applied. The RUSLE was first developed in 1965 by Walt Wischmeier at the USDA-SCS (USLE, USDA 2009). Today, it is still used in many studies concerning the environmental impacts of energy crops (Smeets, Faaij 2009, Dam, Faaij et al. 2009, Smeets, Faaij et al. 2005). The RUSLE is defined as follows:

$$A = R * K * L_s * C * P$$

| | | |
|---|---|---|
| A = | Soil loss | (ton/ha/yr) |
| R = | Rainfall erosion index | (MJ mm/ha h) |
| K = | Soil erodibility factor | (ton ha h/ha MJ mm) |
| $L_s$ = | Slope factor | (-) |
| C = | Crop management factor | (-) |

P = Agricultural practise factor (-)
Source: (USDA 2002).

To account for the worst case scenario, the water erosion will be calculated for the most vulnerable month in the year. This period is characterised by a high rainfall erosion index (R), in combination with a sparsely vegetated soil (C). As field measurements where unavailable, the rainfall erosion index has been calculated by an empirical formula. As there is no specific formula for Ukraine, a formula had to be used from another country. Several options were issued in other researches (Scilands GmbH 2010, OMAFRA (canada) 2010, Renard, Foster et al. 1997). In this study, the rainfall erosion index was calculated according to the formula from the German Scilands GmbH. The formula was selected, as the German precipitation patterns showed the closest resemblance with the Ukrainian patterns. The formula is defined as follows:

$$R = (12 * Pr) * 0.0783 - 12.98$$

R = Maximum rainfall erosion index
Pr = Precipitation (mm/month)
*Source:* (Scilands GmbH 2010)

To determine the monthly precipitation that is required in the formula, long term precipitation data has been taken from 49 weather stations (NOAA ESRL physical science division 2008). As stated in the case study, the precipitation data was interpolated with the Spline tension method. Besides the R-factor, also the C-factor is time dependant. However, as it is not possible to differentiate between the monthly variations of the C-factor (more information below), the most vulnerable period for water erosion is only determined by the rainfall erosion index. Input data can be found in appendix 2.

The second parameter in the water erosion equation is the soil erodibility factor (K). The factor is dependant on the texture and organic matter content of the soil. It has been determined through research from the Ontario State University on the relationship between soil structure and erodibility (OMAFRA (canada) 2010). As the WRB soil classification system differs from van the system used by Ontario (USDA), the soil classes had to be converted before an erodibility factor could be assigned. The conversion has been done according to the available information on the structure, profile and parent material of each soil type, based on the description by the World Reference Base on Soil Resources (IUSS, ISRIC et al. 2006). To confirm the validity of the soil class conversion, the methodology was confirmed in an expert review (Cohen 2010). The conversion, and the corresponding erodibility factors can be found in table 20 of appendix 1.5. For all soils, average organic matter values were assumed, as no site specific data was available.

The next parameter is the slope factor ($L_s$), which is dependant on the slope gradient en the slope length. It was calculated according to the following formula (OMAFRA (canada) 2010):

$$Ls = [0.065 + 0.0456(Sg) + 0.006541(Sg)^2] \times (Sl \div D)^N$$

Ls = Slope factor
Sl = Slope length (m)
Sg = Slope gradient
D = 22.1 (-)
N = factor, dependant on the slope gradient:
- slope <1%: N= 0.2 (-)
- slope 1-3%: N= 0.3 (-)
- slope 3-5%: N= 0.4 (-)
- slope>5%: N= 0.5 (-)

In order to calculate the slope gradient, a detailed altitude map of Ukraine was required. In this study, a digital elevation model has been used from the ASTER module. (NASA, Japan's Ministry of Economy, Trade and Industry (METI) et al. 2010). The resolution of this map was 50x50 m. To calculate the slope gradient from the altitude, a SLOPE calculation has been made with the spatial analyst extension of ArcGIS (ESRI 2010). The altitude and slope maps are given in figure 6, appendix 1.5.

In order to calculate the slope length, a calculation was made with the raster calculator of the spatial analyst extension of ArcGIS. The following calculation has been made. In this calculation, the functions are depicted in bold, and the parameters in italic:

Flow accumulation = F = **FlowAccumulation**(**FlowDirection**([*altitude*]))
Sl= **Pow**([*F*] * 50 / 22.1, 0.4) * **Pow**(**Sin**([*Slope*] * 0.01745) / 0.09, 1.4) * 1.4
*Source:* (Mitasova, Surface Processess Group, North Carolina State University 2010)

The next parameter is the crop management factor (C), which is calculated by a multiplication of the crop type factor and the tillage factor. The crop type factor is mainly dependant on the amount of vegetation and the related leave area index (van Beek 2010). To calculate a monthly crop type factor, a high resolution spatial representation of the monthly leave area index is required. However, as such data could not be included within the timeframe of this project, an more general methodology has been applied, that is also applied in other environmental impact studies (Smeets, Faaij 2009). More information about the effects of this simplification can be found in paragraph 5.5. In stead of a monthly value, each crop type was assigned an annual crop type factor, on the basis of research by the Ontario ministry of agriculture (OMAFRA (canada) 2010). The crop type factors can be found in table 21, appendix 1.5. To determine the crop management factor, the crop type factors were multiplied with tillage-factors, that can be found in table 22, appendix 1.5. To determine the tillage factor, it is assumed that all summer crops in Ukraine are currently spring ploughed. Winter wheat and winter barley[11] are assumed to be fall ploughed. This assumption was confirmed during an expert interview (Gebuis 2010). After the multiplication, the management factor was specified for the arable land per oblast by combining the crop specific management factors with the crop fractions of each oblast.

To estimate the crop type factor of pasture lands, data has been used from the Ontario ministry of agriculture. For the tillage factor, it is assumed that $^{1}/_{20}$ of the cycle is under a spring-tillage regime, and $^{19}/_{20}$ of the cycle is under a no-tillage regime. Values were assigned accordingly.

For the calculation of the wheat bioethanol chain, the same C-factor was used as for the winter wheat in the calculation of current arable land. For the C-factor of switchgrass, the same C-factor was used as for current grassland.

The next parameter is the support practice factor (P), that is dependant on the management that is applied to counteract soil erosion. It was assumed that in both the current situation, and in the two bioenergy chains, cross slope farming is applied. Thereby it is implicitly assumed that today's farmers are aware of the erosion problem, and adjust there management regimes in an attempt to reduce the water erosion. According to the Ontario ministry of agriculture, a P factor of 0.75 should be applied (OMAFRA (canada) 2010).

To calculate the change in the soil erosion, the soil loss of the current situation has been subtracted from the soil loss of the wheat and switchgrass.

### *3.4.3 Wind erosion*

Besides water, also wind can be an erosive agent. Although wind erosion is a natural occurring process, it can be accelerated by improper land management (USDA 2002). Especially lands with loose or dry soils, sparse vegetation or high wind speeds, are vulnerable. Ideally, the wind erosion should be measured in the field. However, as this is very time and capital intensive, the wind erosion equation (WEQ) will be used in stead. The WEQ was developed by Dr. W.S. Chapil in 1963 (USDA 2002), and is often used in environmental studies (Hilst 2009). The equation looks as follows:

$$E = \int (CIKVL)$$

E = Potential average annual soil loss (t/ha/yr)
C = Climate factor
I = Soil erodibility index (T $ha^{-1} \cdot yr$)
K = Roughness factor
V = Vegetation cover (SGe ton/ha)
L = Unsheltered distance across a field (m)
*Source:* (USDA 2002)
*Note: The full equation can be found in appendix 1.5.2.*

[11] Approximately 90% of all Ukrainian wheat is winter wheat. Approximately 10% of the Ukrainian Barley is winter Barley (State Statistics Committee of Ukraine, Ostapchuk et al. 2009).

To account for the worst case scenario, the wind erosion risk will be calculated for the most vulnerable period in the year. In this period, the vegetation factor will be low, and the climate factor will be high, indicating a period with high wind speeds, dry soils and low vegetation barriers.

To calculate the climate factor (C), a formula has been used from the national resources conservation service and Thornthwaite, et.al. (USDA 2002, Thornthwaite 1931):

$$C = 34.48 * \left( \frac{V^3}{\left[ \sum 115 * \left( \frac{P}{T-10} \right)^{10/9} \right]^2} \right)$$

V = Annual average wind velocity ($ms^{-1}$)
P = precipitation (inches)
T= Temperature (F)

The temperature and precipitation data that is required for this calculation, has been taken from 49 weather stations (NOAA ESRL physical science division 2008) (appendix 2). The data on the wind speed was not available from these stations and has hence been taken from the NOAA gridded climate database, at a resolution of 180x280 km (NOAA ESRL physical science division 2010). From the calculations it was estimated that the climate factor is highest in May and October (figure 7, appendix 1.5).

The other factor that determines the seasonal change in wind erosion vulnerability, is the vegetation factor (V). The factor is obtained via Small Grain Equivalents, that have been derived from a worksheet from the USDA (USDA 2006). The vegetation factors differ per crop type and depend on the planting and harvesting dates. Also the orientation of the crop rows is important. It is assumed that farmers will plant their crops perpendicular to the prevailing wind direction, to prevent erosion on vulnerable sites. The V-factors per crop type can be found in table 26, appendix 1.5.

Also grassland is assigned a V-factor from the USDA (USDA 2006). To comply with the 20-year grassland cycle, the V-factor is calculated by adding $^{1}/_{20}$ times the V-factor of 'first year grassland', with $^{19}/_{20}$ times the V-factor of 'subsequent grassland'.

For the V-factor of wheat, the same methodology has been followed as for the winter wheat fraction on current arable land. As specific V-factors for switchgrass were unavailable, the factors of miscanthus have been used in stead. Complying with the 20-year switchgrass cycle, the V-factor is build up by multiplying $^{1}/_{20}$ times the V-factor of first year miscanthus, with $^{19}/_{20}$ times the V-factor of 'subsequent miscanthus'.

The next parameter is the soil erodibility index(I), that accounts for the inherent soil properties that affect the erodibility (USDA 2002). In the wind tunnel tests by van Kerckhoven et.al. (2009), the soil erodibility factor was determined for various soil types. To use this data, the WRB classification of the soil map had to be reclassified to match the USDA classification that is used by van Kerckhoven. However, as the USDA classification is similar to the classification of the RUSLE soil erodibility index, no further action was required. Based on the USDA classification, the WEQ soil erodibility index could be assigned. Both the reclassification, and the corresponding I-factor from van Kerckhoven is shown in table 23 of appendix 1.5.

The soil erodibility factor (K), that describes the effect of ridges and the cloddiness of the soil, is mainly dependant on the use of machinery (USDA 2002). As the machinery use is dependant on the crop type, the K-factor is too. The K-factor was acquired through the work of van Kerckhoven et.al, 2009. Crop specific K-factors were allocated to the corresponding crop types in Ukraine. As not all K-factors were available for the Ukrainian crop types, some crops were assigned an estimated K-factor, on the basis of comparable crop characteristics. Rape and sunflowers have been assigned the same factors as for wheat. Vegetables have been assigned the same value as sugar beet.

Also grassland is assigned a crop specific K-factor from van Kerckhoven. To comply with the 20-year grassland cycle, the K-factor is build up by multiplying $^1/_{20}$ times the K-factor of 'first year grassland', and $^{19}/_{20}$ times the K-factor of 'subsequent grassland'.

For the wheat bioethanol chain, the same methodology has been followed as for the winter wheat fraction on current arable land. As the K-factors for switchgrass were unavailable, miscanthus factors have been used in stead. Complying with the 20-year switchgrass cycle, the K-factor is build up by multiplying $^1/_{20}$ times the K-factor of first year miscanthus, and $^{19}/_{20}$ times the K-factor of 'subsequent miscanthus'. All K-factors can be reviewed in table 24, appendix 1.5.

The field length factor (L), describes the unprotected distance along the prevailing wind direction. With field work or remote sensing, the field length can be accurately indicated. However, as this analysis would require an extensive analysis, it would take to much time and capital to include in this study. It is therefore stated that $L=L_0$, assuming the maximum field length. According to research by can Kerckhoven *et. al.*, the WEQ is not sensitive to changes in the field length.

To calculate the potential soil erosion, the RUSLE was calculated for each crop type separately. The oblast specific average could then be calculated by multiplying the crop specific results with the crop fractions per oblast. To calculate the change in the soil erosion, the soil loss of the current situation has been subtracted from the soil loss of the wheat and switchgrass.

## 3.5 Water

### 3.5.1 Water quantity

Ukraine has over 17,000 rivers, of which 160 with a length over 100 km (UA travelling 2010). The amount of water is however strongly influenced by the season and varies significantly between the oblasts. In March and April, the precipitation and melting snow can lead to floods and inundations in the Central and Northern oblasts (Ukrainian State Committee for Hydrometeorology 1996). In the Southern oblasts, the water availability is much less. Because of the low precipitation and the high evapotranspiration of the crops, many oblasts suffer from a water deficiency, leading to low crop yields.

In this study the water quantity will only focus on the deficiency of water. As only a very small percentage of the water is used during the conversion (<10% of the total water demand) (Berndes 2002, de Fraiture, Berndes 2008, Gerbens-Leenders, Hoekstra et al. 2009), only the water use of the cultivation will be taken into account. To assess the water deficiency, a detailed water balance should be drawn. As a full assessment of the ground- and river water levels is very complex, and requires many local parameters, a simplified balance is made in stead. The balance is calculated according to the difference between the effective precipitation and the evapotranspiration, as given by the following formula (Dam, Faaij et al. 2009, Hilst, Dornburg et al. 2010):

$$WS = \sum \left[ET_0 * K_c\right] - P_{eff}$$

| | | |
|---|---|---|
| WS = | Maximum water shortage at the end of the dry season | (mm) |
| $ET_0$ = | Monthly reference evapotranspiration | (mm/month) |
| $K_c$ = | Crop evapotranspiration coefficient | (-) |
| Peff = | Monthly effective precipitation | (mm/month) |

The evapotranspiration rate from a reference surface that is not short of water, is referred to as the reference evapotranspiration ($ET_0$) (Brouwer, Heibloem et al. 1996). According to the FAO, the $ET_0$ can be calculated according to several methods, such as the Penman-Monteith equation, the pen-evaporation method, and the Blaney Criddle equation (Brouwer, Heibloem et al. 1996). The FAO strongly recommends the use of the Penman-Monteith equation (appendix 1.6), because it is physically based, and explicitly includes both physiological and aerodynamic parameters (Brouwer, Heibloem et al. 1996). The required data for the equation was provided by 12 weather stations that are included in the CLIMWAT database. The database has been specifically developed by FAO to determine the reference evapotranspiration (FAO 2010a). Although the database does not include Ukrainian weather stations, 12 bordering stations from Belorussia, Russia, Hungary and Romania have been used to supply the data[12]. The data has been imported and processed by the CROPWAT software (FAO 2010b), to calculate the ref. evapotranspiration of each station (FAO 2010a). The results of the calculation can be found in table 26, appendix 1.6. To account for the reference evapotranspiration of Ukraine, $ET_0$ has been interpolated, according to the Spline tension method.

The next factor in the equation is the crop evaporation coefficient ($K_c$), that describes the crop specific evapotranspiration as compared to $ET_0$. According to FAO research (Brouwer, Heibloem et al. 1996), the factor has been calculated for various crop types[13], based on four crop development stages (initial stage, crop development stage, mid-season stage, late-season stage). The basic duration of the development stages per crop, and the corresponding Kc-factors, have been issued by Brouwer et.al. (Brouwer, Heibloem et al. 1996). By applying the Ukrainian planting and harvesting dates, and taking the relative length of the development stages per crop, the Kc-factor was adapted to the agricultural system of Ukraine. The distribution of the four development stages per crop and the corresponding Kc factors can be found in figure 10, appendix 1.6. By combining crop specific Kc values, with the crop fractions per oblast (State Statistical Committee of Ukraine), an oblast specific Kc value was determined. The oblast specific Kc values are depicted in table 27 of appendix 1.6.

Besides arable land, also pasture land was assigned a crop evaporation coefficient. As pastures are often cut at random times, the FAO advises to use an average $K_c$ value for all months (Brouwer, Heibloem et al. 1996). The evaporation coefficients have been differentiated for moist and dry climate zones, as can be seen in table 28 of appendix 1.6.

To determine the evaporation coefficient of wheat, the same methodology has been followed as for current wheat on arable land. For switchgrass, the evapotranspiration is assumed to be equal to miscanthus. The data for the miscanthus evapotranspiration coefficient has been derived from {{120 Hilst, van der, F. 2009;}}.

The final parameter is the monthly effective precipitation (P). It was estimated on a basis of the monthly precipitation, on the basis of a calculation method from the USDA. The long term monthly precipitation data was taken from weather stations, as supplied by NOAA (NOAA ESRL physical science division 2008)(appendix 2). The effective precipitation was then calculated as follows:

$P_{eff} = P_{month} * (125 - 0.2 * P_{month}) / 125$ for $P_{month} \leq 250$ mm
$P_{eff} = 125 + 0.1 * P_{month}$ for $P_{month} > 250$ mm
*Source: USDA, through CROPWAT* (FAO 2010b)

$P_{eff}$= Effective precipitation (mm/month)
$P_{month}$= Monthly precipitation (mm/month)

The spatial analysis will focus on the cumulative water shortage at the end of the dry season, when the shortage is maximal.

### *3.5.2 Water quality*

Next to the water quantity, also the water quality is taken into account. If the application of fertilizers exceeds the nutrient uptake by the crops, the remaining nutrients can leach to surface or soil water. High concentrations of $NO_3$ or $PO_4$ are undesirable, as they may lead to eutrophication or acidification.

To assess the nutrients in the soil water, the concentration was calculated by the integrated nitrogen model Miterra-Europe, which is described in (Velthof, Oudendag et al. 2007). The Miterra model was developed by Alterra, and was expanded during this study to include Ukraine. In the model, the $NO_3$ concentration is determined through the calculation of the surplus-N, the denitrification, surface runoff and leaching. A schematic representation of the model can be found in figure 3.1.

[12] Gomel (BL), Brest (BL), Kursk (RUS), Valujki (RUS), Certkovo (RUS), Rostov-na-Donu (RUS), Primorsko Atharsk (RUS), Sulina (RO), Iasi (RO), Debrecen (H)
[13] Crop types, taken into account: wheat, barley, maize, other cereals, potatoes, vegetables, sugar beet, sunflower and rape. The vegetable class has been split up into cabbage (21%), tomatoes (19%), onion (13%), carrots (9%), and others (38%).

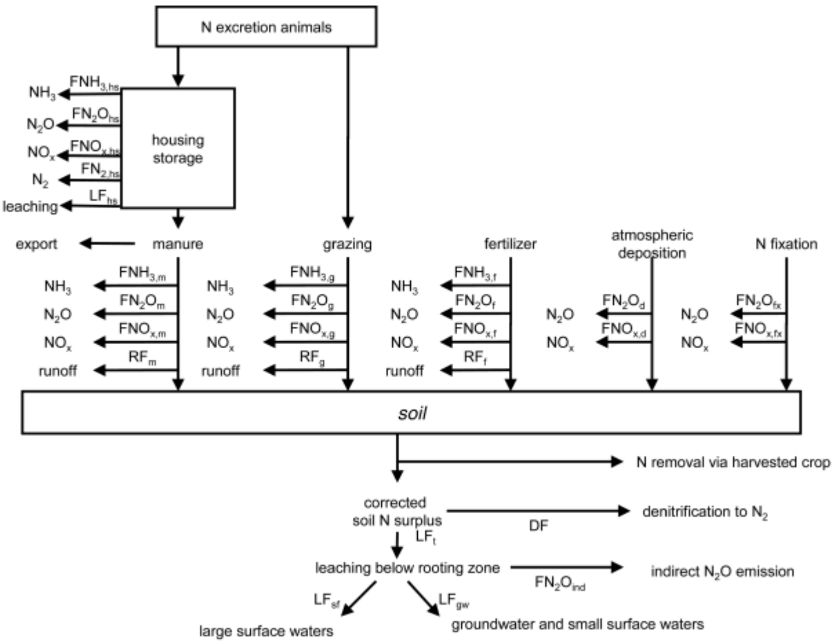



***Figure 3.1:*** *Schematic presentation of Miterra-Europe* (Velthof, Oudendag et al. 2009).

From the figure, it can be seen that the surplus-N is dependant on the input of manure, mineral fertilizers, atmospheric N-deposition, biological fixation and the harvesting of crops. To determine which part of the surplus-N can leach to the soil water, the parameter is corrected for surface runoff (based on slope, precipitation, soil type, and crop type), and $NH_3$, $N_2O$ $_{and}$ $NO_x$-emissions. Then, the surplus-N is multiplied with a denitrification factor, to calculate the loss of N through bacterial denitrification. The denitrification rate is mainly dependant the soil type, the land use type, the soil organic matter content, the precipitation and the temperature. Finally a leaching factor is applied to determine the amount of N that leaches to the groundwater, and to the surface water.

In the Miterra model, both organic and mineral fertilizers have been included. In the wheat chain, it was assumed that the application of mineral fertilizers per hectare, is the same as the fertilization rate of current wheat. The application of organic fertilizers remains unchanged. For switchgrass, a balanced fertilization was assumed, at 5.3 g N/kg dm. harvested. The uptake efficiency was assumed at 100%, as switchgrass has a deep root system, that is able to efficiently take up nutrients the whole year (Lesschen 2010). Also in the switchgrass chain, the application of organic fertilizers does not change, as compared to current practices. For the current crop areas and yields per hectare, data has been used from 2004.

The phosphorous balance could not be determined by the Miterra model. It can however be assumed that the surplus phosphorous follows the same patterns as the nitrogen surplus {{198 Alterra, University of Wageningen 2010;}}.

# 4. Results

## 4.1 Emissions from land use change

The following paragraph describes the GHG emissions/mitigations that occurs if current agricultural land is cultivated by wheat or switchgrass. First, paragraph 4.1.1 describes the changes in the above and below ground biomass, followed by the changes in the soil organic carbon stocks that are described in paragraph 4.1.2. Then paragraph 4.1.3 continues with the description of the land use change related $N_2O$ emissions. Lastly, paragraph 4.1.4 gives an summation of the total land use change emissions.

<u>4.1.1 Biomass change</u>

Figure 4.1 depicts the change in the carbon that is stored in the biomass of crops and grasses. Both the above and below ground biomass are taken into account.

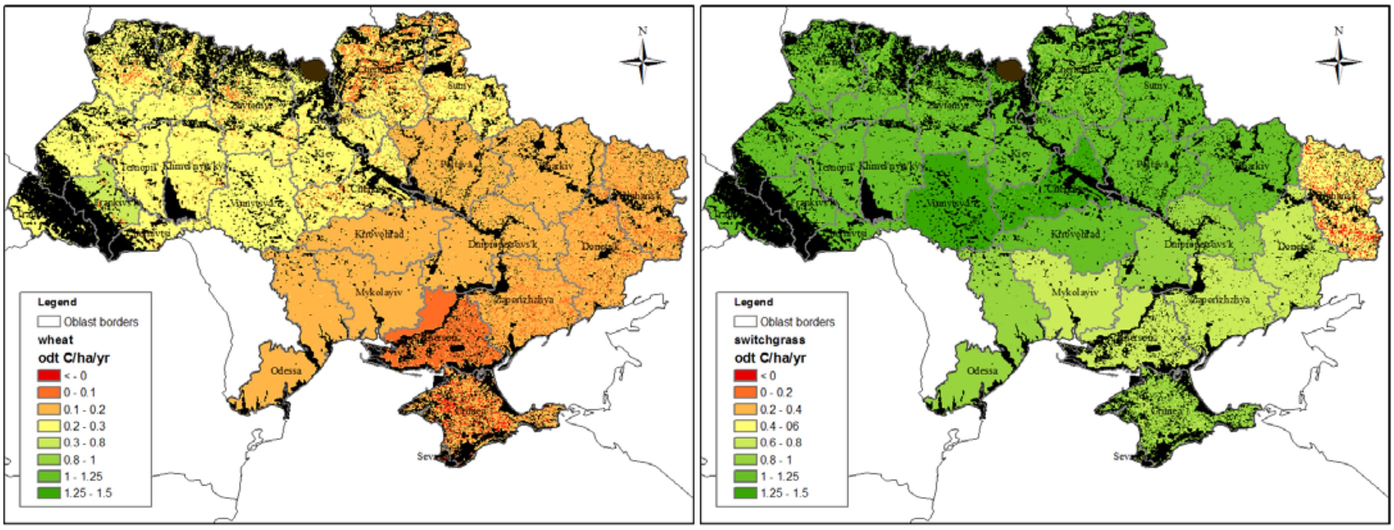



***Figure 4.1:*** *Change in above and below ground biomass (t C/ha/yr) of wheat (left) and switchgrass (right), as compared to the current land use of Ukraine.*

From the results, it can be derived that the cultivation of wheat on current arable land, leads to a carbon stock increase of 0.08-0.31 tC/ha/yr. The change is relatively small, as the arable land is already cultivated with crops. However, because of the intensification of the agriculture, the amount of biomass per hectare may increase. If wheat is cultivated on pasture land, the amount of biomass per hectare may increase with 0.05 - 0.26 tC/ha/yr. Although grassland has more below ground biomass, the intensively cultivated wheat has considerably more above ground biomass than grassland. Consequentially the biomass will increase if pastures are converted to arable land. An exception is the Crimean peninsula, where a modest decrease of 0.1 tC/ha/yr is expected. As the temperature and moisture strongly influence the current biomass stock on grasslands, the warm and moist oblasts tend to have more grass per hectare then the cool and dry oblasts. In Crimea, the combination of a warm and moist climate leads to higher biomass stocks than in the rest of Ukraine. Hence, the biomass stock of Crimea will decrease if pasture land is replaced with wheat.

If switchgrass is cultivated on arable land, the carbon stock change increases with 0.54 - 1.27 t C/ha/yr. This is caused by the high yield levels of switchgrass, and because of the plants extensive root system. The increase is highest in Ukraine's Centre (Vinnytsya and Cherkasy), and lowest in the East (Luhans'k). The difference is mainly caused by the growth potential of switchgrass, that is highest in the central oblasts. On pasture land the carbon stock also increases. The increase ranges from 0.5 (Luhans'k) to 1.28 (Vinnytsya) t C/ha/yr. The increase can be explained by the relatively low production level of pasture lands, in comparison to the high switchgrass yields. Again, the highest carbon increase can be found in the central oblasts, corresponding to the highest potential yield levels of switchgrass.

The main uncertainties in the biomass analysis include the varieties of the local yield levels, and the default biomass carbon increment and loss rates from the IPCC. The influence of these parameters will be discussed in paragraph 5.2.

4.1.2 Soil organic carbon change

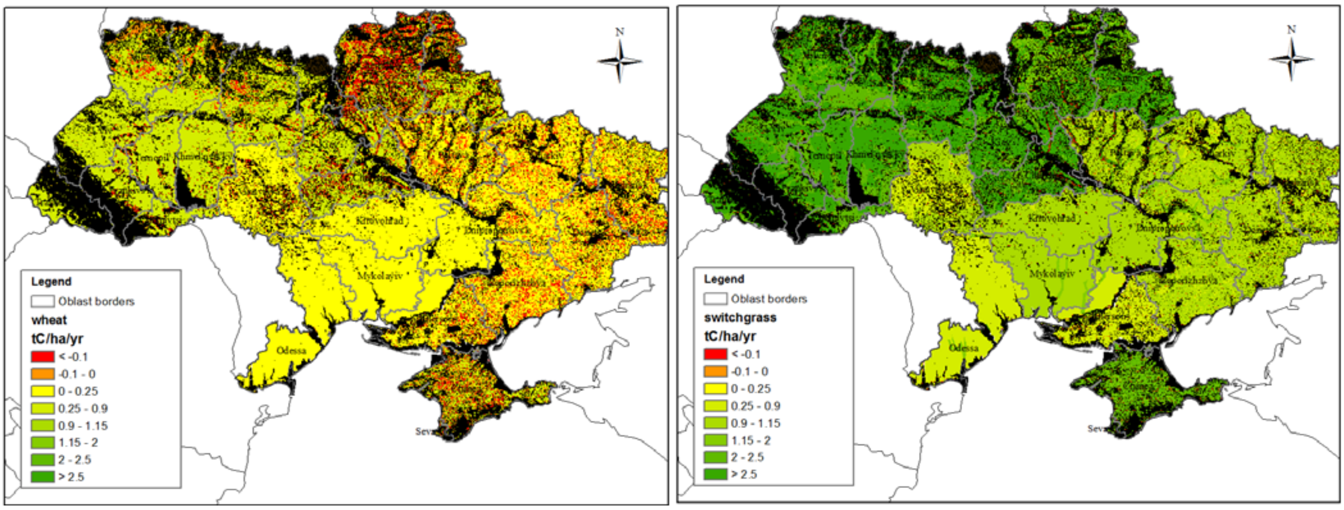



***Figure 4.2:*** *Change in the soil organic carbon content of mineral and organic soils (t C/ha/yr) of wheat (left) and switchgrass (right), as compared to the current land use of Ukraine.*

Figure 4.2 depicts the emissions from the changes in the soil organic carbon content (SOC) on mineral soils, and the emissions from the carbon flux change on the organic soils.

If wheat is cultivated on arable land on mineral soil, there is a small increase in the soil organic carbon content. As the landuse and tillage factors remains the same, the SOC change is mainly influenced by the input of external fertilizers. The relative change of the intensified fertilization regime is the highest in the moist climate zones. The quantitative change is highest on the soils with a high reference SOC, such as high activity (HAC) and wetland soils[14]. On HAC soils the SOC increase increases with 0.08-0.36 1 tC/ha/yr for respectively the dry and moist zones. On low activity soil, the SOC increases with 0.05-0.32 tC/ha/yr for respectively the dry and moist climate zones. If wheat is cultivated on pasture land on mineral soils, the SOC decreases. On high activity soils of the dry oblasts, the SOC decreases with 0.19 tC/ha/yr. On the moist oblasts, this it decreases with 0.30 tC/ha/yr. On low activity soils, the decrease is slightly less than on the high activity soils, ranging from 0.20 to 0.79 t C/ha/yr for respectively the dry and moist climate zones. The main driver behind the decrease of the SOC, is the change from a no-tillage to a full tillage regime. The effect is partly undone by the increased application of synthetic fertilizers, that leads to an increase of the SOC.

If switchgrass is produced on arable land on mineral soils, the SOC will increase with 2.61 tC/ha/yr in the dry climate zones, and with 1.10 t C/ha/yr in the moist climate zones. On low activity soils the increase is somewhat less than on high activity soils, ranging from 2.33-0.73 tC/ha/yr for the dry and moist climate zones. The overall increase can be explained by the replacement of the full tillage regime of arable land with the no-tillage regime of the switchgrass. When switchgrass is cultivated on pasture land, the SOC will increase with 1.37 t C/ha/yr in the dry climate zones to 0.73 t C/ha/yr in the moist zones. On low activity soils, the SOC increases from 0.23-0.48 t C/ha/yr for respectively the dry and moist climate zones. The SOC increase is mainly caused because of the intensified fertilization regime. The tillage regime is unchanged.

The driver of SOC related emissions from organic soils, is the carbon flux. The flux is mainly dependant on the climate (temperature) and the land use. Because of the similarities in their management regimes, the carbon flux of wheat is assumed to be the same as the carbon flux of current arable land. Therefore wheat cultivation on organic arable land does not lead to a change of the SOC. If pasture land is converted to wheatland, the carbon flux increases, leading to an emission of approximately 4.75 t C/ha/yr in the cool climate zones, and 7.5 t C/ha/yr in the warm climate zones. Besides wheat, also switchgrass can be cultivated on organic soils. A conversion of arable land to switchgrass, leads the decrease of the carbon flux with approximately 4.75 t C/ha in the cool climate zones, and 7.5 in the warm climate zones. As it has been assumed that switchgrass has the same carbon flux as pasture land, the net SOC changes of pasture land are zero.

[14] The reference SOC, and therefore the SOC increase is higher on volcanic and spodic soils than on HAC or wetlands soils. However, as the former soils are minority groups (together 1,5% of the total area), they were left out of the general discussion of the results.

The main uncertainties in the SOC analysis include the local differences in the yield levels and crop management regimes, the uncertainties in reference soil C stocks and the uncertainties of the default carbon fluxes. The influence of these parameters will be discussed in paragraph 5.2.

4.1.3 LUC related $N_2O$ emissions

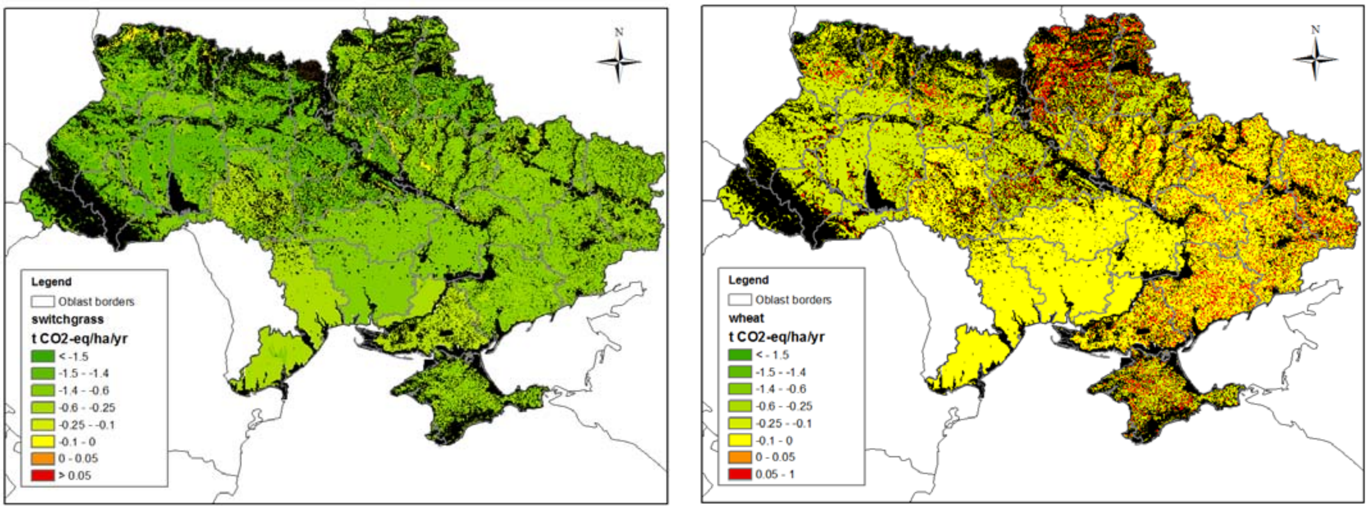



***Figure 4.3:*** *$N_2O$ emissions from land use changes (t $CO_2$-eq/ha/yr) to wheat (left) or switchgrass (right), as compared to the current land use of Ukraine.*

The LUC related $N_2O$ emissions, are depicted in figure 4.3. Both the direct and indirect $N_2O$ emissions on mineral soils are directly related to the change of the organic matter content of the soil. During the cultivation of wheat on arable land, the SOM will increase, leading to a mitigation in stead of an emission. The mitigation will be approximately 0.04-0.21 t $CO_2$-eq/ha/yr for the HAC soils in respectively the dry and moist climate zones. On low activity soils, the mitigation is somewhat less, because of the lesser SOM reduction: 0.03-0.19 t $CO_2$-eq/ha/yr. On pasture land on mineral soils, the cultivation of wheat leads to a decrease of the SOM, and there to an emission. The emission will be approximately 0.11 t $CO_2$-eq/ha/yr in the dry climate zones, and 0.33 t $CO_2$-eq/ha/yr in the moist zone. On low activity soils, the emission is somewhat smaller: 0.07-0.30 t $CO_2$-eq/ha/yr, for respectively the dry and moist zones.

The cultivation of switchgrass leads to an increase of the SOM, and therefore to a reduction of the $N_2O$ emission. On HAC soils on arable land, the cultivation of switchgrass leads to a mitigation of 0.63t $CO_2$-eq/ha/yr for the dry climate zones, and 1.50 t $CO_2$-eq/ha/yr for the moist climate zones. On low activity soil, the mitigation ranges from 0.42-1.34 t $CO_2$-eq/ha/yr, for respectively the dry and moist zones. On HAC pasture land, the SOM also decreases, leading to a decrease of 0.28-0.52 t $CO_2$-eq/ha/yr for the dry and moist climate zones. On low activity soils, the decrease ranges from 0.18 to 0.47 t $CO_2$-eq/ha/yr, for respectively the dry and moist zones.

According to the IPCC, there are no changes to the $N_2O$ emissions from drained organic soils. This can be explained as the denitrification rate that determines the emission, is the same for both arable land and pasture land (IPCC).

The main uncertainties in the above analysis include the calculation of the crop residue fraction, and the use of standard IPCC emission factors. The influence of these parameters will be discussed in paragraph 5.2.

4.1.4 Total emissions from land use changes

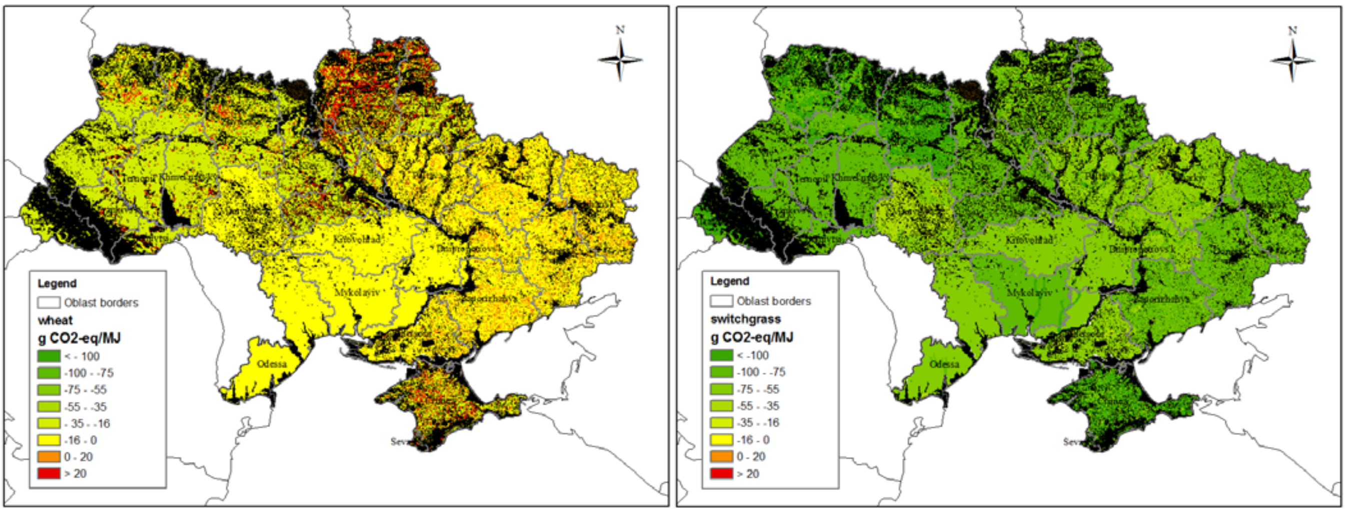



***Figure 4.4:*** *The total land use change emissions for wheat (left) and switchgrass (right), in g $CO_2$-eq/$MJ_{ethanol}$.*

In figure 4.4, the three land use change emissions are combined, and recalculated per $MJ_{ethanol}$ (including allocation). The results show that the land use change from current mineral arable land to wheat, leads to a modest emission reduction, ranging from 9 to 27 g $CO_2$-eq/$MJ_{ethanol}$. The mitigation is highest in the warm moist climate zone and lowest in the dry cool climate zone. The emission reduction is caused by a slight increase in biomass and SOC, and a slight decrease of the $N_2O$ emissions. The cultivation of wheat on mineral pasture land, leads to an emission of approximately 10-28 g $CO_2$-eq/$MJ_{ethanol}$ in the two cool- and the warm dry climate zones and 55 g $CO_2$-eq/$MJ_{ethanol,}$ in the warm moist zone (Crimea). The amount of biomass decreases, and the SOC related emissions increase. Furthermore, the $N_2O$ emissions also contribute to the net emission.

If switchgrass is cultivated on arable land, there will be a net mitigation of GHG. The mitigation ranges from 48-89 g $CO_2$-eq/$MJ_{ethanol}$ in the dry climate zones to 100-118 g $CO_2$-eq/$MJ_{ethanol}$ in the moist zones. On pasture land, the emission reduction is somewhat less varying from 49-64 g $CO_2$-eq/$MJ_{ethanol}$ in the dry zones to 33-66 g $CO_2$-eq/$MJ_{ethanol}$ in the moist zones.

If the arable land is situated on organic soils, wheat cultivation will lead to a mitigation of 9 g $CO_2$-eq/$MJ_{ethanol}$. As the carbon flux and the $N_2O$ related changes are zero, the mitigation is caused by the increase of above and below ground biomass. If the wheat is cultivated on organic pastureland, approximately 139 g $CO_2$-eq/$MJ_{ethanol}$ will be emitted, because of the increased carbon flux. As opposed to wheat cultivation, the production of switchgrass on arable organic land leads to an emission mitigation, due to the crops low carbon flux. Including the increase in biomass and the reduced $N_2O$ emissions, the total mitigation is approximately 157 g $CO_2$-eq/$MJ_{ethanol}$. Switchgrass cultivation on organic pasture land also results in a mitigation. As the carbon flux between pasture land and switchgrass is assumed to be the same, the only differences are the changes in biomass that lead to a mitigation of approximately 23 g $CO_2$-eq/$MJ_{ethanol}$.

## *4.2 Green house gas balance*

Figure 4.5 depicts the contribution of various factors to the GHG emissions of wheat and switchgrass based bioethanol. Besides the feedstock, the figure discriminates between the emissions of pasture and arable land, and mineral and organic soils.

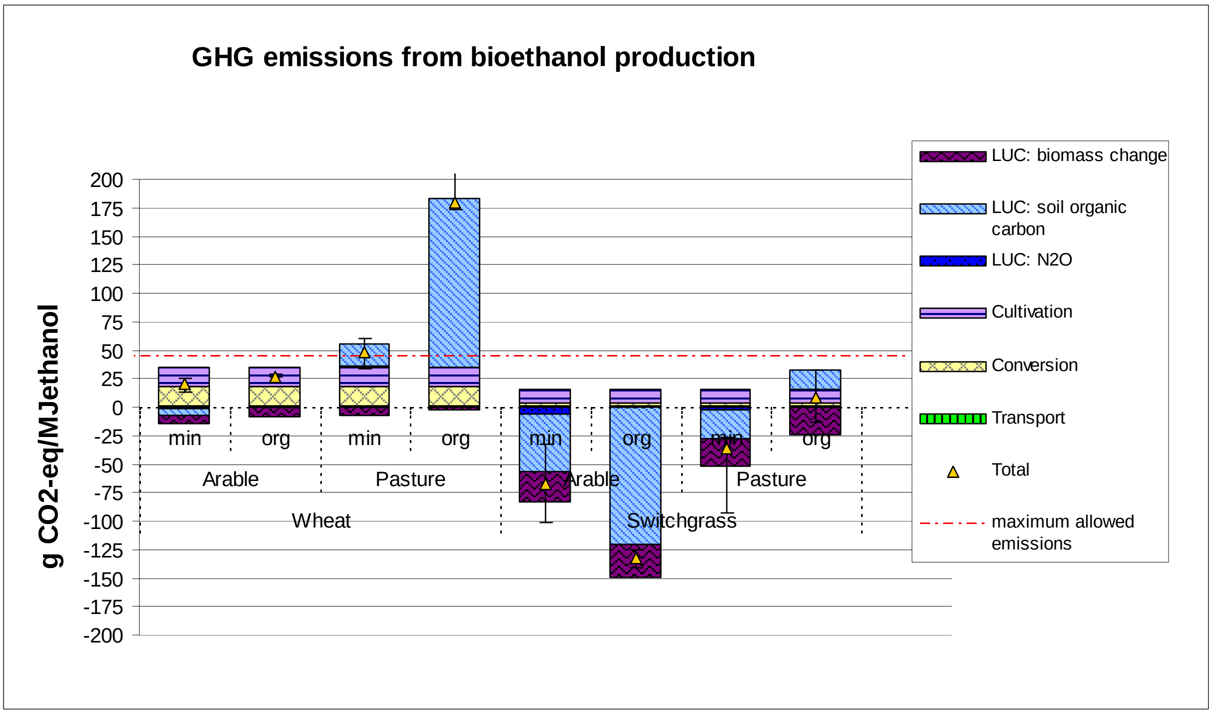



***Figure 4.5:*** *The main GHG-emissions from the production of wheat and switchgrass bioethanol on mineral and organic soils, including the maximum allowed emission at 65% of the fossil ethanol emission intensity (g $CO_2$-eq/MJ). The yellow triangles indicate the sum of the GHG emissions. These emissions are based on an average production potential of 6,700 kg ds wheat/ha/yr, and 15,400 kg ds switchgrass/ha/yr.*

From the figure it can be derived, that current arable land can be used for wheat-bioethanol, without exceeding the maximum allowable GHG-emission limit. As the wheat cultivation on mineral soils leads to a minor increase of the SOC, the cultivation on arable land generates slightly less emissions than organic land. The majority of the emissions on both soil types are emitted during the cultivation and conversion phase. In the cultivation phase, the production and use of mineral fertilizers is the largest contributor to the GHG emissions. During the conversion process, the steam production (natural gas) produces most emissions.

If wheat is cultivated on pasture land, the life cycle emissions remain the same as on arable land. On the other hand, the LUC related emissions increase significantly. The increase is mainly caused by the change of the pastures no-tillage regime to the full-tillage regime of intensive agriculture. Especially the cultivation of wheat on organic pasture land leads to a large change in the carbon flux, resulting in large additional emission. The conversion of both mineral and organic pasture land to wheat leads to emissions that exceed the maximum allowable emission constraint.

The cultivation of switchgrass on arable land leads to a significant decrease of the LUC related emissions. The increase is mainly caused by the change from a full-tillage to a no-tillage regime. Especially on the cultivated lands on organic soils, the carbon flux decreases considerably, leading to a net mitigation of GHGs. Also the amount of biomass per hectare increases, further contributing to the GHG mitigation. A third factor that influences the GHG-balance is the conversion. A clear difference can be observed with the wheat conversion. As the lignin fraction of switchgrass is used for the required heat and electricity of the conversion process, no additional electricity or natural gas are required. Consequentially, the GHG emissions that are generated during the conversion are limited to the use of CaO and $H_2SO_4$. Although the conversion related emissions are limited, the conversion process consumes most of the lignin, leading to a low yield of by-products. This in turn reduces the allocation of the other emissions to the lignin fraction.

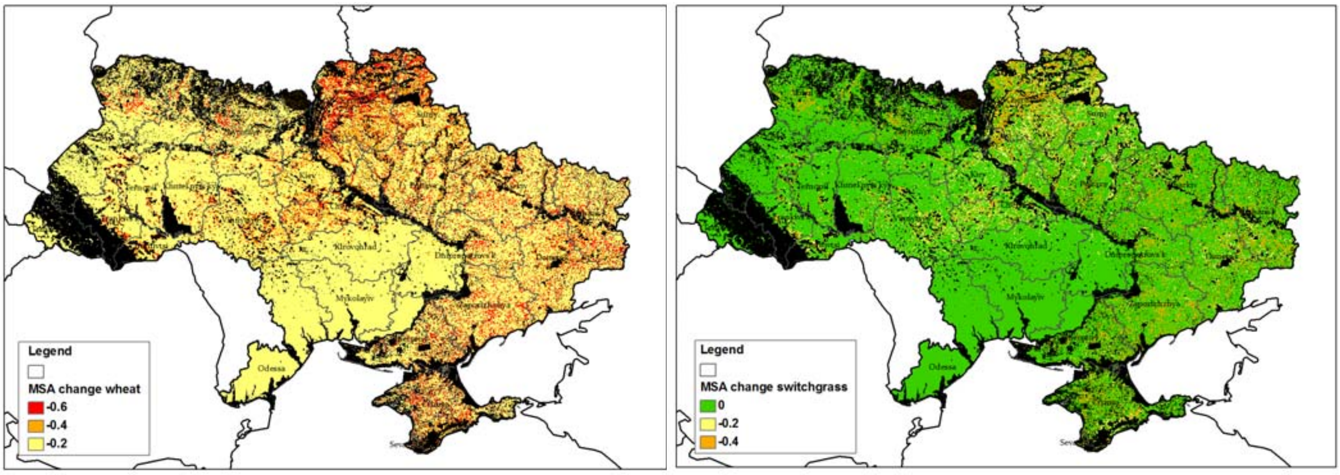
Switchgrass can also be cultivated on pasture land. Although the LUC related GHG mitigation is considerably less then the mitigation on cultivated arable land, the total GHG-balance is still negative if the cultivation takes place on mineral soils. The mitigation is mainly caused by an increase of the biomass, as switchgrass has a higher biomass density then pasture land, and because of an increase of the SOC. Also the SOC increases moderately, because of the intensified fertilization regime. On organic pasture land, the carbon flux is assumed to remain unchanged, except for the first year in the cycle, where the tillage leads to an emission.

The life cycle assessment includes several uncertainties, that are mainly related to the accuracy of the local yield levels, and to the application rates of the various additives. Chapter 5.2 discusses the uncertainties in more detail.

## *4.3 Biodiversity*

In the wheat bioenergy chain, extensively managed agricultural land is converted to intensively managed cropland. As can be seen in figure 4.6, the intensification leads to a significant loss of biodiversity on all land cover types. The relatively lowest loss in the wheat chain is caused by the conversion of arable land, during which the $MSA_{lu}$ decreases with 0.2 (-65%). The conversion of the Northern bio-forestry plantations leads to an even higher loss, as the $MSA_{lu}$ decreases with 0.4 (-80%). On current pasture land, the biodiversity loss is highest. The $MSA_{luc}$ decreases with 0.6 (-85%).

In the switchgrass chain, the intensification of agricultural land is much less then in the wheat chain. Hence, also the biodiversity loss is less. If current arable land is used for switchgrass cultivation, there will be no biodiversity change. On bio-forestry land, the biodiversity decreases slightly, because of the high current biodiversity on those lands. With a loss of 0.2 (40%), the decrease is however less than the decrease in the wheat chain. Also on pasture land, the switchgrass cultivation leads to a decrease. The biodiversity is expected to decrease with 0.4 (-58%)




.***Figure 4.6:*** *Biodiversity change as compared to the current MSA, comparing the current agricultural system with wheat (left) switchgrass (right) cultivation.*

The main uncertainty of the biodiversity assessment, stems from the estimation of the intensiveness of the current management regimes on agricultural land. The implications of the uncertainty will be discussed in paragraph 5.3.

## *4.4 Soil*

To assess the soil criterion, the soil organic matter, the wind erosion and the water erosion are taken into account.

<u>Soil organic matter</u>
The change in soil organic matter shows a similar pattern to the change of soil organic carbon. The Soil organic carbon change, as described in paragraph 4.1 should therefore be regarded as an indicator for both criteria.

<u>Water erosion</u>
The annual soil loss related to water erosion will be calculated with the RUSLE equation. Taking the monthly rainfall erosion index (R – figure 4.7) into account, it can be derived that the potential soil loss is highest in July. Consequentially, the results in this paragraph will focus on July.

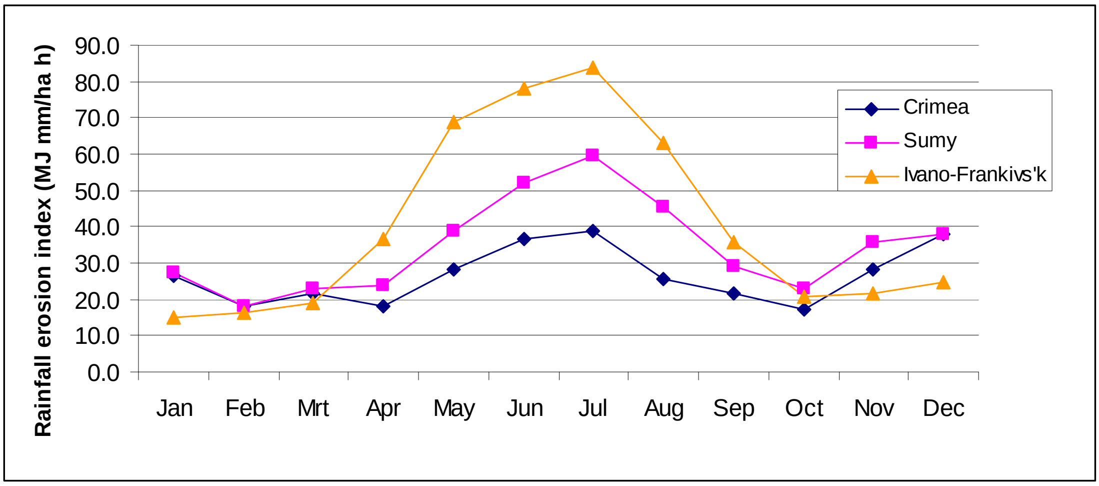



***Figure 4.7:*** *The differentiation of the average rainfall erosion index of three Ukrainian.*

The results from RUSLE are depicted below:

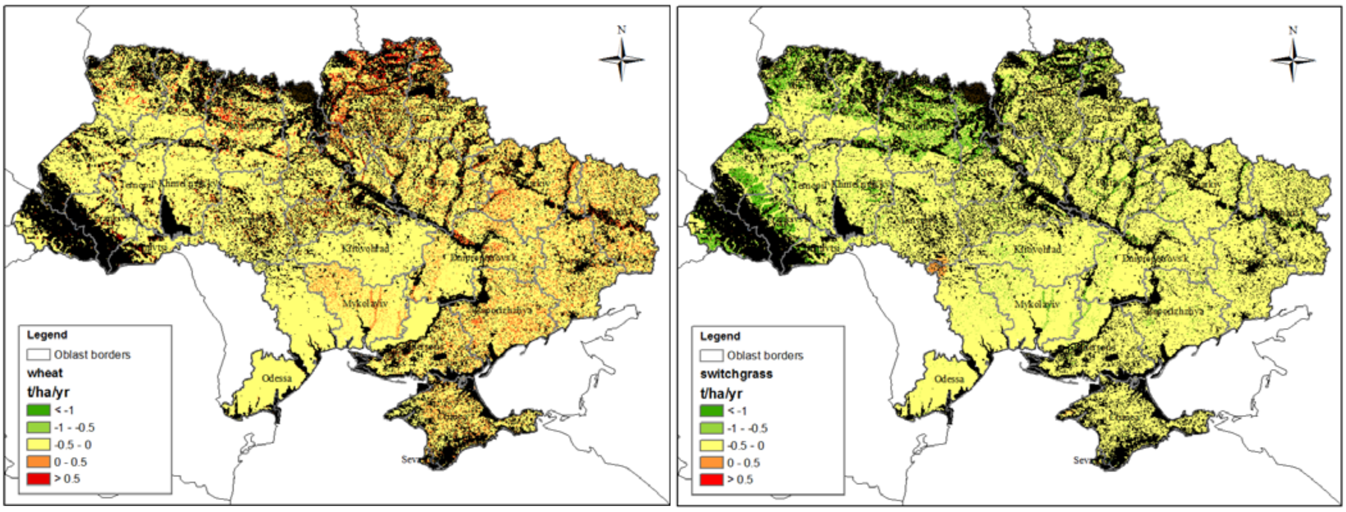



***Figure 4.8:*** *The increase of the soil loss due to water erosion in the wheat (left) and switchgrass (right) bioethanol chains in t/ha/yr.*

The water erosion risk is mainly dependant on the slope gradient and the precipitation. Areas with a low slope gradient (<2.5%) are only slightly influenced by water erosion. The conversion of these slopes to bioenergy crops will therefore not yield large changes in the erosion risk (< 1 kg/ha/yr).

The cultivation of wheat on arable land on moderately sloped (2.5-5%) areas, does not lead to a significant change of the water erosion risk. This can be explained by the similarity in the crop characteristics and management regime between the current crops and the wheat. If wheat is cultivated on pasture land, the potential soil erosion will increase up to 0.5 t/ha/yr. The increase is related to the crop factor of pastureland, that is even smaller then the crop factor of wheat. Besides the crop type factor, the increase is also caused by the change in the tillage regime. The no-tillage regime of pasture land prevents the exposure of the soil to heavy rain showers. If the grass is replaced by wheat, the tillage regime changes to full tillage, leading to an increased erosion risk. In the Northern oblast (Volyn, Rivne, Zjitomir, Kiev and Chernihiv) the erosion risk is larger than in the Southern oblast. Although the Northern oblasts  are not very mountainous, they are susceptible to water erosion, because of the clayish Podzoluvisol soils that covers a large part of the area. The cultivation of the moderately sloped pastures in the Northern oblasts, leads to a potential loss of  up to 1.5 t/ha/yr.

If moderately sloped arable land is converted to switchgrass, the erosion risk will decrease with approximately 0-1 t/ha/yr. This is mainly caused by the reduced tillage, as compared to the current situation. Switchgrass also has a considerable root system, that keeps the soil particles together. In the Northern oblast the reduction of the soil loss can add up to 2 t/ha/yr. On pasture land, the crop specific characteristics of switchgrass are assumed to match the characteristics of pastures. Also the tillage regime remains the same. Consequentially, the water erosion risk remains unchanged in both the Southern and Northern oblasts.

In mountainous areas, the changes of the water erosion risk is largest. Although most of the mountains in Ukraine are covered with forest, a small fraction of Ukraine's pasture land is situated on sloped areas with a gradient of over 5%. The majority of the cultivated slopes are located around the Carpathians and the Crimea mountain range. On arable land, that is seldom situated on steep slopes, wheat cultivation can potentially mitigate up to 1 t/ha/yr. Pasture land is more often situated on steep slopes. The additional emissions can arise to a maximum of 8 t/ha/yr. In the case of switchgrass cultivation on sloped arable land, the benefits can arise to a maximum of 0.5 t/ha/yr.

The main uncertainties of the water erosion analysis include the applicability of an annual crop factor, the applicability of a German rainfall erosion index. Furthermore, also the slope adds to the uncertainty, as various gradients can occur within the 860x860m resolution that has been used in this analysis. The implications of the uncertainties will be discussed in paragraph 5.4.

Wind erosion

To determine the most sensitive period for wind erosion, Kiev's monthly climate factor has been compared with the monthly vegetation factor for the Kiev oblast. According to the assessment, that can be reviewed in figure 4.9, March is the most critical month for wind erosion in Ukraine. In this month, the wind speeds are high (3.4-5.7 m/s), and the precipitation is still relatively low (8-60 mm/month). Because of the rising temperature (7-14 °C), the soil is no longer frozen or snowed under. Furthermore, the vegetation is still relatively small, as compared to May and September/October, which also have a high climate factor. As the potential soil loss in highest, all further wind erosion results will be calculated for March.

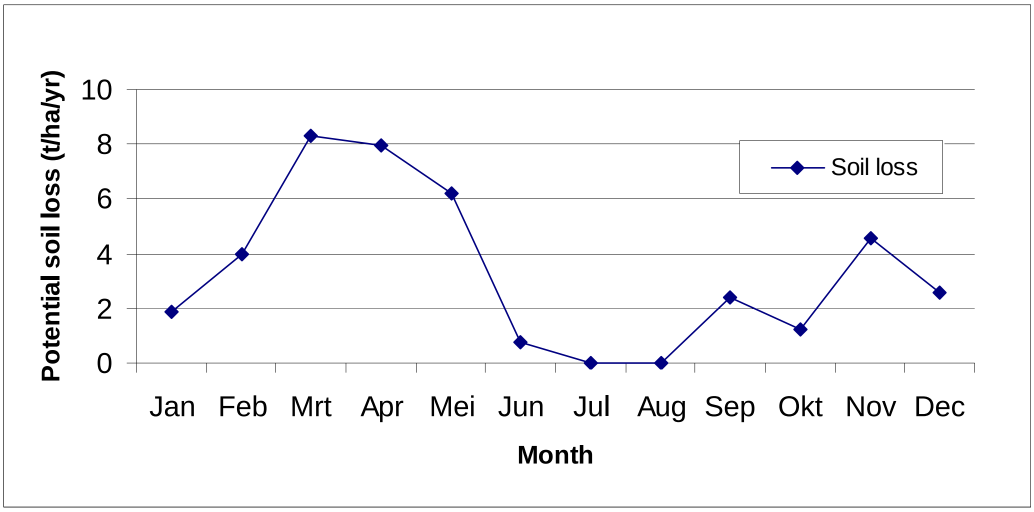
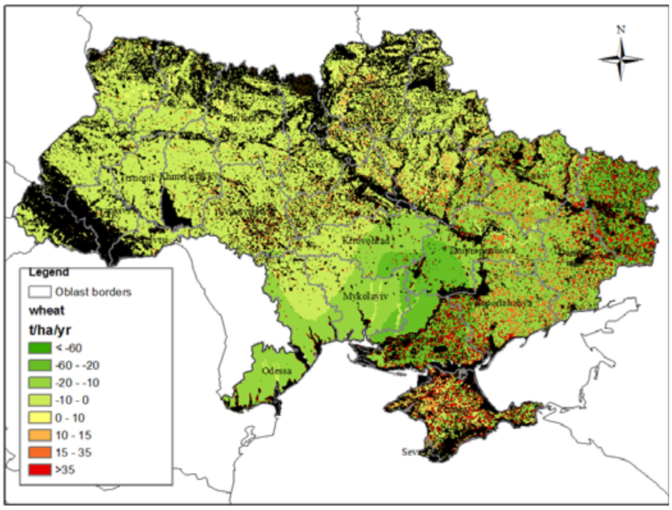



***Figure 4.9:*** *Current soil loss due to wind erosion on arable land in Kiev ($L=L_0$, $I=128$, $K=0.77$ .)*

The wind erosion has been assessed with the Wind Erosion Equation. The results from this equation are depicted in figure 4.10.



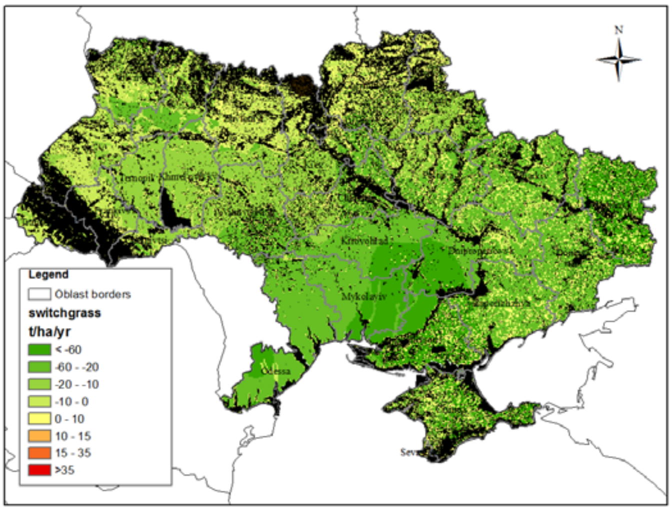




***Figure 4.10:*** *Additional soil loss due to wind erosion in the wheat (left) and switchgrass (right) bioethanol chains.*

From the figure it can be derived, that the cultivation of wheat on current arable land leads to a decrease of the wind erosion risk with approximately 1-35 t/ha/yr. The decrease is caused by the wheat's growth characteristics and it's management regime. As the wheat is sown in fall, it has a higher biomass density in March than most current crops. The strongest reductions are achieved in the South-Western oblasts, as the high wind speeds in those areas lead to a higher initial soil erosion. Because of this, also the mitigation effect is higher. If wheat is cultivated on current pasture land, the wind erosion risk increases. In March, pasture land has a higher biomass density per hectare than wheat. The increase ranges from 7-75 t/ha/yr. Also for the pasture land, the change is highest in the South-West of Ukraine.

The cultivation of switchgrass on current arable land leads to an decrease of the wind erosion risk. As switchgrass is harvested during the end of March, it has a large amount of biomass during the majority of the month. Consequentially switchgrass cultivation leads to a reduced soil loss of 4-110 t/ha/yr. If switchgrass is cultivated on pasture land, the wind erosion risk will not be affected, as the vegetation factor switchgrass is assumed to be the same as grassland.

The main uncertainties of the wind erosion analysis include the accuracy of the vegetation factor and the influence of the excluded soil sedimentation. The implications of the uncertainties will be discussed in paragraph 5.4.

## *4.5 Water*

Water quantity

To assess the water quantity, the current water deficiency was compared with the water deficiency of the bioenergy crops, during the driest period of the year. To determine this period, the water shortage has been calculated per month, for three Ukrainian oblasts. The results of this comparison can be seen in figure 4.11.

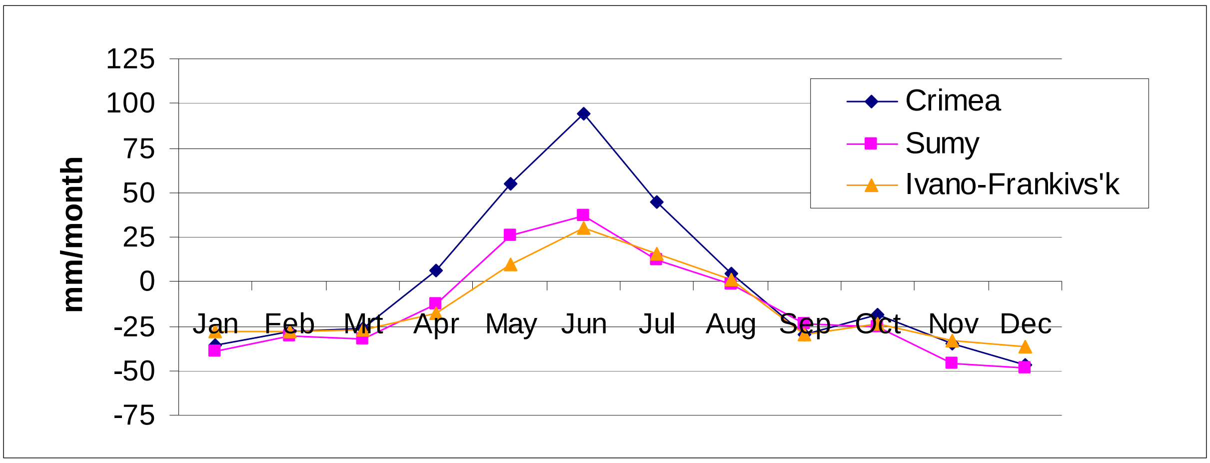



***Figure 4.11:*** *Water shortage on current arable land of three oblasts per month.*

As can be seen from the monthly water shortages in the figure, the driest period in Ukraine occurs from the end of July until the middle of August. As the shortage does not occur in a fixed timeframe, the water shortage of each ha will be calculated when the water shortage is largest at that specific location.

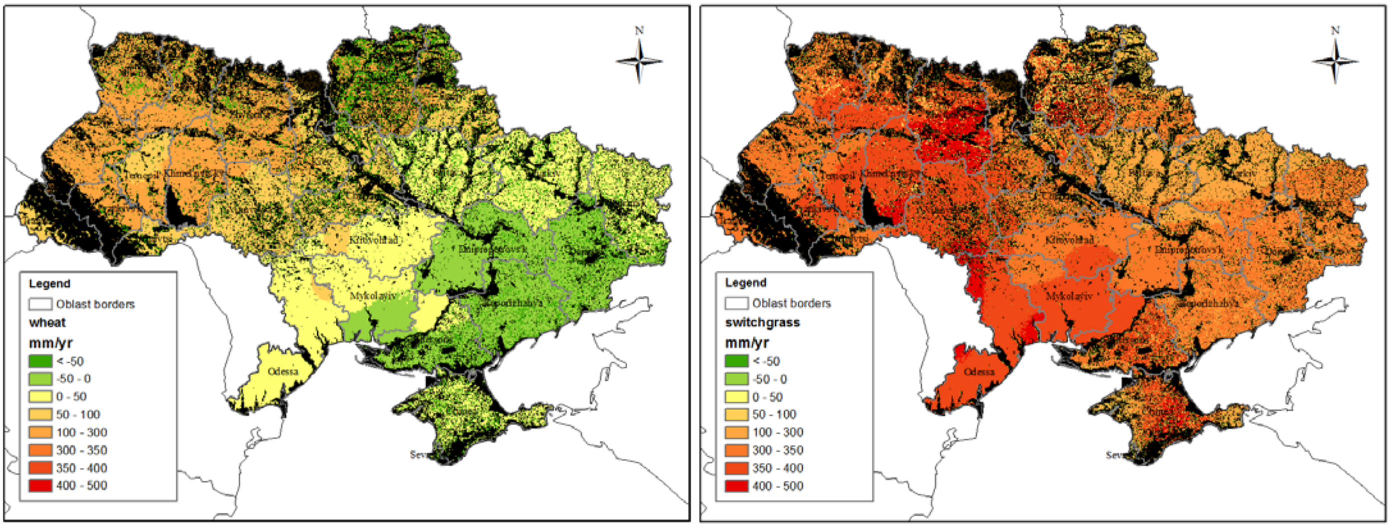



***Figure 4.12:*** *Difference, compared to the current situation, of the maximum average water deficiency (in mm), for the wheat (left) and switchgrass (right) bioethanol chains.*

The change of the maximum water shortage has been depicted in figure 4.12. If wheat is cultivated on arable land, the deficit can be increased or decreased. In the North-Eastern oblasts, the deficit tends to increase with a maximum of 170 mm/yr. The main reason for the increase is the low current water shortage, caused by the cultivation of crops like potatoes, onions and cabbages, that evaporate relatively small amounts of water. If the current crops are replaced with winter wheat, the evapotranspiration will increase, leading to a larger shortage. In the Southern oblasts, the precipitation is less than in the Northern oblasts, leading to higher current water shortages. Furthermore, there are relatively low amounts of potatoes, and large amounts of sunflowers. Sunflowers evaporate relatively large amounts of water, therefore adding to the current shortage. If the crops are replaced with wheat, the water shortage will decrease with a maximum of 20 mm/yr. If pasture land is cultivated, the water shortage tends to decrease in all oblasts. The decrease ranges from 100-250 mm/yr. It is caused by the high specific evaporation of grass, which leads to a high current water shortage.

If switchgrass is cultivated on current arable land, the water deficiency increases with approximately 300-400 mm/yr. The increase is caused by the high specific evaporation of switchgrass. Furthermore, because of the low precipitation level in the Southern oblasts, the water shortage of switchgrass plantations occurs in a relatively long period of the year, stretching from March to October. If pasture land is used for switchgrass cultivation, the water shortage increases with approximately 100-150 mm/yr.

Although switchgrass uses a lot of water, the water use efficiency is much higher then for most other crops, including wheat. More information about the water use efficiency can be found in table 29, appendix 1.6.

The main uncertainty in the water quantity analysis is the accuracy of the interpolated reference evapotranspiration. The implications of the uncertainty are described in chapter 5.5.

<u>Water quality</u>
To assess the water quality, Miterra-Europe has been used to analyse the theoretical concentrations of $NO_3$ in the soil water. To understand the differences in the $NO_3$ concentrations, the current situation will be discussed first.

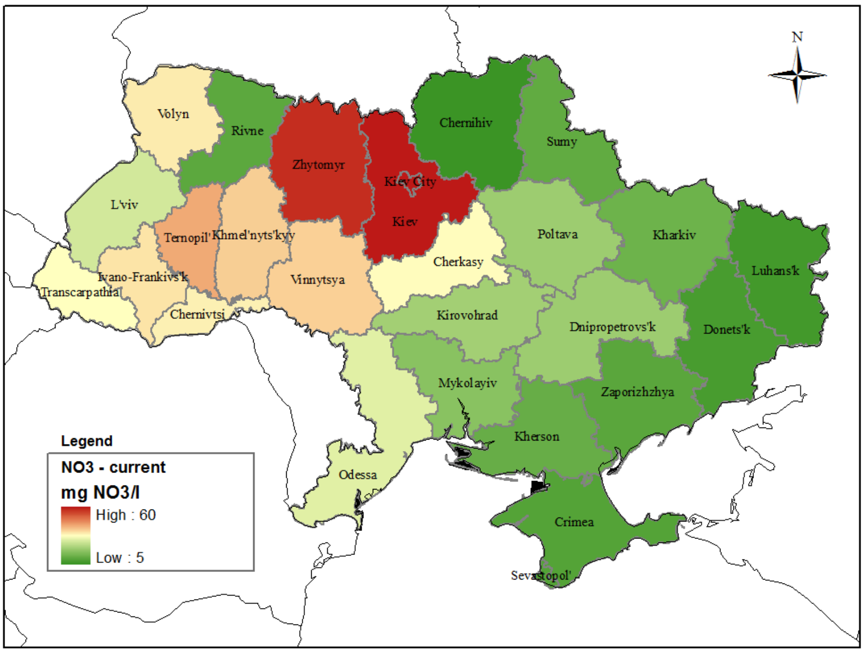



***Figure 4.13:*** *The current $NO_3$ concentration of the groundwater (mg $NO_3$/l), as derived from Miterra.*

From figure 4.13, it can be seen that the current $NO_3$ concentration varies considerably per oblast. The concentration depends on the difference between the nitrogen input, and the N output. The input of nitrogen mainly depends on the fertilization rate. Consistent with the figure, the fertilization of both organic and mineral fertilizers is highest in the North-West and lowest in the South-East. The N-output mainly depends on the N runoff, the harvest of biomass, and the leaching factor.

If the current crops are replaced with wheat and switchgrass, also the $NO_3$ concentration changes. In Miterra, the main changes include the mineral fertilization regime, the crop type distribution, and the runoff factor. However, many of the modelled parameters, such as the climate- and the organic fertilization regime, remain unchanged. The concentrations change is depicted in figure 4.14.

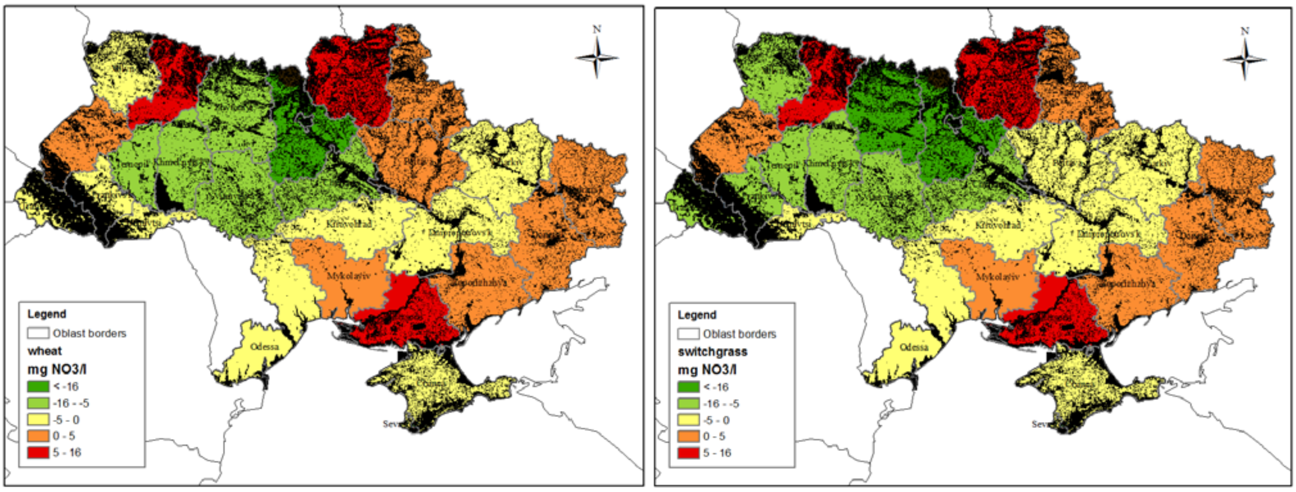



***Figure 4.14:*** *The change of the $NO_3$ concentration of the groundwater (mg $NO_3$/l) in the wheat (left) and switchgrass (right) bioethanol chains, as derived from Miterra.*

From the results, it can be seen that the oblasts with a high current concentration will experience a $NO_3$-decrease, and the oblasts with a low concentration experience an $NO_3$-increase. Consequently, the new $NO_3$ concentration is more balanced than the current concentration. The balancing can be explained because of the transition from an agricultural system with many crop types, to a system with a single crop. Nonetheless, there can still be considerable differences between the oblasts. The differences are mainly caused by differences in the N-surplus, that is caused by the variation of yield levels per hectare (N-uptake), and the application rates of organic and mineral fertilizers. Furthermore, also the precipitation influences the concentration, as it deludes the $NO_3$ concentration. Precipitation levels are highest in the North-Western oblasts.

If the results of wheat and switchgrass are compared, it can be derived that wheat cultivation leads to a slightly higher $NO_3$ concentration then the cultivation of switchgrass. Although the nitrogen input is higher during the cultivation of switchgrass, the high N-uptake during it's growth leads to a lower nitrogen content of the soil.

The main uncertainties of the water quality analysis are inherent to the use of the Miterra model. The implications of the use of Miterra are therefore described in paragraph 5.5.

# 5. Discussion

The assessments in this study include many assumptions and uncertainties. In this chapter, the extend and influence of these uncertainties will be discussed. First, paragraph 5.1 will elaborate on the accuracy of the main spatial datasets, that overarch the individual criteria. The four subsequent paragraphs will elaborate on the uncertainties of each specific criterion.

## *5.1 Main spatial datasets*

General
In this study, spatial datasets with different resolutions have been combined. As high-resolution data is in some cases combined with parameters with a lower resolution, the results section could give too optimistic impressions of the results' accuracy.

Land cover
One of the most influential parameters in this study is the land cover, that has been taken from the Corine database. The land cover data of Corine has been produced by remote sensing, during which a high resolution infrared instrument (HRVIR) is used to estimate the land cover at a certain location (EEA ). Remote sensing is however not flawless, as the infrared signature of different areas, such as forests, crops, natural grassland and man-made pastures, can be difficult to indentify. As a result, the land cover data may not always match the actual land cover on site. The effect of this uncertainty may be profound, as all of the environmental impacts are directly dependant on the current land cover. The uncertainty of the land cover is even further increased by the spatial resolution, as different land uses may occur within the 863x863 meter grid cells of Corine. Consequently, the visualisations of the results should be interpreted with care, as the current land use type at a certain location is not necessarily correct and may be heterogeneous in nature.

Climate
Also in the climate related datasets, that include precipitation, wind speed, evapotranspiration and temperature, the spatial resolution can cause uncertainties. The climate data has been gathered from climate stations, and is interpolated to increase the spatial resolution. However, local variations that may be caused by rivers, mountains, and cities, could not be identified by the interpolation. Therefore, the environmental impacts may not always be accurate on a local level.

Also the climate zoning in the GHG assessment adds to the uncertainty, as it creates artificial boundaries in the results, at the location were the climate zones converge. Consequently, the GHG emissions in the border areas may be under- or overestimated. Therefore, the results at the climate border areas should be interpreted with care.

Potential yield levels
Two other parameters that significantly influences the results, are the anticipated yield levels of wheat and switchgrass. The local yield levels can vary significantly from the oblast averages, based on differences in the local soil types, the soil acidity, and other parameters. To illustrate the local yield differences, figure 5.1 shows the suitability of the arable land for wheat cultivation, according to REFUEL estimations *{{101 Refuel 2008}}*. The oblast of L'viv has been chosen as a random example. From the figure it can be seen that the average productivity of the arable land of L'viv, has been estimated at 8.4 odt/ha/yr. However, approximately 75% of the land has a higher yield potential and 25% of the land has a lower yield potential.

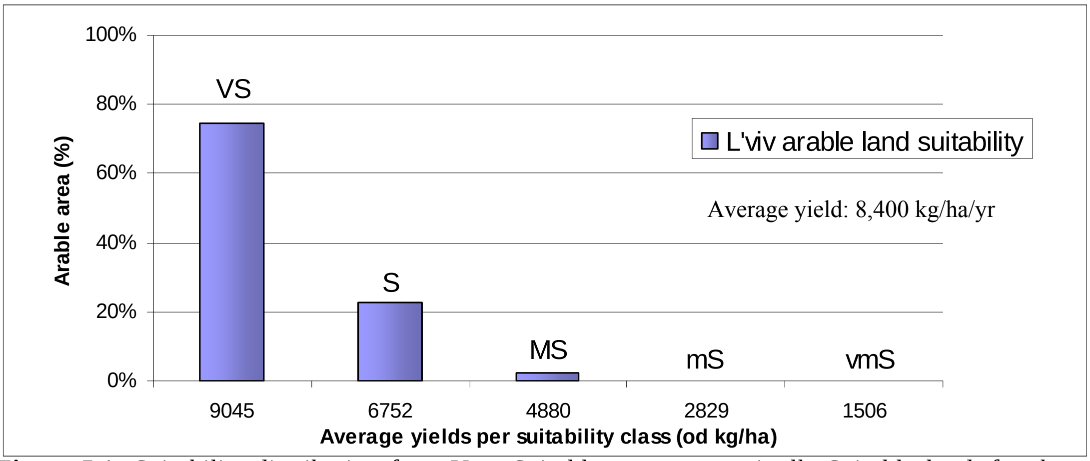



***Figure 5.1:*** *Suitability distribution from Very Suitable to very marginally Suitable land, for the cultivation of wheat on arable land for the oblast of L'viv, according to REFUEL estimations* (Refuel 2008).

As most of the environmental impacts are calculated per hectare, a lower yield level directly leads to a higher environmental impact per harvested tonne. Furthermore, also the absolute impacts can change. If the local yields are for example lower than the oblast-average, the absolute LUC emissions will be higher than the calculated result, as the amount of biomass on the field is less than was expected from the average. Furthermore, the vulnerability to water and wind erosion may be increased, and the water deficiency may be decreased.

Tillage and fertilization

The tillage and fertilization regimes of the current and future crop types, have not been taken into account on a spatial level. Nonetheless there may be considerable local differences.

For all current crops, a full tillage regime has been assumed. However in reality, approximately 25% of the arable land is under a reduced tillage regime (Lahmar 2006). If a reduced tillage regime is changed to a full tillage regime, the environmental impacts on the GHG balance, the biodiversity, the soil organic matter and the soil erosion may be severe. Therefore, as current land is taken as 100% full tillage, the environmental impacts of a conversion to bioenergy crops may be underestimated. On the other hand, if the bioenergy crops are also cultivated under a reduced tillage regime, the environmental impacts of a conversion of the 'full tillage lands' will be considerably less than estimated in this report.

In the wheat bioenergy chain, also the fertilization regime has been taken into account in a non-spatial way. In practice, the fertilization might be linked to the removal of nutrients from the system, and hence to the wheat's yield level. As the fertilization in this study has been assumed to be constant, due to a lack of data, the fertilization, and related impacts on the GHG-balance and water quality may be either over- or underestimated. The application of local data or the inclusion of field measurements, could significantly decrease the uncertainty.

## 5.2 GHG emissions

General

Research by Hoefnagels et.al (Hoefnagels, Smeets et al. 2008), and van Dam et.al. (Dam, Faaij et al. 2009) shows that the calculations of the LUC and the GHG emissions are very sensitive to the system boundaries, the input data and the allocation method. The results of the GHG analysis should therefore be interpreted with care.

Land use changes

The LUC emissions have been estimated on the basis of the tier 1 methodology from the IPCC. The main drawback of this method is the use of default factors, with uncertainty ranges of up to 90%. Furthermore, many relevant processes have been included in a simplified way[15]. A more thorough analysis with a tier 2, or tier 3

[15] Simplifications include for example the $N_2O$ emissions from the degradation of soil organic matter, that neglects the variations per soil and crop type. Further examples include the calculation of the reference soil carbon, that is only dependant on the climate zone and soil type; the influence of tillage and external inputs on the SOC, that is

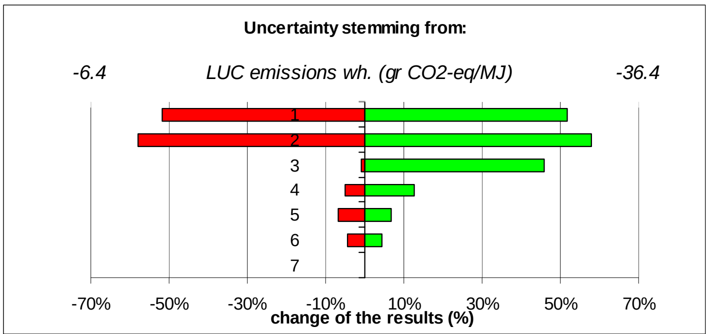
approach is recommended for a more accurate assessment (Hilst 2009, Smeets, Bouwman et al. 2010)(IPCC 2006a).

The LUC emissions have been calculated by assessing the changes of the above and below ground biomass, the SOC changes and the LUC related $N_2O$ emissions. One of the main uncertainties in the above/below ground biomass assessment, is the local distribution of the current crop types. Although an oblast specific average of the crop type distribution could be provided, the distribution on a local level is unknown. A more accurate biomass assessment could be done with more detailed data on the current crop type. Furthermore, the default biomass factors from the IPCC, that were used to estimate the biomass on pasture land, also add to the uncertainty. By using country- and soil specific factors, this uncertainty could be significantly decreased.

The main uncertainties in the SOC assessment, include the estimations of the reference SOC and the carbon flux, as both have error ranges of ±90%. Both parameters are based on default factors from the IPCC, that depend on the soil type and the climate zone. The uncertainty can be considerably decreased by applying country specific data, complemented with field measurements.

The main uncertainties of the $N_2O$ analysis involve the use of default IPCC residue factors and the use of default emission factors. As these factors have error margins up to 50%, and are not spatially differentiated, the uncertainty can be decreased by using country-, crop-, or soil specific data, and by including field measurements.

Figure 5.2 shows the impacts of the main uncertainties on the results. In the uncertainty assessment, the values of several key parameters are varied, according to their minimum and maximum value in Ukraine. Consequentially, the results from the initial analysis change with the percentage that is given in the figure.



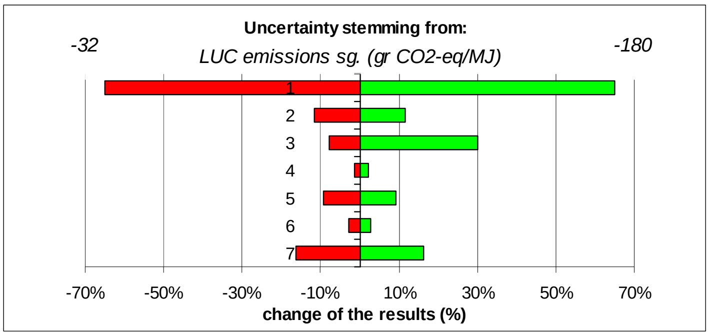




***Figure 5.2:*** *Uncertainty analysis of the land use change assessment for wheat (left) and switchgrass (right). Valid for arable land in Ivano-Frankivs'k, on HAC soils.*

*1. Reference SOC*

*The reference SOC was varied along it's error range of 90%, as provided by the IPCC (2006).*

*2. Input factor*

*The input factor of the current crop mixture, wheat and switchgrass, was varied along the minimum and maximum percentages, that are derived from the respective error ranges, as indicated in table 8, appendix 1.2 (IPCC, 2006).*

*3. Potential yield level*

*For Ukrainian wheat, the lowest oblast specific yield potential was estimated at 4.0, and the highest potential at 8.6 odt/ha/yr* (Refuel 2008). *For switchgrass, the lowest potential was estimated at 8.9, and the highest potential at 19.2 odt/ha/yr* (Refuel 2008).

*4. Converted crop type*

*The LUC emissions are also dependent on the current crop type. Therefore, the yield levels of the current agricultural system have been varied between 1.3-6.8 odt/ha/yr, representing the minimum and maximum current crop yield levels in Ivano-Frankivs'k (respectively sunflower and sugar beet)* (State Statistics Committee of Ukraine, Ostapchuk et al. 2009).

*5. Land use factor*

*The land use factor was varied along it's error range, indicated in table 8, appendix 1.2 (IPCC, 2006).*

*6. C-content*

*As the uncertainties regarding the C-factor are unknown, the factor was multiplied with 90-110% to estimate the impact of possible uncertainties.*

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only dependent on a default factor. Other simplifications can be found in the guidelines of the IPCC (IPCC 2006a).

7. *Management factor*

*The management factor was varied along it's error range, indicated in table 8, appendix 1.2 (IPCC, 2006).*

From the figure it can be seen that the largest uncertainty in the LUC assessment stems from the reference SOC. In the wheat chain, also the input factor adds to the uncertainty. In the switchgrass chain however, the uncertainty of the input factor is significantly smaller than in the wheat chain. The main reason for this is the smaller error range (IPCC, 2006) of the switchgrass I-factor, if compared to the I-factor for wheat. Furthermore, the relative influence of the input factor is lower in the switchgrass chain, because of the large increase of the biomass fixed carbon, that also contributes to the LUC change.

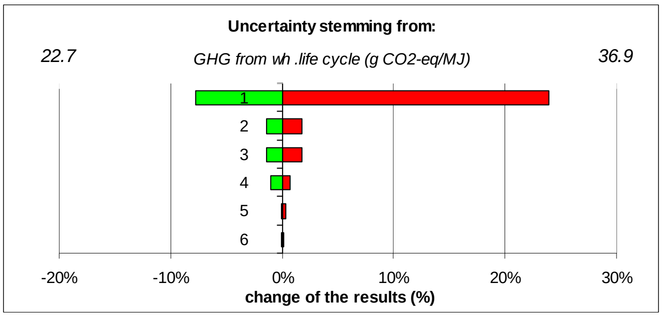
Life cycle emissions

The life cycle analysis has been performed by assessing the emissions from the cultivation, transport and conversion. The cultivation related emissions mainly depend on the application rates of seeds, fertilizers, pesticides and the use of diesel. Although a fixed application rate is assumed, there can be considerable differences in the rates that are applied on a local level. The ranges of the application rates are unclear.

The main uncertainty of the transport emission assessment, is the travel distance. The travel distance is directly related to the catchment area of each plant, which is mainly dependant on the number of plants and therefore to the average size of each plant.

The main uncertainties of the conversion step, are related to the number and size of the conversion plants. As Ukraine is currently not producing bioethanol in large quantities, the estimated size of the conversion plants is uncertain. Furthermore, the construction of the required number of plants may not be realistic in the given time span. In the case of switchgrass conversion, further uncertainties stem from the technical feasibility and cost-effectiveness of lignin-cellulosic biomass conversion. As second generation bioethanol production processes are currently not commercially available on a large scale, it is questionable if the extensive production of switchgrass ethanol is feasible before 2015 (Gnansounou 2010).

To quantify the uncertainties in the life cycle assessment, figure 5.3 shows the impact of the uncertainty on the results. In the uncertainty assessment, the values of several key parameters are adjusted, according to their minimum and maximum value. Consequentially, the results from the initial analysis change with the percentage that is given in the figure.



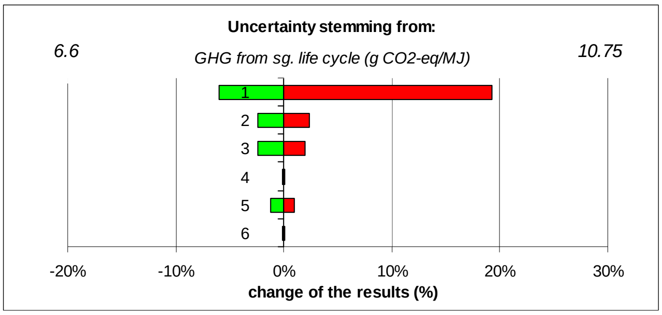




***Figure 5.3:*** *Uncertainty analysis of the life cycle assessment for wheat (left) and switchgrass (right). Valid for arable land in Ivano-Frankivs'k, on HAC soils.*

1. *Potential yield level.*

*For Ukrainian wheat, the lowest average yield potential per oblast was estimated at 4.0, and the highest potential at 8.6 odt/ha/yr* (Refuel 2008). *For switchgrass, the lowest potential was estimated at 8.9, and the highest potential at 19.2 odt/ha/yr* (Refuel 2008).

2. *Fertilizer application rate*

*As the uncertainties of the fertilization regime are unknown, the fertilization rates of wheat and switchgrass were multiplied with 90-110%.*

3. *Diesel (machinery) application*

*As the uncertainties regarding the use of diesel are unknown, the diesel use of the cultivation phase was multiplied with 90-110%.*

4. *Transport distance*

*The transport distance (by road) was varied between 1-59 km, to include all locations in the 50 km (strait line) radius of each conversion plant.*

5. *Pesticide application rate*

*As the uncertainties of the pesticide application are unknown, the pesticide use was multiplied with 90-110%.*

*6. Seed application rate*

*For wheat and switchgrass, the fertilization rate was multiplied with 90-110%.*

As can be seen from the figure, the main uncertainty in the biofuel chains stems from the potential yield levels. As the yield levels vary significantly within Ukraine, locally explicit yield estimations are required to decrease the uncertainty. The second source of uncertainty stems from the application of fertilizers and diesel. As the variability of these substances is based on estimations, further research is recommended to validate the application rates.

Besides the parameter related uncertainty, further inaccuracies stem from the use of the life cycle methodology. On of the main methodological inaccuracies is the exclusion of organic fertilizers. Although manure is only applied on 3.6% of the arable land, the exclusion of organic fertilizers may to lead to an underestimation of the GHG emissions, due to the relatively high $CH_4$ and $N_2O$ emissions of manure.

## 5.3 Biodiversity

The biodiversity has been assessed by the mean species abundance (MSA). Even though the MSA is a commonly used indicator (PBL 2009), it has several drawbacks that strongly influence the accuracy of the results. As the MSA only takes original species into account, the settlement of new species is disregarded. Consequently, the biodiversity loss that is caused by the cultivation of bioenergy crops, may be overestimated. Furthermore, also soil animals, reptiles and amphibians are not taken into account, adding to the uncertainty of the results.

Another drawback of the MSA, is its incapability to include local variations of the biodiversity. As the MSA factors are allocated per land cover class, the methodology does not account for diversity within the land cover types. Crop specific characteristics, soil types, management regimes, and climate parameters are not included into the analysis. As a consequence, the arable land in for example Sweden or Portugal, has the same MSA value as the arable land of Ukraine. Although the results of this study cannot provide a detailed local biodiversity assessment, they can be used to quantify the general effect of a shift to bioenergy crops.

A further uncertainty in the biodiversity assessment is caused by the intrinsic intensification of the agricultural sector in Ukraine. Although the conversion to bioenergy crops involves a change from extensive to intensive agriculture, intensification may also take place if the land is not converted to bioenergy crops (Wit, Faaij 2008). Furthermore, as bioenergy crops can only be cultivated on free land, an overall land intensification step is required before the crops can be sown. Consequently, the decrease of the biodiversity due to bioenergy crop cultivation, might be significantly overestimated. To visualise the possible impact of this uncertainty, the MSA change due to the conversion of both extensively and intensively managed arable land to wheat and switchgrass, have been depicted in figure 5.4.

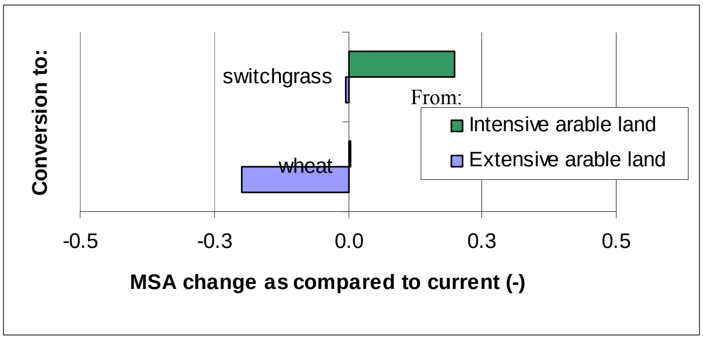



***Figure 5.4:*** *The MSA change, for the conversion of intensively and extensively cultivated arable land to intensive wheat and switchgrass cultivation.*

Although the MSA can provide a qualitative indication of the biodiversity changes, caused by a land use change, an accurate quantitative analysis on a local level cannot be achieved. Further research, including field measurements, is required to include an accurate representation of the current MSA. Additional research is required to determine the rate of the agricultural intensification, and it's effects on biodiversity.

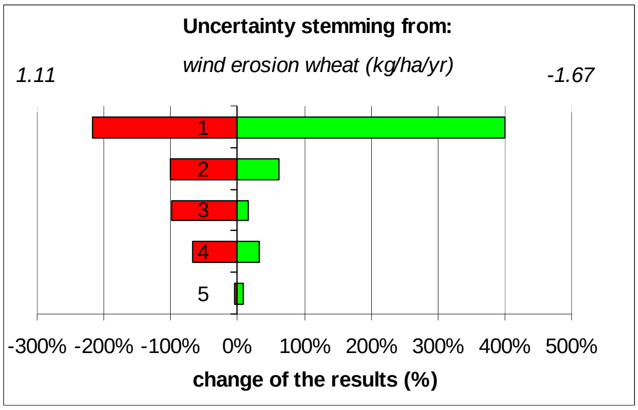
## 5.4 Soil

Soil organic matter

The main uncertainties in the soil organic matter calculation, is the applicability of the soil organic carbon as a proxy. Further uncertainties regarding the calculation of the soil organic carbon, can be found in paragraph 5.2.

Water erosion

The water erosion has been calculated on the basis of the RUSLE equation. The uncertainty analysis of the main parameters of RUSLE, have been depicted figure 5.5.



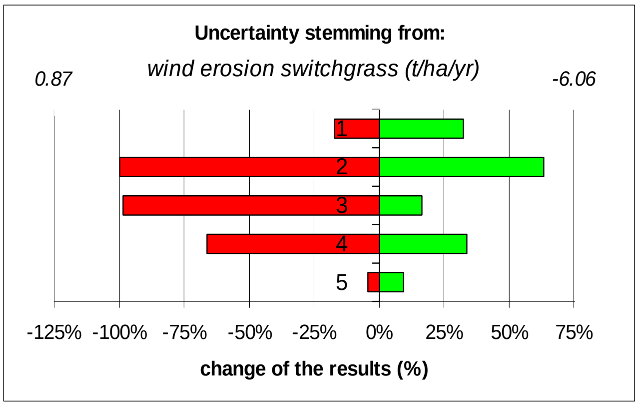




***Figure 5.5:*** *Uncertainty analysis of the water erosion assessment for wheat (left) and switchgrass (right). Valid for arable land in Ivano-Frankivs'k, on HAC soils, with a slope of 5%.*

*1. C-factor*

> *The crop factor, that describes the crop related erosion vulnerability, has been varied between 0.315-0.5, representing the minimum and maximum C-factors in Ukraine. The value 0.315 represents the least vulnerable system, which encompasses cereal cultivation under a spring tillage regime. 0.5 represents the most vulnerable system, encompassing corn/beans/canola cultivation under a fall tillage regime.*

*2. Ls. Factor*

> *The Ls-factor represents the slope gradient. As the slope data was available on a detailed level (50x100m), the data had to be resampled on a 850x850 grid, for the including into the analysis. To analyse the uncertainties, that stem from the resolution decrease, the highest and lowest slope within the assessed gridcell have been analysed. Hence, the Ls-factor has been varied between 0.09-1.06, representing slopes of 0.5-10%.*

*3. Precipitation*

> *The precipitation has been varied between 15-120 mm/year, representing the minimum and maximum precipitation in Ukraine in July.*

*4. P-factor*

> *It is assumed that the agricultural practice factor does not change during the conversion to bioenergy crop cultivation. However, as the agricultural practice factor can vary per location, a range from 0.25-1.00 has been taken into account. The value of 0.25 represents an involved farmer, using representing strip cropping to prevent soil erosion. The value of 1.00 represents an uninvolved farmer, that uses up&down cropping patterns, unaware of soil erosion problems.*

*5. K-factor*

> *The main uncertainty of the K-factor stems from the uncertainties regarding the soil organic matter. A high organic matter content decreases the vulnerability for water erosion. Depending on the SOM, the K-factor can vary between 0.21-0.24.*

As can be seen from the figure, the main uncertainty in the water erosion analysis stems from the crop factor (in the case of wheat) and the Slope factor (in the case of wheat switchgrass). Furthermore also the rainfall erosion index and the P-factor include considerable uncertainties.

Besides the parameter related uncertainty, there is also a methodological uncertainty. On of the main methodological uncertainties of the water erosion assessment is the calculation of the rainfall erosion index. As the R-factor was based on an empirical equation from Germany, it is uncertain if the factor is accurate for Ukraine. A further drawback of the R-factor is that it is based on a single monthly average. Consequently, it is unsuitable to predict specific erosion events associated with single storms (USDA 2002). An incidental storm, that lasts for a few hours, can have a significant impact on the soil loss. As the rainfall factor is the main driver of water erosion, further research is advisable.

Another uncertainty in the water erosion calculation is the crop management factor (C). In this study the C-factor is taken as an annual average. However, as the C-factor is determined by the vegetation cover, land management and the canopy cover, it is expected to vary significantly throughout the year. By applying the average annual C-factor in July, the C-factor is underestimated, leading to an over-estimation of the water erosion. Furthermore, as the most vulnerable period is determined by a combination of the precipitation and the C-factor, it is uncertain if July is indeed the most vulnerable month. Although the C factor is estimated to be low in July, the precipitation peaks in July, and decreases considerably in the preceding and subsequent months. It is therefore uncertain how the water erosion risk would be influenced with a monthly C-factor. Research is advised.

Wind erosion
The climate factor of the WEQ is analysed on a basis of long term monthly data. Therefore, it inherently underestimates the erosion risk, as it's parameters are balanced out over the month. An incidental storm, that has a significant impact on the soil loss, may be invisible in the monthly wind velocity data. A day-to-day erosion assessment would be more accurate to analyse the influence of peaks in the soil erosion.

To estimate the vegetation factor, USDA growth factors have been combined with the crop planting dates. As the growth curves are valid for the US, they are assumed to be applicable to a wide range of agricultural systems and landscapes. Because of this range, they are also assumed to be applicable for Ukraine. However, to improve the quality of the analysis, further research is required to include crop specific V-factors, that are exclusively applicable to Ukraine.

Although the wind erosion is estimated to increase with a maximum of 75 t/ha/yr, the actual soil loss will be less, as sedimentation has not been taken into account (van Beek November 2010). Although the results can estimate the magnitude of the soil displacement, they cannot be used to quantify the actual soil loss at a specific location. Additional research, including the sedimentation, is required to quantify the exact soil loss.

## *5.5 Water*

Water quantity
To calculate the monthly precipitation deficit, a simplified water balance has been constructed, on the basis of the monthly precipitation and the crop related evapotranspiration. The uncertainty analysis of the main parameters of this method, has been depicted figure 5.6.

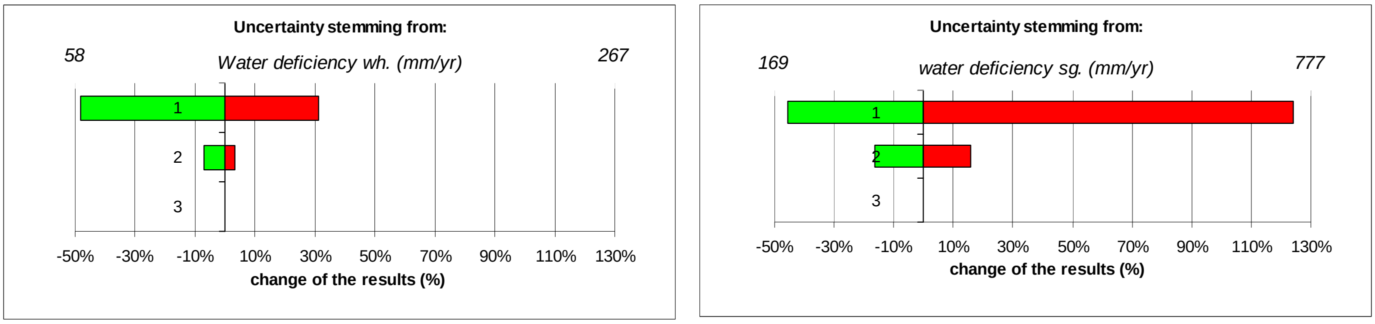



***Figure 5.6:*** *Uncertainty analysis of the water quantity assessment for wheat (left) and switchgrass (right). Valid for arable land on the border of L'viv and Ivano-Frankivs'k.*

*1. Reference evapotranspiration ($ET_o$)*

*The reference evapotranspiration has been varied between the minimum and maximum monthly $ET_0$-values, that where calculated by the interpolation of the data from the CROPWAT database. The minimum values varied between 0.11-3.73 mm/month, and the maximum values varied between 1.32-5.06 mm/month.*

*2. Crop evapotranspiration coefficient (Kc)*

*The Kc-factor has been multiplied with 90-110%.*

*3. Effective precipitation*

*The effective precipitation has been varied between 10-150 mm/mnd, representing the minimum and maximum monthly effective precipitation in Ukraine.*

From the figure, it can be seen that the main uncertainty of the current water quantity analysis is the reference evaporation coefficient ($ET_0$). As $ET_0$ has been based on 12 climate stations, an interpolation was required to estimate $ET_0$ in Ukraine. Consequently, accurate local variations in $ET_0$ could not be included in the research. The precipitation level does not lead to uncertainty. The reason for this, is the calculation of a water deficiency difference, as opposed to the absolute water deficiency. As the precipitation level is assumed to remain the same, before and after the conversion to bioenergy crops, the absolute precipitation does not lead to differences in the results.

Besides the parameter related uncertainty, there are also methodological uncertainties. Although a theoretical water deficiency can be calculated, also other factors, such as the current water table and the ground- and surface water flows should be taken into account. Furthermore, the water levels are often regulated by an extensive system of dams and levees, that control the level on a local scale. The precipitation deficit is therefore only an indication to where droughts might occur, and does not provide insides in the actual occurrence of droughts, or the damage of these incidents. As the modelling of the Ukrainian water system is beyond the scope of this research, more research is advised to provide more accurate insides in the occurrence of water shortages.

Another methodological source of uncertainty stems from the monthly Kc factor, that is related to the crops planting date and growth curve. As the planting dates and the growth curves are based on US data, this can lead to inaccuracies in the Kc value. It is assumed that the growth curves are applicable to Ukraine, as they also cover the range of the American agricultural systems. However, the accuracy of the analysis could be improved by the inclusion of more accurate Kc values.

Water quality

The water quality has been assessed by the Miterra-Europe model. The primary uncertainties of Miterra are related to the simplifications of the agricultural system, the linearly modelled N-flows, and the models algorithms. Furthermore, also the input data adds to the uncertainty, as it is based on many different sources, and includes many assumptions and approximations. Unfortunately, the structure of Miterra did not allow for a quantitative assessment of the uncertainties in the input variables. More detailed information on the Miterra input data and methodology can be found in Veldhof et.al. (Velthof, Oudendag et al. 2007).

Although the $NO_3$ concentration has been estimated by the Miterra model, other pollutants such as Phosphorous, Potassium and agricultural chemicals, could not be included in the water quality assessment. Although it is expected that the phosphorous fraction will follow a similar trend as the N-surplus (Lesschen 2010), further research is required to quantify the influence of the pollutants.

## *5.6 Actual vs. theoretical impacts*

In the results section of this study, an increased impact is always marked as being negative. However, a negative change does not necessarily have to be a disadvantage. If for example the water quantity decreases, it is only a disadvantage if the decrease causes a water shortage which affects other crops. In addition, a decreased water table may also affect the other criteria, such as the carbon stock, the biodiversity or the soil erosion. In this study the inter-linkages of the various criteria have been disregarded.

# 6. Conclusions

In this report, the environmental impacts of bioethanol production from wheat and switchgrass have been spatially assessed for Ukraine, in order to answer the following research questions:

- *Can the variations of the environmental impacts be assessed in a spatially explicit manner, using the methodology by van der Hilst, 2009?*
- *What are the spatial variations of the environmental impacts of potential winter wheat and switchgrass bio-ethanol chains in Ukraine?*
- *What are the differences between environmental impacts of wheat and switchgrass bio-ethanol?*

Green house gas balance
The LUC emissions were calculated according to the IPCC methodology. By using a spatial representation of the attainable crop yields, the soil, the landuse and the climate, the method is found to be suitable for a spatial analysis. However, because of the large uncertainty of several parameters in the assessment, only a qualitative comparison between regions can be provided. The emissions from the life cycle are not assessed in a spatially explicit way, as they are only depending on the crop type.

In accordance to the EU regulations for 2015, the maximum GHG emission of bioethanol may not surpass 65% of the emission of fossil gasoline. The maximum allowed GHG emission from bioethanol is therefore set at 45 g $CO_2$-eq/MJ $LHV_{ethanol}$. Although further research is necessary to determine the actual on-site emissions, this research indicates that the production of wheat bioethanol on pasture land exceeds this limit. Based on the above criterion, this ethanol cannot be exported to the European Union. Especially on the pastures on organic soils, wheat production should be prevented, due to the large GHG emissions that occur during a land use change. Wheat production on arable land is not expected to exceed the 65% limit, and therefore passes the GHG criterion.

On the basis of the GHG analysis, it can be concluded that switchgrass ethanol produces significantly lower GHG-emissions than wheat ethanol. In all cases, except for the cultivation on organic pasture land, the GHG-mitigations of the land use change, exceed the emissions of the cultivation and conversion phase, leading to a net negative emission. The GHG criterion for switchgrass bioethanol is therefore met. The largest emission mitigation is achieved during the production of ethanol from switchgrass on organic arable land.

Biodiversity
The biodiversity has been assessed with the mean species abundance (MSA). From the analysis, it can be concluded that the cultivation of bioenergy crops leads to a decrease of the biodiversity, with the exception of switchgrass cultivation on arable land. For both crops, the decrease is worst on grasslands. In comparison, switchgrass leads a lower biodiversity decrease than wheat, because of the less intensive management regime of switchgrass.

Although the MSA has been specifically designed for spatial analysis, a more specific method is recommended for future research, as the MSA is not able to grasp local differences. Although the general biodiversity trend can be depicted, the influence of the climate, soil, crop type and crop management should be included to provide a more accurate picture.

Soil organic matter
As the soil organic matter content could not be accurately modelled, the soil organic carbon (SOC) content has been used as a proxy. The soil organic carbon content was calculated by the IPCC methodology. By using spatial representations of the soil type, the climate and the land use, the method is assumed to be suitable for a spatial analysis. However, because of uncertainty issues concerning the local current crop management practices, only a qualitative comparison between regions could be provided. For future research, a more local analysis is advised.

From the SOC analysis, it can be concluded that the cultivation of wheat or switchgrass on arable land, leads to a modest increase of the soil organic matter. The increase is largest in the Northeastern oblasts, and on the Crimean peninsula, caused by the moist climate in those regions. If wheat is cultivated on pasture land, the soil organic matter decreases. Also the cultivation of wheat on organic soils should be prevented, due to the large soil organic matter flux that is caused by the wheat's management regime. As switchgrass has a low-tillage regime, it can be cultivated on pasture lands or organic land without a soil organic matter loss. On arable organic land, the cultivation of switchgrass should be encouraged, because of the benefits to the carbon flux and related soil organic matter stock.

Water erosion

The water erosion has been assessed with the RUSLE equation. The main spatial components include the precipitation, the slope gradient and slope length, the soil type and the crop type.

The general influence of water erosion in Ukraine is relatively low, because of the low precipitation levels of on average 570 mm/yr. Also, the majority of the sloped areas are used for natural purposes, leaving a relatively small part for agriculture. Following the natural precipitation pattern, water erosion is estimated to be highest in July. If wheat is cultivated on sloped arable areas, the water erosion does not change, due to the similarities of the wheat to the current crops type. If wheat is cultivated on pasture land, the soil erosion increases, because of the increased tillage regime, and because of the ability of grass to bind the soil with it's extensive root system. Switchgrass cultivation on sloped arable areas leads to a decrease of the soil erosion, because of it's low-tillage regime and it's large root system. If switchgrass is cultivated on pasture land, the erosion will remain unchanged.

As the crop type factor could only be described by an annual average, it was not possible to attain accurate monthly results. Therefore only a qualitative comparison could be made. For future analysis, more research is advised to find local crop type factors, leading to the improvement of the spatial results for water erosion.

Wind erosion

The wind erosion has been assessed with the wind erosion equation. The main spatial parameters are the precipitation, temperature and wind speed, the soil type and the crop type. The wind erosion is also depending on specific crop development data. In this study the crop development data have been taken from US research, and adapted to Ukraine according the local planting and harvesting dates. However to improve the quality of the spatial analysis, local validation of the growth curves is advised.

Research has shown that the Ukrainian wind erosion is highest in March. In this month, the wind speeds are high and the vegetation is low. Both the cultivation of wheat and switchgrass leads to a decrease of the wind erosion, because of an increase of the biomass stock, as compared to the current biomass in March. As switchgrass provides more biomass than current wheat, the wind erosion decreases most during switchgrass cultivation. For both crops, the decrease is highest in the South-Eastern oblasts, as the current erosion risk is highest there. If pastures are used for the cultivation of wheat, the wind erosion tends to increase, as grassland is a perennial plant and hence provides more land cover in March. In the case of switchgrass the wind erosion remains unchanged.

Water quantity

The water quantity has been assessed with a water balance, depicting the difference between the precipitation and the evapotranspiration. The evapotranspiration is depending on specific crop development data. In this study general crop development data has been taken from the FAO, and adapted to Ukraine, on a basis of planting and harvesting dates. However, in order to improve the accuracy of the research, more local research is advised. Furthermore, as the actual water quantity is also depending on local water levels, and an extensive water management system, the water quantity analysis is only suitable for a qualitative representation of the spatial effects.

From the analysis it can be concluded that the water deficiency is largest during the end of August. If wheat is cultivated on arable land, the deficit can be either increased or decreased. In the North-Western oblasts, wheat cultivation leads to an increase of the water deficit, because of the current cultivation of many low water-consuming crop types. In the Southwest, the water shortage decreases, as the current crop mixture is more water consuming than wheat. If wheat is cultivated on pasture land, the water deficiency also tends to decrease, because of the high water consumption of grassland.

Although the water use efficiency of switchgrass is considerably higher than the efficiency of wheat, and most of the currently cultivated crops, the high biomass density of switchgrass leads to a high water consumption. Consequently, the cultivation of switchgrass leads to a an overall increase of the water deficiency, regardless of the current land use type. The largest deficiency is attained if switchgrass is replacing arable land in the North-Western oblasts.

Water quality

The water quality has been assessed with the Miterra model, that describes the $NO_3$ concentration of soil water (Alterra 2010). As Miterra includes many key parameters, and combines various spatial datasets in a consistent way, it provides valuable information on the relative differences of the water quality on a spatial level. However, the Miterra model is not designed to include the concentrations of phosphor, potassium or chemical residues. The water quality assessment could therefore be improved by an additional analysis of these substances.

The conversion of agricultural land to bioenergy crops, can both lead to an increase or a decrease of the water quality. In the oblasts with a high concentration, the $NO_3$ concentration decreases, and in the oblast with a low concentration, the water quality increases.

According to the results from Miterra, the cultivation of wheat leads on average to slightly higher $NO_3$ concentrations than the cultivation of switchgrass. The main reason for this is the high nitrogen uptake of switchgrass as compared to wheat. However, as Miterra includes various uncertainties, the differences between the two crops should be interpreted as insignificant.

General conclusions

In general it can be concluded there are considerable spatial differences in the environmental impacts of bioethanol production in Ukraine, thereby justifying the spatial approach. Furthermore, wheat cultivation leads in all cases, except for the water use criterion, to a larger environmental impacts than wheat. Also, the use of current arable land should be preferred over the use of pasture land.

As the research includes many uncertainties, further research is recommended to improve the accuracy of the individual impacts. Additionally, as this study is designed to assess the environmental impacts on a region level, a local environmental impact assessment is required to estimate the environmental impacts on a local scale.

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# Appendix 1: Input data

## 1. Current crop areas and production

***Table 1:*** *The harvested area of Ukrainian crops, differentiated per oblast, in the year 2008* (State Statistics Committee of Ukraine, Ostapchuk et al. 2009). *Note: Olives, fruits and flowers have been excluded, as it is not likely that these will be converted to bioenergy crop land because of their economic value.*

| **Harvested area - 2008** | **Grain & leguminous** | | | | **Potatoes** | **Vegetables**[*3] | **Industrial crops** | | | **Other** | **Feed crops** | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *[Thousand hectares]* | *Wheat*[*1] | *Barley*[*2] | *Maize for grain* | *Other cereals* | | | *Sugar beet* | *Sunflower* | *Rape* | | | |
| Crimea | 368 | 209 | 5 | 32 | 24 | 17 | 0 | 31.6 | 33.1 | 0 | 66 | **785** |
| Vinnytsya | 386 | 206 | 166 | 66 | 102 | 16 | 62 | 118.7 | 133.3 | 57.2 | 191 | **1,503** |
| Volyn | 135 | 32 | 9 | 83 | 67 | 12 | 10 | 0.5 | 12.5 | 8.7 | 120 | **489** |
| Dnipropetrovs'k | 510 | 327 | 205 | 45 | 48 | 31 | 2 | 540.8 | 63.5 | 22.5 | 70 | **1,864** |
| Donets'k | 394 | 207 | 89 | 67 | 61 | 27 | 1 | 443.1 | 2.2 | 6.1 | 137 | **1,434** |
| Zhytomyr | 111 | 61 | 66 | 134 | 58 | 10 | 11 | 5 | 33.2 | 31 | 200 | **720** |
| Transcarpathia | 34 | 9 | 38 | 6 | 35 | 13 | 0 | 1.5 | 0.5 | 0 | 54 | **190** |
| Zaporizhzhya | 516 | 249 | 44 | 47 | 32 | 22 | 0 | 594.4 | 36.2 | 20.9 | 65 | **1,627** |
| Ivano-Frankivs'k | 47 | 23 | 33 | 20 | 54 | 8 | 2 | 0.7 | 10.1 | 12.3 | 97 | **308** |
| Kiev | 271 | 142 | 151 | 84 | 96 | 24 | 30 | 44.6 | 63.8 | 58.8 | 146 | **1,110** |
| Kirovohrad | 354 | 297 | 132 | 50 | 45 | 18 | 14 | 409 | 148.6 | 68.8 | 62 | **1,597** |
| Luhans'k | 295 | 93 | 67 | 76 | 40 | 14 | 0 | 333.5 | 9.7 | 8.3 | 65 | **1,000** |
| L'viv | 147 | 36 | 31 | 46 | 91 | 22 | 16 | 0.1 | 23.3 | 8.6 | 115 | **536** |
| Mykolayiv | 452 | 304 | 41 | 35 | 20 | 18 | 1 | 420.2 | 118.2 | 16.6 | 60 | **1,484** |
| Odessa | 536 | 471 | 111 | 93 | 36 | 30 | 1 | 232.6 | 181.7 | 0 | 99 | **1,791** |
| Poltava | 361 | 268 | 330 | 79 | 62 | 22 | 64 | 212.1 | 37.8 | 101.3 | 158 | **1,695** |
| Rivne | 115 | 54 | 23 | 69 | 65 | 11 | 23 | 1.5 | 28 | 6.1 | 109 | **504** |
| Sumy | 235 | 144 | 143 | 141 | 64 | 10 | 10 | 63.1 | 24.7 | 37.5 | 122 | **992** |
| Ternopil' | 230 | 130 | 64 | 46 | 58 | 10 | 42 | 6.9 | 66.5 | 34.2 | 69 | **756** |
| Kharkiv | 478 | 270 | 150 | 80 | 78 | 29 | 28 | 326.4 | 14.4 | 42.3 | 135 | **1,632** |
| Kherson | 406 | 195 | 32 | 37 | 24 | 42 | 0 | 327.8 | 93.3 | 108.1 | 82 | **1,346** |
| Khmel'nyts'kyy | 214 | 161 | 78 | 97 | 71 | 10 | 21 | 14.1 | 109.8 | 52.1 | 144 | **972** |
| Cherkasy | 254 | 179 | 187 | 51 | 64 | 22 | 26 | 123.1 | 100.4 | 62.8 | 132 | **1,200** |
| Chernivtsi | 31 | 22 | 61 | 6 | 31 | 11 | 3 | 5.6 | 8.6 | 19.6 | 74 | **273** |
| Chernihiv | 174 | 81 | 188 | 231 | 84 | 12 | 10 | 22.6 | 26.2 | 34.2 | 185 | **1,048** |

***Table 2:*** *The yield levels of Ukrainian crops (fresh t/ha), differentiated per oblast, in the year 2008* (State Statistics Committee of Ukraine, Ostapchuk et al. 2009). *Note: Olives, fruits and flowers have been excluded, as it is not likely that these will be converted to bioenergy crop land because of their economic value. Also feed crops have been excluded in this figure, as the production figures are unavailable.*

| **Average yield per crop** | **Cereals** | | | | **Potatoes** | **Vegetables** | **Industrial crops** | | | | | **Average yield per ha for each oblast** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *fresh t./ha* | *Wheat* | *Barley* | *Maize* | *Other cereals* | | | *Sugar beet* | *Sunflower* | *Rape* | *Other* | *Feed* | |
| Crimea | 2.7 | 2.8 | 7.8 | 3.0 | 14.3 | 16.4 | 0.0 | 0.9 | 1.1 | 0.0 | 11.5 | 4.1 |
| Vinnytsya | 4.3 | 3.4 | 5.5 | 1.9 | 15.2 | 20.1 | 36.0 | 1.8 | 2.5 | 1.7 | 11.5 | 6.9 |
| Volyn | 3.1 | 2.7 | 6.0 | 2.0 | 13.9 | 20.2 | 31.7 | 0.0 | 2.4 | 1.7 | 11.5 | 7.4 |
| Dnipropetrovs'k | 3.8 | 2.9 | 3.5 | 2.1 | 12.0 | 17.5 | 25.3 | 1.6 | 2.0 | 1.7 | 11.5 | 3.6 |
| Donets'k | 3.6 | 2.6 | 2.8 | 1.9 | 10.3 | 15.2 | 19.2 | 1.7 | 1.8 | 1.7 | 11.5 | 4.0 |
| Zhytomyr | 3.4 | 2.9 | 5.1 | 1.6 | 18.3 | 22.2 | 30.6 | 1.4 | 2.3 | 1.7 | 11.5 | 7.2 |
| Transcarpathia | 3.1 | 2.9 | 4.7 | 1.8 | 16.3 | 18.5 | 0.0 | 1.3 | 2.0 | 0.0 | 11.5 | 9.2 |
| Zaporizhzhya | 3.5 | 3.0 | 2.8 | 2.0 | 9.7 | 12.7 | 20.0 | 1.4 | 1.7 | 1.7 | 11.5 | 3.1 |
| Ivano-Frankivs'k | 3.2 | 2.9 | 4.6 | 1.7 | 10.2 | 12.9 | 27.0 | 1.4 | 2.2 | 1.7 | 11.5 | 7.4 |
| Kiev | 4.0 | 3.7 | 5.3 | 2.2 | 15.5 | 21.6 | 33.5 | 1.8 | 2.5 | 1.7 | 11.5 | 6.8 |
| Kirovohrad | 3.9 | 2.8 | 5.3 | 2.0 | 10.7 | 14.1 | 36.7 | 1.6 | 2.2 | 1.7 | 11.5 | 3.8 |
| Luhans'k | 3.8 | 2.4 | 2.4 | 1.8 | 13.5 | 22.4 | 12.5 | 1.4 | 1.9 | 1.7 | 11.5 | 3.7 |
| L'viv | 3.1 | 2.8 | 6.2 | 1.8 | 15.1 | 19.3 | 36.5 | 0.0 | 2.4 | 1.7 | 11.5 | 8.6 |
| Mykolayiv | 3.1 | 2.7 | 2.9 | 1.8 | 9.2 | 15.6 | 20.0 | 1.2 | 1.8 | 1.7 | 11.5 | 2.9 |
| Odessa | 3.3 | 2.9 | 3.2 | 1.6 | 5.6 | 16.3 | 19.2 | 1.3 | 1.8 | 0.0 | 11.5 | 3.4 |
| Poltava | 4.3 | 3.4 | 5.7 | 2.3 | 14.7 | 17.2 | 42.1 | 2.2 | 2.0 | 1.7 | 11.5 | 6.5 |
| Rivne | 3.2 | 2.8 | 5.7 | 1.8 | 15.5 | 20.1 | 37.0 | 2.0 | 2.3 | 1.7 | 11.5 | 8.3 |
| Sumy | 3.9 | 3.3 | 4.9 | 2.0 | 14.1 | 14.3 | 34.5 | 1.8 | 1.6 | 1.7 | 11.5 | 5.4 |
| Ternopil' | 3.5 | 3.0 | 5.3 | 1.6 | 13.7 | 21.7 | 33.1 | 1.6 | 2.3 | 1.7 | 11.5 | 6.6 |
| Kharkiv | 4.6 | 3.2 | 3.8 | 1.9 | 10.9 | 17.5 | 29.5 | 1.8 | 1.9 | 1.7 | 11.5 | 5.0 |
| Kherson | 3.3 | 3.1 | 6.0 | 2.2 | 10.2 | 16.7 | 20.0 | 1.1 | 1.3 | 1.7 | 11.5 | 3.5 |
| Khmel'nyts'kyy | 3.5 | 3.0 | 5.3 | 1.7 | 17.9 | 20.5 | 41.5 | 1.4 | 2.1 | 1.7 | 11.5 | 6.3 |
| Cherkasy | 4.7 | 3.7 | 5.3 | 2.4 | 13.1 | 13.5 | 32.7 | 1.9 | 3.0 | 1.7 | 11.5 | 5.9 |
| Chernivtsi | 3.2 | 2.6 | 5.1 | 1.8 | 14.9 | 17.9 | 34.1 | 1.6 | 2.0 | 1.7 | 11.5 | 7.9 |
| Chernihiv | 3.3 | 3.4 | 4.6 | 2.0 | 17.9 | 20.2 | 36.7 | 1.6 | 1.9 | 1.7 | 11.5 | 6.2 |

[*]1: Approximately 91% of the harvested wheat area is winter wheat, and 9% summer wheat.
[*]2: Approximately 89% of the harvested barley area is spring barley, and 11% is winter barley.
[*]3: Vegetables: 22% cabbage, 20% tomatoes, 14% onion, 10% cucumbers, table beet and carrots, 7% pumpkins, 6% melons, 3% other vegetables.

To estimate the current biomass on arable land, the yields had to be converted from fresh weight to dry weight. To this end, the moisture content of each crop type is given in table 3.

***Table 3:*** *Moisture content of various crops.*

| Crop: | Moisture |
|---|---|
| Wheat | *13.5%* [2] |
| Barley | *13.5%* [3] |
| Maize for grain | *30%* [5] |
| Other cereals | *13.5%* [3] |
| Sugar beet | *75%* [2] |
| Sunflower | *10%* [2] |
| Rape | *10%* [2] |
| Potatoes | *80%* [4] |
| Vegetables | *80%* [4] |

Sources:
1: Fresh weight: (State Statistics Committee of Ukraine, Ostapchuk et al. 2009)
2: Dry fraction: (JRC: 2008)
3: Assumed to be equal to wheat
4: Potatoes: (San Luis Hills Farm ). All other vegetables are assumed to have a comparable water content.
5: (de Wolf, van der Klooster 2006)

In the second step, the harvest ratio[16] was applied to account for the total above- and belowground biomass. The data for this calculation is given in table 4.

***Table 4:*** *Harvest index of various crops.*

| Crop | Harvest index | Source |
|---|---|---|
| Wheat | 0.459 | *1* |
| Barley | 0.451 | *1* |
| Maize for grain | 0.363 | *2* |
| Other cereals | 0.450 | *3* |
| Sugar beet | 0.690 | *1* |
| Sunflower | 0.292 | *4* |
| Rape | 0.328 | *5* |
| Potatoes | 0.690 | *1* |
| Vegetables | 0.690 | *6* |

Sources:
1: (Kuikman, de Groot et al. 2003). Wheat is 91% winter wheat, and 9% summer wheat. Barley is 89% spring barley and 11% winter barley. Straw and leaves are left on the field.
2: (Mollier, Pellerin 1999)
3: Assumed, based on the value for spring barley.
4: Above ground biomass has a harvest index of 0.35 (Ahmad, Hassan et al. October 1, 2007). Below ground has a root-to-shoot ratio comparable to wheat (0.2): (Sultana, Ruhul Amin et al. 2009)
6: Assumed, based on the value of sugar beet

To estimate the current biomass on pastures, data from the IPCC has been used. This data for this calculation is given in table 5.

[16] Harvest ratio: ratio between the yield levels, and the total biomass

***Table 5:*** *The biomass on pasture land in the reference case (kg dm./ha).*

| Pasture land | Total above and below (kg/ha) | Error[*1] |
|---|---|---|
| Cold temperate moist | 13,600 | ±75% |
| Cold temperate dry | 6,500 | ±75% |
| Warm temperate moist | 13,500 | ±75% |
| Warm temperate dry | 6,100 | ±75% |

Source: (IPCC 2006a)

[*]1 Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

Figure 1 indicates the planting and harvesting dates of the main crop types in Ukraine. Although the planting dates are taken from American sources, and are therefore not specifically applicable to Ukraine, they are assumed to resemble Ukrainian planting dates.

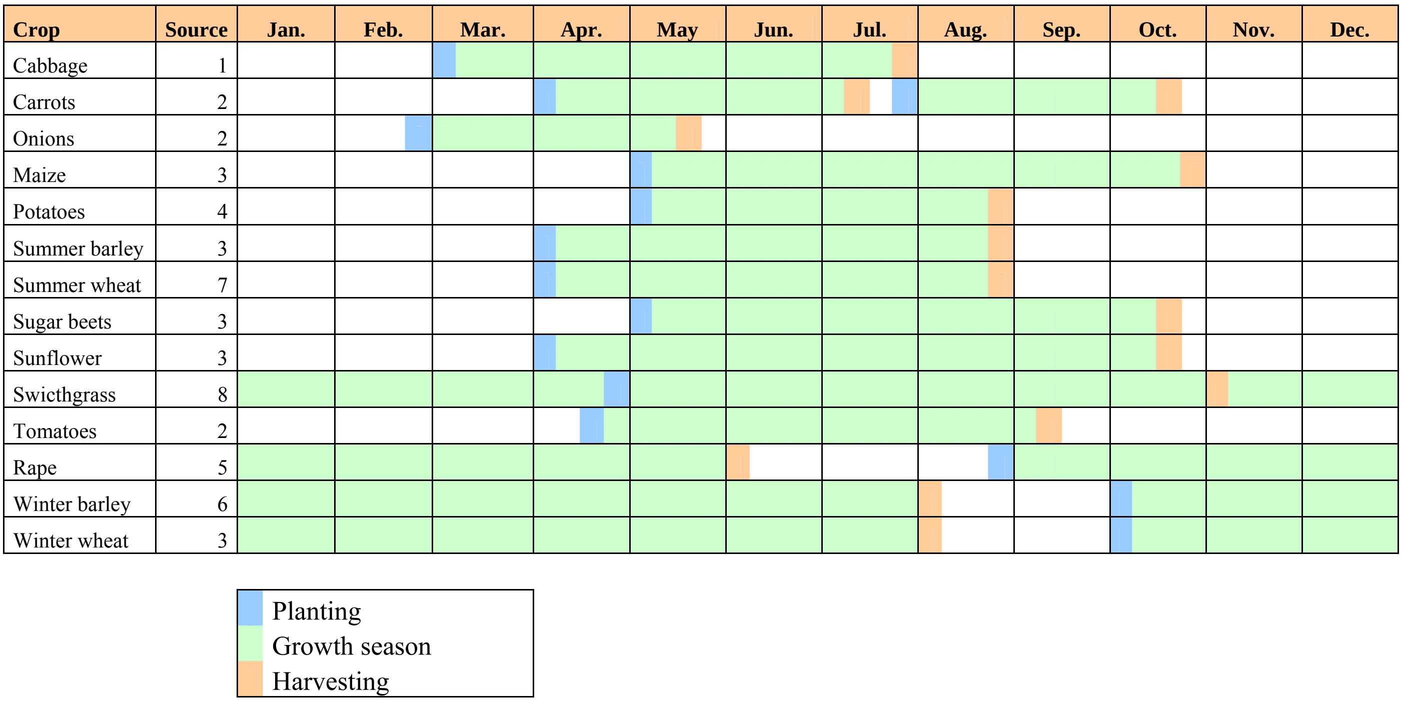


***Figure 1:*** *Planting and harvesting dates of the main crop types.*

*Sources:*

*1.* (harvestwizard.com )

*2.* (The garden helper 2010)

*3.* (Nasa earth observatory, world data centre for Geoinformatics and Sustainable Development et al. 2010

*4.* (Rogovska, Iowa State University )

*5.* (Bernelot Moens, Wolfert 2003)

6. Estimated on the basis of winter wheat

7. Estimated on the basis of spring barley

8. (Garland 2005)

## 2. Land use changes

Above and below ground biomass.

When current land is converted to bioenergy crop cultivation, the current biomass needs to be removed. The initial biomass change ($C_b$) has been calculated, according to the following formulas:

$$\Delta C_{biomass} = \frac{Bafter - Bbefore}{D}$$

$$B_{before} = \sum \left( \Pr oduction \ * Hr * CF \right)$$

$$B_{after} = Potential \ * Hr * CF$$

$\Delta C_{biomass}$ = Change of the above and below ground biomass on land that is converted to another land category. Negative values indicate emissions in [tC $ha^{-1}$/yr].
$B_{after}$ = The biomass on a plot of arable land after the transition time period [t dm $ha^{-1}$]
$B_{before}$ = The biomass on a plot of arable land, before the conversion [t dm $ha^{-1}$]
D = Time period of the transition [yr]
Production = The annual yield level of a specific crop on one hectare [t dm $ha^{-1}$ $yr^{-1}$]
Potential = The potential annual yield level of wheat or switchgrass on one hectare [t dm $ha^{-1}$ $yr^{-1}$]
CF = Carbon fraction of dry matter [fraction]
Hr = Harvest ratio, the ratio between the total biomass and the yield [-]

Using the information of appendix 1.1, the current biomass per hectare is given in table 6.

***Table 6:*** *Total biomass production per crop type in 2008 on arable land per oblast, including aboveground and belowground biomass (1000x odt).*

| Year: 2008 *[1000x odt]* | Wheat | Barley | Maize | Other | Sugar beet | Sunflower | Rape | Potatoes | Vegetables | Total *[1000x odt]* | **Average *odt/ ha*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Crimea | 1,895 | 1,139 | 73 | 185 | 0 | 89 | 104 | 101 | 83 | 3,670 | **5.1** |
| Vinnytsya | 3,099 | 1,342 | 1,753 | 238 | 811 | 672 | 905 | 449 | 92 | 9,361 | **7.5** |
| Volyn | 778 | 169 | 98 | 317 | 109 | 0 | 82 | 272 | 68 | 1,893 | **5.3** |
| Dnipropetrovs'k | 3,665 | 1,804 | 1,379 | 179 | 16 | 2,623 | 357 | 165 | 157 | 10,344 | **5.8** |
| Donets'k | 2,692 | 1,012 | 484 | 239 | 9 | 2,302 | 11 | 181 | 120 | 7,051 | **5.5** |
| Zhytomyr | 712 | 337 | 648 | 407 | 124 | 22 | 209 | 307 | 61 | 2,827 | **5.8** |
| Transcarpathia | 194 | 50 | 341 | 20 | 0 | 6 | 3 | 167 | 70 | 851 | **6.2** |
| Zaporizhzhya | 3,431 | 1,427 | 239 | 175 | 3 | 2,540 | 167 | 89 | 81 | 8,151 | **5.3** |
| Ivano-Frankivs'k | 279 | 127 | 291 | 64 | 20 | 3 | 60 | 160 | 31 | 1,035 | **5.2** |
| Kiev | 2,050 | 1,005 | 1,537 | 353 | 362 | 253 | 442 | 428 | 149 | 6,578 | **7.3** |
| Kirovohrad | 2,576 | 1,616 | 1,342 | 187 | 187 | 1,960 | 908 | 140 | 72 | 8,988 | **6.1** |
| Luhans'k | 2,118 | 420 | 312 | 259 | 2 | 1,415 | 49 | 155 | 90 | 4,820 | **5.2** |
| L'viv | 869 | 194 | 372 | 158 | 212 | 0 | 154 | 397 | 122 | 2,477 | **6.0** |
| Mykolayiv | 2,623 | 1,565 | 226 | 117 | 5 | 1,593 | 587 | 52 | 79 | 6,848 | **4.9** |
| Odessa | 3,358 | 2,612 | 687 | 291 | 9 | 965 | 884 | 58 | 141 | 9,003 | **5.3** |
| Poltava | 2,932 | 1,762 | 3,618 | 347 | 979 | 1,412 | 211 | 264 | 109 | 11,633 | **8.1** |
| Rivne | 695 | 288 | 247 | 236 | 302 | 9 | 176 | 293 | 63 | 2,309 | **5.9** |
| Sumy | 1,705 | 903 | 1,356 | 551 | 119 | 345 | 110 | 260 | 40 | 5,388 | **6.5** |
| Ternopil' | 1,517 | 738 | 648 | 138 | 508 | 34 | 423 | 229 | 60 | 4,295 | **6.6** |
| Kharkiv | 4,145 | 1,678 | 1,097 | 294 | 299 | 1,809 | 77 | 248 | 148 | 9,794 | **6.7** |
| Kherson | 2,504 | 1,156 | 364 | 156 | 1 | 1,125 | 343 | 72 | 202 | 5,924 | **5.1** |
| Khmel'nyts'kyy | 1,419 | 922 | 795 | 325 | 313 | 62 | 623 | 366 | 62 | 4,886 | **6.3** |
| Cherkasy | 2,246 | 1,285 | 1,917 | 235 | 309 | 734 | 818 | 243 | 86 | 7,872 | **7.8** |
| Chernivtsi | 188 | 109 | 602 | 21 | 39 | 28 | 47 | 134 | 55 | 1,223 | **6.8** |
| Chernihiv | 1,083 | 523 | 1,655 | 875 | 133 | 114 | 137 | 437 | 69 | 5,027 | **6.1** |
| **Total** | **48,772** | **24,184** | **22,082** | **6,367** | **4,869** | **20,114** | **7,886** | **5,666** | **2,309** | **142,249** | **6.1** |

For wheat, the total potential production, including the above and below ground biomass, varies between 8.6-18.8 odt/ha. For switchgrass the total biomass varies between 26.6-57.7 odt/ha.

<u>Soil organic carbon</u>
Besides the changes in the above and below ground biomass, the soil carbon should also be taken into account. A differentiation was made between the soil carbon in organic and mineral soils.

The carbon change in mineral soils is mainly dependant on the climate, soil type and management regime. It can be calculated as follows:

$$\Delta C mineral = \frac{SOC_0 - SOC_{(0-T)}}{D} \qquad SOC = \sum \left( SOC_{ref_{c,s,i}} * F_{lu_{c,s,i}} * F_{MG_{c,s,i}} * F_{I_{c,s,i}} \right)$$

| | |
|---|---|
| $\Delta C_{mineral}$ | = Annual SOC change in mineral soils (tonne C/ha/yr) |
| $SOC_0$ | = Soil organic carbon in the last year of the inventory time (tonne C/ha) |
| $SOC_{0-T}$ | = Soil organic carbon at the beginning of the inventory time (tonne C/ha). |
| D | = Years in a cycle (20 years). |
| C,s,i | = represents climate zone (c), soil type (s) and the set of management systems (i) that are applied. |
| $SOC_{ref}$ | = Reference Soil organic carbon content. |
| $F_{lu}$ | = Factor for a particular land use |
| $F_{mg}$ | = Factor for a particular management/tillage regime |
| $F_i$ | = Factor for a particular input of organic material |

The reference soil organic carbon has been calculated according to the data in the following table.

***Table 7:*** *Reference SOC per soil type*

| Climate | Soil type | SOC reference | Error[*1] |
|---|---|---|---|
| Cool moist | LAC | 85 | ±90% |
| Warm moist | LAC | 63 | ±90% |
| Cool dry | LAC | 33 | ±90% |
| Warm dry | LAC | 24 | ±90% |
| Cool moist | Wetland | 87 | ±90% |
| Cool dry | Wetland | 87 | ±90% |
| Warm dry | Wetland | 88 | ±90% |
| Cool moist | HAC | 95 | ±90% |
| Warm moist | HAC | 88 | ±90% |
| Cool dry | HAC | 50 | ±90% |
| Warm dry | HAC | 38 | ±90% |
| Cool moist | Spodic | 115 | ±90% |
| Cool moist | Volcanic | 130 | ±90% |

Source: IPCC volume 4, table 2.3: (IPCC 2006a)

*Note: As the soil classification system of the European soil database is incompatible with the IPCC, the systems had to be harmonised prior to the calculation. This harmonisation is depicted in Appendix 1.3.*

[*]1 The nominal error estimate, expressed as 2x the standard deviations as percent of the mean.

The three other factors that are required to calculate the SOC change, are depicted in table 8:

***Table 8a,b,c:*** *The land use factor, the management factor and the input factor, according to the IPCC methodology* (IPCC 2006a).

| **A. Land use factor (Flu)** | | **current** | | **wheat** | | **switchgrass** | |
|---|---|---|---|---|---|---|---|
| *Climate* | *Land use type* | *Fle* | *Error*[*1] | *Flu - wh* | *Error* | *Flu - sg* | *Error* |
| Temperate dry | Arable land | 0.80 | ±9% | 0.80 | ±9% | 0.990 | ±0% |
| Temperate moist | Arable land | 0.69 | ±12% | 0.69 | ±12% | 0.985 | ±1% |
| Temperate dry | Grassland | 1.00 | ±0% | 0.80 | ±9% | 0.990 | ±0% |
| Temperate moist | Grassland | 1.00 | ±0% | 0.69 | ±12% | 0.985 | ±1% |

| **B. Management factor (Fmg)** | | **current** | | **wheat** | | **switchgrass** | |
|---|---|---|---|---|---|---|---|
| *Climate* | *Land use type* | *Fmg* | *Error*[*1] | *Fmg - wh* | *Error* | *Fmg - sg* | *Error* |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Temperate dry | Arable land | 1.00 | ±0% | 1.00 | ±0% | 1.133 | ±10% |
| Temperate moist | Arable land | 1.00 | ±0% | 1.00 | ±0% | 1.133 | ±10% |
| Temperate dry | Grassland | 0.95 | ±13% | 1.00 | ±0% | 1.133 | ±10% |
| Temperate moist | Grassland | 0.95 | ±13% | 1.00 | ±0% | 1.133 | ±10% |

| **C. Input factor (Fi)** | | **current** | | **wheat** | | **switchgrass** | |
|---|---|---|---|---|---|---|---|
| *Climate* | *Land use type* | *Fi* | *Error*[*1] | *Fi - wh* | *Error* | *Fi - sg* | *Error* |
| Temperate dry | Arable land | 1.00 | ±0% | 1.04 | ±13% | 1.107 | ±7% |
| Temperate moist | Arable land | 1.00 | ±0% | 1.11 | ±10% | 1.110 | ±7% |
| Temperate dry | Grassland | 1.00 | ±0% | 1.04 | ±13% | 1.107 | ±7% |
| Temperate moist | Grassland | 1.00 | ±0% | 1.11 | ±10% | 1.110 | ±7% |

[*]1 Error: The nominal error estimate, expressed as 2x the standard deviations as percent of the mean.

The SOC change in organic soils is mainly dependant on the carbon flux. Because of the similarities in their management regimes, the carbon flux of wheat is assumed to be the same as the carbon flux of current arable land. Switchgrass shows a close resemblance to pasture land, and was hence assigned the same flux as pasture land. However, in the first year of the cycle, the crop shows more resemblance to annual crops. Consequentially, the carbon flux of switchgrass is assigned $^{1}/_{20}$ of the carbon flux of arable land, and $^{19}/_{20}$ of the flux that is applicable to grassland. In table 9, the carbon fluxes are depicted.

***Table 9:*** *carbon fluxes on organic soils.*

| **Climate** | **Land use type** | **Carbon flux** | **Unit** | **Error**[*1] |
|---|---|---|---|---|
| Temperate cool | Arable land | 5 | tonnes C/ha/yr | ±90% |
| Temperate warm | Arable land | 10 | tonnes C/ha/yr | ±90% |
| Temperate cool | Grassland | 0.25 | tonnes C/ha/yr | ±90% |
| Temperate warm | Grassland | 2.5 | tonnes C/ha/yr | ±90% |

Source: (IPCC 2006a)

[*]1 Error: The nominal error estimate, expressed as 2x the standard deviations as percent of the mean.

$N_2O$ emissions from managed soils

For the calculation of the $N_2O$ related emissions for the LUC and GHG balance, the following equations were used:

Direct emissions:

$$N_2O\_directN = N_2O - N_{inputs} + N_2O - N_{os}$$ main equation

$$N_2O - N_{inputs} = (F_{sn} + F_{cr} + F_{som}) * EF_1$$ a

$$N_2O - N_{os} = F_{os,cg,temp} * EF_{2cg,temp}$$ b

$$F_{cr} = Crop * frac_{renewed} * \left\lfloor R_{bg,t} * N_{bg,t} \right\rfloor$$ c

$$F_{som} = \sum_{LU}\left[\left(\Delta C_{\min eral,lu} * \frac{1}{R}\right) * 1000\right]$$ d

| | |
|---|---|
| $N_2O$Direct –N | = annual direct $N_2O$–N emissions produced from managed soils, kg $N_2O$–N $yr^{-1}$ |
| $N_2O–N_{inputs}$ | = annual direct $N_2O$–N emissions from N inputs to managed soils, kg $N_2O$–N $yr^{-1}$ |
| $N_2O–N_{OS}$ | = annual direct N2O–N emissions from managed organic soils, kg $N_2O$–N $yr^{-1}$ |
| $F_{SN}$ | = annual amount of synthetic fertiliser N applied to soils, kg N $yr^{-1}$ |
| $F_{CR}$ | = annual amount of N in crop residues (below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N $yr^{-1}$ |
| $F_{SOM}$ | = annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N $yr^{-1}$ |
| $F_{OS}$ | = annual area of managed/drained organic soils, ha (Note: the subscripts CG, Temp refer to Cropland and Grassland, and Temperate |
| $EF_1$ | = emission factor for $N_2O$ emissions from N inputs, kg $N_2O$–N (kg N input)$^{-1}$ |
| $EF_2$ | = emission factor for $N_2O$ emissions from drained/managed organic soils, kg $N_2O$–N $ha^{-1}$ $yr^{-1}$ |
| Crop | = harvested annual dry matter yield for crop T, kg d.m. $ha^{-1}$ |
| $Frac_{Renewed}$ | = fraction of total area under crop T that is renewed annually. |
| $R_{BG}$ | = ratio of below-ground residues to harvested yield for crop T, kg d.m. (kg d.m.)$^{-1}$ |
| $N_{BG}$ | = N content of below-ground residues for crop T, kg N (kg d.m.)$^{-1}$ |
| $\Delta_{CMineral, LU}$ | = average annual loss of soil carbon for each land-use type (LU ), (tonnes C) |
| R | = C:N ratio of the soil organic matter. |
| LU | = land-use and/or management system type |

*Source: IPCC 2006*

Indirect emissions:

$$N_2O\_indirectN = N_2O_{(ATD)} - N + N_2O_{(L)} - N$$ main equation

$$N_2O_{(ATD)} - N = F_{sn} * F_{gasm} * EF_4$$ a

$$N_2O_{(L)} - N = (F_{sn} + F_{cr} + F_{som}) * frac_{leach-(H)} * EF_5$$ b

| | |
|---|---|
| $N2O_{(ATD)}$–N | = annual amount of $N_2O$–N produced from atmospheric deposition of N volatilised from managed soils, kg N2O–N $yr^{-1}$ |
| $F_{SN}$ | = annual amount of synthetic fertiliser N applied to soils, kg N $yr^{-1}$ |
| $F_{ON}$ | = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N $yr^{-1}$ |
| $F_{CR}$ | = amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, kg N $yr^{-1}$ |
| $F_{SOM}$ | = annual amount of N mineralised in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, kg N $yr^{-1}$ |
| FracGASF | = fraction of synthetic fertiliser N that volatilises as NH3 and NOx, kg N volatilised (kg of N applied)$^{-1}$ |
| FracLEACH-(H) | = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$ |

$EF_4$ = emission factor for $N_2O$ emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N2O (kg NH3–N + NOx–N volatilised)$^{-1}$]
$EF_5$ = emission factor for N2O emissions from N leaching and runoff, kg N2O–N (kg N leached and runoff)$^{-1}$

*Source: IPCC 2006*

The following input data have been used:

***Table 10:*** *input data for the calculation of direct $N_2O$ emissions.*

| **N2O – direct emissions** | | | |
|---|---|---|---|
| *Subject* | *Value* | *Unit* | Uncertainty range *2 |
| Emission factor for N additions from fertilizers and crop residues. | 0.01 | kg $N_2O$–N (kg N)$^{-1}$ | 0.003-0.03 |
| Harvested annual dm wheat, varying per oblast.*1 | 4.0-8.7 | odt. ha-1 | 4.0-8.7 |
| Harvested annual dm. switchgrass, varying per oblast *1 | 8.9-19.2 | odt. ha-1 | 8.9-19.2 |
| Fraction of the area that is renewed annually (wheat) | 1 | fraction | N/A |
| Fraction of the area that is renewed annually (switchgrass) | 0.05 | fraction | N/A |
| Fraction of the above ground residues that are removed after the harvesting (wheat and switchgrass). | 1 | fraction | N/A |
| Ratio of below ground residues to yields (wheat). | 0.23 | odt. (odt.)$^{-1}$ | ±41% |
| Ratio of below ground residues to yields (switchgrass). | 0.8 | odt. (odt.)$^{-1}$ | ±50% |
| N content of below ground residues (wheat) | 0.009 | t N (odt.)$^{-1}$ | N/A |
| N content of below ground residues (switchgrass) | 0.012 | t N (odt.)$^{-1}$ | N/A |
| C:N ratio of the soil organic matter on arable land | 10 | fraction | 8-15 |
| C:N ratio of the soil organic matter on pasture land | 15 | fraction | 10-30 |
| Emission factor for temperate organic agricultural soils. | 8 | kg $N_2O$–N ha$^{-1}$ | 2-24 |

*Sources :* (IPCC 2006a) ; *1 source: (Refuel 2008)
*2 Error: The nominal error estimate, expressed as 2x the standard deviations as percent of the mean.

***Table 11:*** *input data for the calculation of indirect $N_2O$ emissions.*

| **$N_2O$ – indirect emissions** | | | |
|---|---|---|---|
| *Subject* | *Value* | *Unit* | Uncertainty range |
| Fraction N that volatilises from fertilizers | 0.1 | kg N volatilised (kg of N applied or deposited)$^{-1}$ | 0.03-0.3 |
| Fraction N that volatilises from manure | 0.2 | kg N volatilised (kg of N applied or deposited)$^{-1}$ | 0.05-0.5 |
| Emission factor for atmospheric depositions | 0.01 | kg N–N2O (kg NH3–N + NOx–N volatilised)-1 | 0.002-0.05 |
| Emission factor for leaching/runoff | 0.0075 | kg N2O–N (kg N leached and runoff)-1 | 0.0005-0.025 |

*Source* (IPCC 2006a)

# 3. Life cycle assessment

Cultivation related emissions:
The following input data has been used:

***Table 12:*** *Use of seeds, pesticides and fertilizer for wheat and switchgrass production.*

| Additive | Wheat | Switchgrass | Unit |
|---|---|---|---|
| Seeds[*1] | 90 | 10 | kg/ha |
| Fertilizer – establishment phase[*2] | N/A<br>annual crop | 28<br>17.5<br>49.8 | kg N /ha<br>kg P /ha<br>kg K /ha |
| Fertilizer – production phase[*3] | 224<br>41.5<br>125 | 115<br>14<br>39 | kg N /ha/yr<br>kg P /ha/yr<br>kg K /ha/yr |
| Pesticide – establishment phase[*4] | N/A<br>annual crop | 2 kg Advance;<br>7.7 kg MCPA;<br>2 kg IPC | kg/ha/yr |
| Pesticide – production phase[*5] | 2.3 | 2.5 | kg glyphosate/ha/yr |

*Source:*
1: wheat: (NDSU 2010b); switchgrass: (Bullard, Metcalfe 2001)
2: (Bullard, Metcalfe 2001)
3: wheat: (NDSU 2010a); switchgrass nutrient composition: (Elbersen, Christian et al. )
4: (Bullard, Metcalfe 2001)
5: wheat: (JRC 2008) ; switchgrass: (Bullard, Metcalfe 2001)

The following emission factors have been applied for seeds, pesticides and fertilizers for wheat and switchgrass production.

***Table 13:*** *Emission factors of seeds, pesticides and fertilizers for wheat and switchgrass production*

| Additive | Wheat | Switchgrass | Unit |
|---|---|---|---|
| Seeds[*1] | 36 | 8 | kg CO2-eq/ha |
| Fertilizer*[2] | 2.329<br>0.714<br>0.456 | | kg CO2-eq/kg N<br>kg CO2-eq/kg P<br>kg CO2-eq/kg K |
| Pesticides [*3] | 13.5<br>28.5<br>51<br>33.5 | | kg CO2-eq/kg Advance<br>kg CO2-eq/kg MCPA<br>kg CO2-eq/kg IPU<br>kg CO2-eq/kg glyphosate |

*Source:*
1: wheat: (West, Marland 2002) switchgrass: (Bullard, Metcalfe 2001)
2: Nitrogen: (Wood, Cowie 2004) Phosphor and Potassium: (Kaltschmitt, Reinhardt 1997)
3: (Bullard, Metcalfe 2001)

Next to the emissions from seeds, fertilizers and pesticides, also the diesel that is used in agricultural machinery produces emissions. The emission factor of diesel is 69.3 kg $CO_2$-eq/GJ LHV (IPCC 2006b). The diesel use has been depicted in table 14.

***Table 14:*** *Diesel use during the cultivation of wheat and switchgrass.*

| **Diesel use** | **Energy use switchgrass (l/ha/yr)** | | | |
|---|---|---|---|---|
| *Production phase:* | *yr 1* | *yr 2 - 19* | *yr 20* | *average for cycle* |
| Total (l/ha/yr) | 135 | 57 | 57 | 60 |

| **Wheat** |
|---|
| *All years* |
| 162 |

Source:
Wheat: JRC (JRC: 2008)
Switchgrass: (Bullard, Metcalfe 2001)

Transport related emissions:
After the cultivation phase, the feedstock needs to be transported to the conversion facility. During the transport phase, various emissions take place. The parameters that describe these emissions have been added to the table below.

***Table 15:*** *Parameters of feedstock transportation that are used in this study.*

| | Wheat | Switchgrass | Unit |
|---|---|---|---|
| Fuel use of loading *1 | 0.63 | | l/ton freight |
| Fuel use of unloading *1 | 0.63 | | l/ton freight |
| Fuel use of transport *2 | 66 | | g $CO_2$-eq/tkm |
| Required conversion plants | 115 | 332 | # in Ukraine |
| Average distance to plant | 29 | 17 | km |
| Loading capacity per truck | 27 | | t/40t truck |

*Note: The trucks return empty.*

Source:

1: (Smeets, Lewandowski et al. 2009); The emission from loading and unloading has been recalculated to 0.59 g $CO_2$-eq/$MJ_{ethanol}$ for wheat and 0.70 g $CO_2$-eq/$MJ_{ethanol}$ for switchgrass. The input data for this calculation was the energy content (wh= 17 MJ/dry ton, sg= 17.8 MJ/ dry ton), a moisture content of 15% (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008), the conversion efficiency (wh= 1.864 $MJ_{feedstock}$/$MJ_{ethanol}$, sg= 2.377 $MJ_{feedstock}$/$MJ_{ethanol}$) (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008) and a diesel emission factor of 3.664 kg $CO_2$-eq/l (Kaltschmitt, Reinhardt 1997).

2: (Kaltschmitt, Reinhardt 1997)

Conversion related emissions:

***Table 16:*** *GHG emissions of wheat conversion.*

| **Wheat conversion** | **Input** | **Emission factor** | **Emission** |
|---|---|---|---|
| | *MJ/$MJ_{ethanol}$* | *gr $CO_2$-eq/MJ* | *gr. $CO_2$-eq/$MJ_{ethanol}$* |
| Electricity*1 | 0.061 | 51.7 | 3.2 |
| Natural gas*2 | 0.404 | 66.2 | 26.8 |

*1 For the electricity, the input was estimated according to (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). The emission factor from the electricity has been estimated, by using data from the GEMIS model[17] (Oeko institut 2010). In this model, the emissions from the Ukrainian electricity sector are extrapolated into the future. As the emission factor of 2015 was not directly available, an interpolation has been made, using the emissions from 2005, and the emission estimations for 2010 and 2020.

*2 For the natural gas, the input was estimated according to (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). The emission factor of Russian natural gas has been used to estimate the emissions (Biograce, Harmonised calculations of Biofuel Green house gas emissions in Europe 2010).

***Table 17:*** *GHG emissions of switchgrass conversion.*

| **Switchgrass conversion** | **Input** | **Emission factor** | **Emission** |
|---|---|---|---|
| | kg/$MJ_{ethanol}$ | gr. $CO_2$-eq/kg | gr. $CO_2$-eq/$MJ_{ethanol}$ |
| CaO | 0.002 | 1070 | 2.6 |
| $H_2SO_4$ | 0.004 | 213 | 0.9 |

Source: Input according to (JEC-WTW, JRC-EUCAR-CONCAWE collaboration 2008). Emission factors according to (JEC-WTW 2007).

The sum of the ethanol emissions are compared to the emissions of fossil gasoline. According to the IPCC these are 69.3 kg $CO_2$-eq/GJ LHV (IPCC 2006b).

[17] Global Emission Model for Integrated Systems. Developed by the German Institute for applied ecology.

# 4. Biodiversity

***Table 18:*** *The influence of land use factors on the Mean Species Abundance.*

| Land use class | Description | MSA_luc*1 |
|---|---|---|
| Mosaic: cropland/grassland | Livestock grazing | 0.7 |
| Mosaic: cropland/forest | Agricultural production intercropped with (native) trees | 0.5 |
| Low input agriculture | Low-external input and sustainable agriculture; subsistence and traditional farming; extensive farming | 0.3 |
| Intensive agriculture | High external input agriculture. | 0.1 |
| All agricultural land in the wheat bioenergy chain. | High external input agriculture. | 0.1 |
| All agricultural land in the switchgrass bioenergy chain. | Perennial bioenergy crops | 0.3*2 |
| Other | Natural areas, build-up areas, other unsuitable areas | n/a |

*Source:*
*1: (Alkemade, Oorschot et al. 2009)
*2: (van Rooij 2008)

# 5. Soil

The reclassification of the soil types from the World Reference Base (WRB) to the IPCC soil types, has been done on the basis of IPCC methodology. The result of the reclassification can be reviewed in the table below:

***Table 19:*** *Reclassification of the WBR soil classes to the IPCC classification system.*

| WRB class | IPCC class | WRB class | IPCC class |
|---|---|---|---|
| Water body | Water body | Haplic Chernozem | HAC |
| March | Wetland | Haplic Arenosol | LAC |
| Umbric Gleysol | Wetland | Hapic Phaeozem | Wetland |
| Umbric Albeluvisol | HAC | Gleyic Podzoluvisol | HAC |
| Terric Histosol | organic | Gleyic Phaeozem | Wetland |
| Stagnic Podzoluvisol | HAC | Gleyic Cambisol | HAC |
| Rendzic Leptosol | HAC | Gleyic Cambisol | HAC |
| Mollic Planosol | LAC | Gleyic Luvisol | HAC |
| Mollic Gleysol | Wetland | Folic Histosol | organic |
| Luvic Phaeozem | HAC | Fibric Histosol | organic |
| Luvic Kastanozem | HAC | Eutric Podzoluvisol | HAC |
| Luvic Chernozem | HAC | Eutric Gleysol | Wetland |
| Leptic Podzol | Spodic | Eutric Fluvisol | HAC |
| Humic Andosol | Volcanic | Eutric Cambisol | HAC |
| Histic Fluvisol | HAC | Dystric Fluvisol | HAC |
| Haplic solonetz | HAC | Dystric Fluvisol | HAC |
| Haplic Podzol | Spodic | Dystric Cambisol | HAC |
| Haplic Podzol | Spodic | Dystric Cambisol | HAC |
| Haplic Phaeozem | LAC | Chromic Cambisol | HAC |
| Haplic Phaeozem | Wetland | Cambic Podzol | Spodic |
| Haplic Luvisol | HAC | Cambic Arenosol | LAC |
| Haplic Leptosol | Spodic | Calcic Chernozem | HAC |
| Haplic Kastanozem | HAC | Calcaric Fluvisol | HAC |
| Haplic Greyzem | LAC | Calcaric Cambisol | HAC |

*Source:* (IPCC 2006a)

The reclassification, has been based on the following flow sheet, that is issued by the IPCC (IPCC 2006a) has been applied:

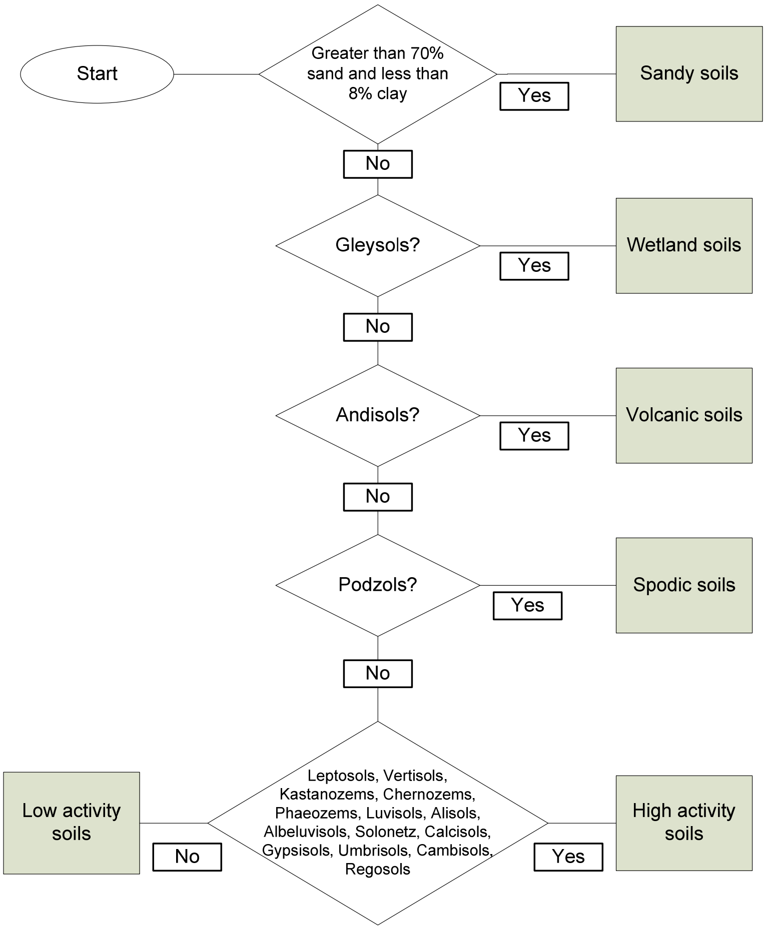


***Figure 2:*** *Soil reclassification according to the IPCC method:*

The results of the classification looks as follows:

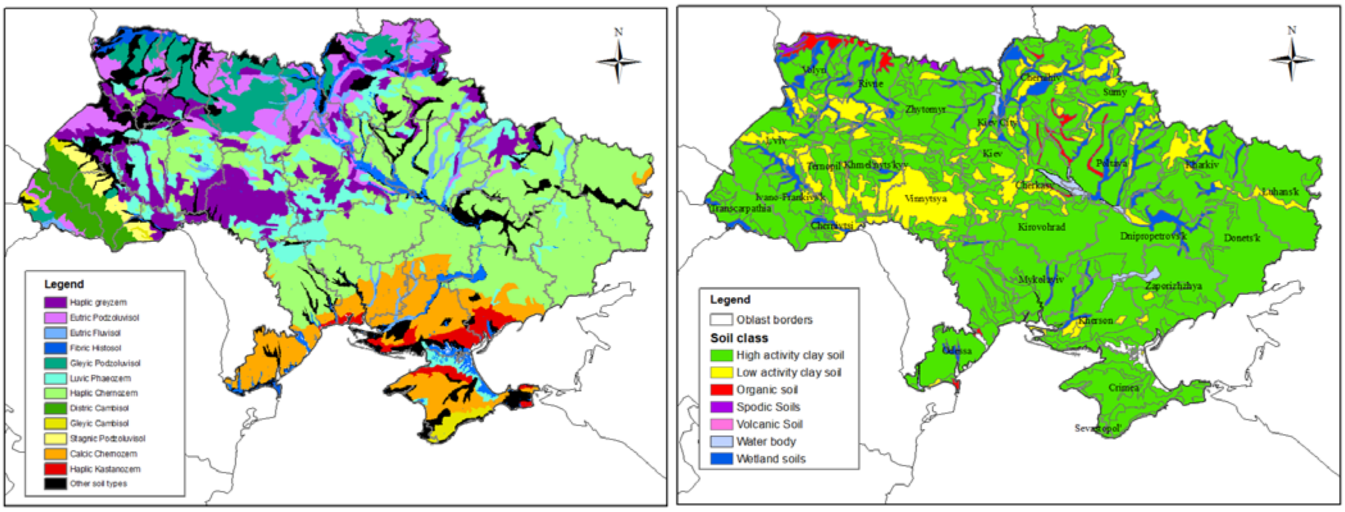


***Figure 3:*** *Soil map reclassification, from WRB (left) to IPCC (right).*

5.1 Water erosion

The water erosion is calculated with the RUSLE-equation. The equation is described as follows:

$$A = (R * K * L_s * C * P)$$

| | | |
|---|---|---|
| A = | Soil loss | (ton/ha/yr) |
| R = | Rainfall erosion index | (MJ mm/ha h) |
| K = | Soil erodibility factor | (ton ha h/ha MJ mm) |
| $L_s$ = | Slope factor | (-) |
| C = | Crop management factor | (-) |
| P = | Agricultural practise factor | (-) |
| Source: | (USDA 2002). | |

The rainfall erosion index has been calculated by the following formula:
follows:

$$R = (12 * Pr) * 0.0783 - 12.98$$

R = Maximum rainfall erosion index
Pr = Precipitation (mm/month)

As an example, the rainfall erosion index has been calculated for three weather stations, namely Al-Petri (far South), Sumy (East) and Ivano-Frankivsk (West). Also the average rainfall erosion index is indicated.

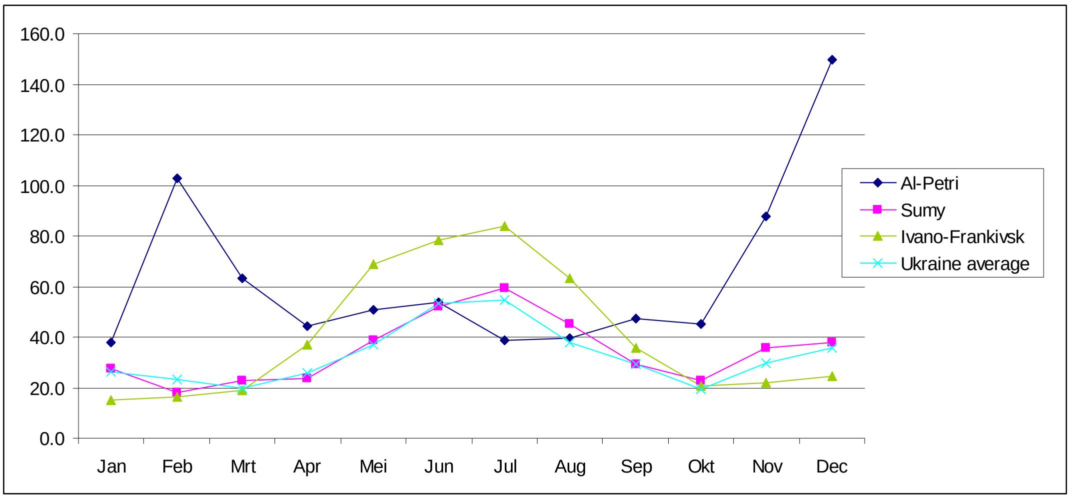


***Figure 4:** Rainfall erosion index of Al-Petri, Sumy and Ivano-Frankivsk, including the Ukrainian average.*

K-factors have been assigned on a basis of the soils textural class (OMAFRA (canada) 2010). However, first the soil classes had to be reclassified, according to the USDA standards. The reclassification has been done according to soil descriptions in the World Reference Base on Soil Resources (IUSS, ISRIC et al. 2006), and an expert interview (Cohen 2010). The following table shows the soil-reclassification from the WRB to the USDB classification. Also the corresponding K-factors were indicated:

***Table 20:*** *Reclassification of the WRB system, towards the required system for the K-factor. K-factors were applied on a basis of average soil organic matter content.*

| WRB classification | Reclassification to USDA soil types: | Soil erodibility factor (K) |
|---|---|---|
| Water body | Wetland | 0 |
| March | Wetland | 0 |
| Umbric Gleysol | Wetland | 0 |
| Umbric Albeluvisol | Clay | 0.22 |
| Terric Histosol | Organic | 0.21 |
| Stagnic Podzoluvisol | Clay | 0.22 |
| Rendzic Leptosol | Stone | 0 |
| Mollic Planosol | Heavy clay | 0.17 |
| Mollic Gleysol | Wetland | 0 |
| Luvic Phaeozem | Loamy sand | 0.05 |
| Luvic Kastanozem | Loamy sand | 0.05 |
| Luvic Chernozem | Loamy sand | 0.05 |
| Leptic Podzol | Sand | 0.02 |
| Humic Andosol | Very fine sand | 0.43 |
| Histic Fluvisol | Clay | 0 |
| Haplic solonetz | Heavy clay | 0.17 |
| Haplic Podzol | Sand | 0.02 |
| Haplic Podzol | Sand | 0.02 |
| Haplic Phaeozem | Loamy sand | 0.05 |
| Haplic Phaeozem | Loamy sand | 0.05 |
| Haplic Luvisol | Clay | 0.22 |
| Haplic Leptosol | Stone | 0 |
| Haplic Kastanozem | Loamy sand | 0.05 |
| Haplic Greyzem | Loamy sand | 0.05 |
| Haplic Chernozem | Loamy sand | 0.05 |
| Haplic Arenosol | Dune sand | 0.46 |
| Hapic Phaeozem | Loamy sand | 0.05 |
| Gleyic Podzoluvisol | Clay | 0.22 |
| Gleyic Phaeozem | Loamy sand | 0.05 |
| Gleyic Cambisol | Sand | 0.02 |
| Gleyic Cambisol | Sand | 0.02 |
| Gleyic Luvisol | Clay | 0.22 |
| Folic Histosol | Organic | 0.21 |
| Fibric Histosol | Organic | 0.21 |
| Eutric Podzoluvisol | Clay | 0.22 |
| Eutric Gleysol | Wetland | 0 |
| Eutric Fluvisol | Clay | 0.22 |
| Eutric Cambisol | Sand | 0.02 |
| Dystric Fluvisol | Clay | 0.22 |
| Dystric Fluvisol | Clay | 0.22 |
| Dystric Cambisol | Sand | 0.02 |
| Dystric Cambisol | Sand | 0.02 |
| Chromic Cambisol | Sand | 0.02 |
| Cambic Podzol | Sand | 0.02 |
| Cambic Arenosol | Dune sand | 0.46 |
| Calcic Chernozem | Loamy sand | 0.05 |
| Calcaric Fluvisol | Clay | 0.22 |
| Calcaric Cambisol | Sand | 0.02 |

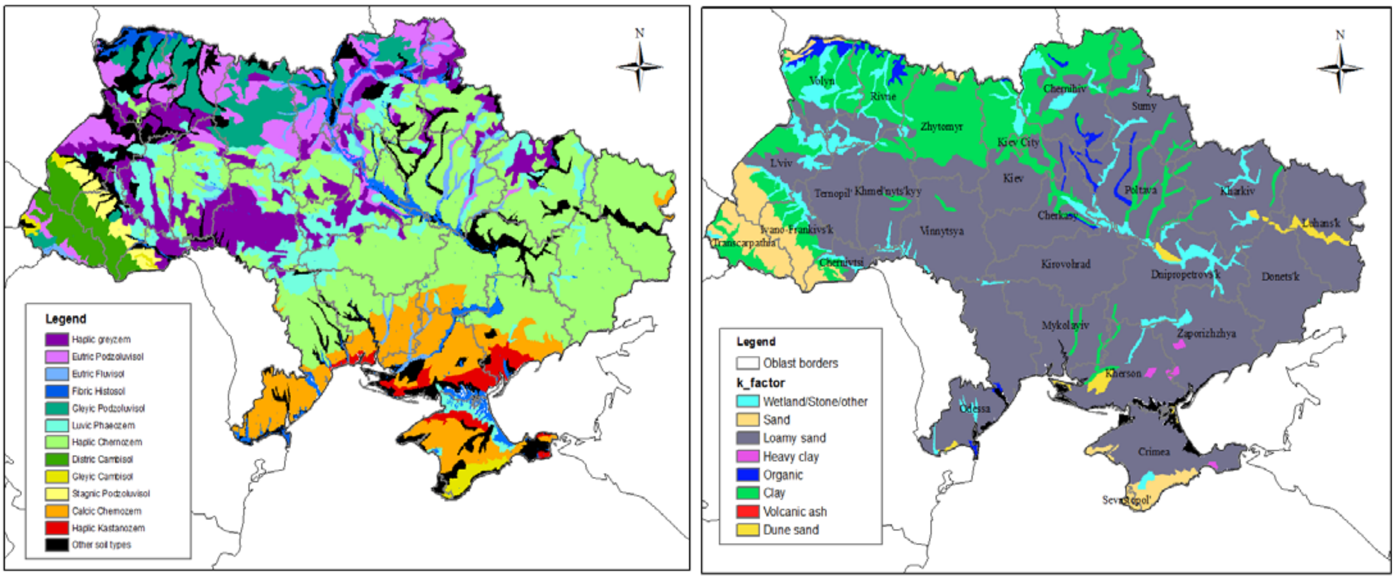


***Figure 5:*** *Soil map reclassification, from WRB (left) to USDA (right).*

In order to determine the slope factor (Ls), first the slope gradient and slope length have been derived from a Ukrainian altitude map. In this study a 50x50m altitude map from ASTER has been consulted.

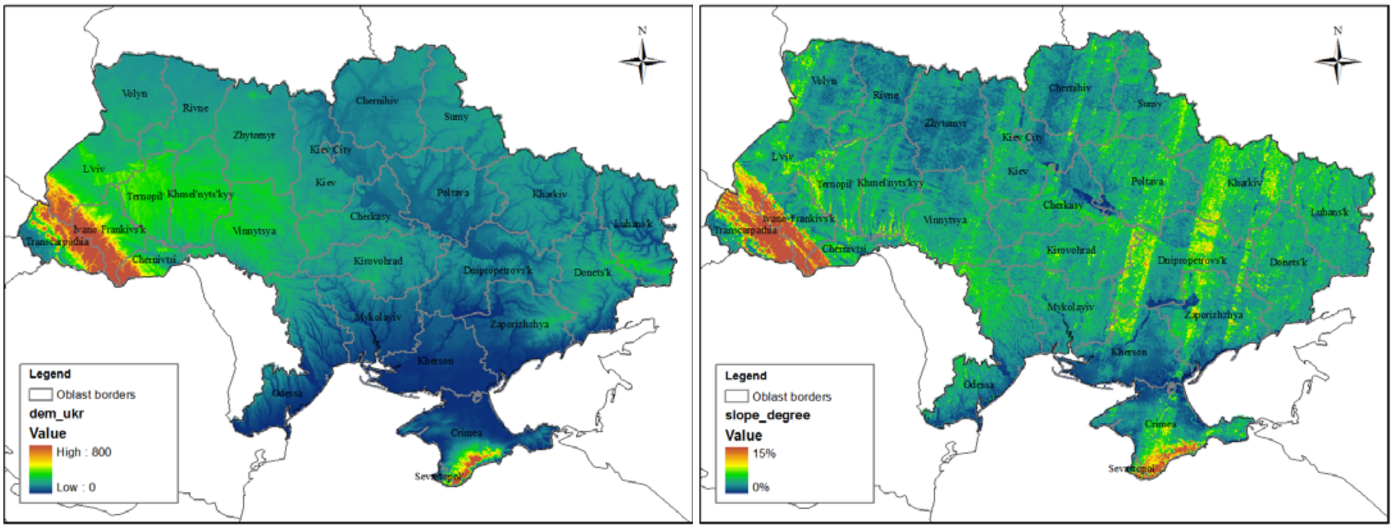


***Figure 6:*** *Altitude (m above sea level) and slope (%) map of Ukraine* (NASA, Japan's Ministry of Economy, Trade and Industry (METI) et al. 2010).

To determine the management factor (C), a crop and tillage factor were required. According to the Ontario ministry of agriculture, the following factors were applied:

***Table 21:*** *crop type factors for the RUSLE calculation.*

| Crops | Crop Type factor of: | Factor |
|---|---|---|
| Maize for grain | Grain Corn | 0.40 |
| Rape | Silage Corn, Beans & Canola | 0.50 |
| Wheat, barley, other cereals and sunflowers[*1]. | Cereals (Spring & Winter) | 0.35 |
| Potatoes, vegetables, and sugar beet[*1] | Seasonal Horticultural Crops[18] | 0.50 |
| Pasture land and switchgrass | Hay and Pasture | 0.02 |

*Source:* (OMAFRA (canada) 2010)

[18] According to the Random House Dictionary, horticulture is defined as: "
The cultivation of flowers, fruits, vegetables, or ornamental plants." Therefore the inclusion of potatoes, vegetables and sugar beet is justified.

***Table 22:** tillage factors for the RUSLE calculation.*

| **Crops** | **Tillage Method** | **Factor** |
|---|---|---|
| Winter wheat, winter barley*1 | Fall Ploughing | 1 |
| Summer wheat, spring barley, maize for grain, other cereals, potatoes, vegetables, sugar beet, sunflower, rape, pasture (first cycle year), switchgrass (first cycle year) *1 | Spring Ploughing | 0.9 |
| Pastures (subsequent cycle years), switchgrass (subsequent cycle years) | No Tillage | 0.25 |

*Source:* (OMAFRA (canada) 2010)
*1 Approximately 90% of all Ukrainian wheat is winter wheat. Approximately 10% of the Ukrainian Barley is winter Barley.

For the support factor (P), it was assumed that in both the current situation, and in the bioethanol chains, cross slope farming is applied. Thereby it is implicitly assumed that today's farmers are aware of the erosion problem, and adjust there management regimes in an attempt to reduce the water erosion. According to the Ontario ministry of agriculture, a P factor of 0.75 should be applied (OMAFRA (canada) 2010).

5.2 Water erosion
The wind erosion is calculated by the Wind Erosion Equation, that was developed by Dr. W.S. Chapil in 1963. The equation looks as follows:

$$E = \int (CIKVL) \qquad \text{Main equation}$$

$$E_1 = I \qquad \textbf{a}$$

$$E_2 = E_1 \cdot K \qquad \textbf{b}$$

$$E_3 = E_2 \cdot C \qquad \textbf{c}$$

$$E_4 = \left(F^{0.3484} + E_3^{\ 0.3484} - E_2^{\ 0.3484}\right)^{2.87} \qquad \textbf{d}$$

$$F = E_2 \cdot \left(1 - 0.1218\left(\frac{L}{L_0}\right)^{-0.3829} \cdot \exp\left(-3.33\frac{L}{L_0}\right)\right) \qquad \textbf{e}$$

$$L_0 = 1.56 \cdot 10^6 \cdot E_2^{\ -1.26} \cdot \exp(-0.00156 \cdot E_2) \qquad \textbf{f}$$

$$E_5 = g \cdot E_4^{\ h} \qquad \textbf{g}$$

$$g = \exp\left(-0.759 \cdot V - 4.74 \cdot 10^{-2} \cdot V^2 + 2.95 \cdot 10^{-4} \cdot V^3\right) \qquad \textbf{h}$$

$$h = 1.0 + 0.893 \cdot 10^{-2} \cdot V + 8.51 \cdot 10^{-3} \cdot V^2 - 1.5 \cdot 10^{-5} \cdot V^3 \qquad \textbf{i}$$

E = Potential average annual soil loss (t/ha/yr)
I = Soil erodibility index (T $ha^{-1} \cdot yr$) - Includes properties as : texture, organic matter, calcium carbonate concentration
K = Roughness factor - A measure of the effect of ridges and cloddiness made by field operations
V = Vegetation cover (SGe ton/ha) - Includes the kind, amount and orientation of the vegetation of the surface
C = Climate factor - Local climatic erosivity such as wind speed and surface soil moisture
L = Unsheltered distance across a field (m) - Unprotected distance along the prevailing wind direction
$L_{0=}$ Maximum field length (m)
Source: (Kerckhoven, Riksen et al. 2009)

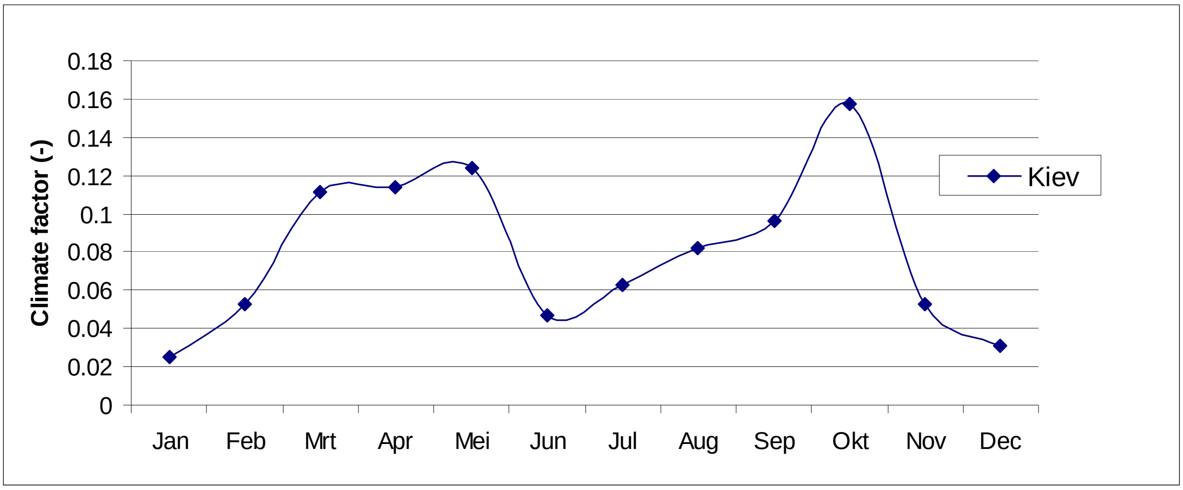


***Figure 7:*** *Average monthly climate factor in the Kiev oblast.*
*Source: Spatial data provided by NOAA/OAR/ESRL PSD, http://www.esrl.noaa.gov/psd/*

To determine the most vulnerable month, the potential soil loss has been calculated for the oblast of Kiev. The calculation assumes clay soils, and a K-factor of 0.77. From this graph it was determined that March was the most sensitive.

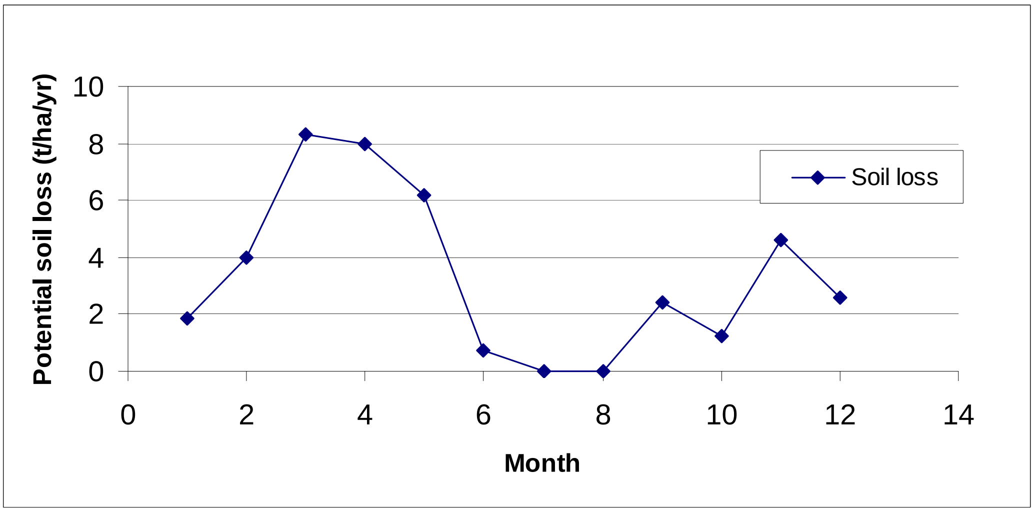


***Figure 8:*** *Potential soil loss caused by wind erosion in the oblast of Kiev (t/ha/yr).*

The table below describes the soil types that can be found in Ukraine according to classification by the 'World reference base for soils', including the assigned erodibility factors, that are required for the WEQ equation.

***Table 23:*** *The soil types according to the according to classification by the 'World reference base for soils' and the soil erodibility indexes.*

| WRB classification | IPCC Classification | USDA classification | Soil erodibility index (I) |
|---|---|---|---|
| - | - | - | *Ton/ha/yr* |
| Water | Water body | Wetland | 0 |
| March | Wetland | Wetland | 0 |
| Umbric Gleysol | Wetland | Wetland | 0 |
| Umbric Albeluvisol | HAC | Clay | 128 |
| Terric Histosol | Organic | Organic | 188 |
| Stagnic Podzoluvisol | HAC | Clay | 128 |
| Rendzic Leptosol | HAC | Stone | 0 |
| Mollic Planosol | LAC | Heavy clay | 188 |
| Mollic Gleysol | Wetland | Wetland | 0 |
| Luvic Phaeozem | HAC | Loamy sand | 304 |
| Luvic Kastanozem | HAC | Loamy sand | 304 |
| Luvic Chernozem | HAC | Loamy sand | 304 |
| Leptic Podzol | Spodic | Sand | 384 |
| Humic Andosol | Volcanic | Ash | 384 |
| Histic Fluvisol | HAC | Clay | 128 |
| Haplic solonetz | HAC | Heavy clay | 188 |
| Haplic Podzol | Spodic | Sand | 384 |
| Haplic Podzol | Spodic | Sand | 384 |
| Haplic Phaeozem | Wetland | Loamy sand | 304 |
| Haplic Phaeozem | Wetland | Loamy sand | 304 |
| Haplic Luvisol | HAC | Clay | 128 |
| Haplic Leptosol | HAC | Stone | 0 |
| Haplic Kastanozem | HAC | Loamy sand | 304 |
| Haplic Greyzem | LAC | Loamy sand | 304 |
| Haplic Chernozem | HAC | Loamy sand | 304 |
| Haplic Arenosol | LAC | Dune sand | 695 |
| Hapic Phaeozem | Wetland | Loamy sand | 304 |
| Gleyic Podzoluvisol | HAC | Clay | 128 |
| Gleyic Phaeozem | Wetland | Loamy sand | 304 |
| Gleyic Cambisol | HAC | Sand | 384 |
| Gleyic Cambisol | HAC | Sand | 384 |
| Glecyic Luvisol | HAC | Clay | 128 |
| Folic Histosol | organic | Organic | 188 |
| Fibric Histosol | organic | Organic | 188 |
| Eutric Podzoluvisol | HAC | Clay | 128 |
| Eutric Gleysol | Wetland | Wetland | 0 |
| Eutric Fluvisol | HAC | Clay | 128 |
| Eutric Cambisol | HAC | Sand | 384 |
| Dystric Fluvisol | HAC | Clay | 128 |
| Dystric Fluvisol | HAC | Clay | 128 |
| Dystric Cambisol | HAC | Sand | 384 |
| Dystric Cambisol | HAC | Sand | 384 |
| Chromic Cambisol | HAC | Sand | 384 |
| Cambic Podzol | Spodic | Sand | 384 |
| Cambic Arenosol | LAC | Dune sand | 695 |
| Calcic Chernozem | HAC | Loamy sand | 304 |
| Calcaric Fluvisol | HAC | Clay | 128 |
| Calcaric Cambisol | HAC | Sand | 384 |

In tables 24-25, the crop specific soil roughness factors and vegetation factors have been given. As not all the crops could be assigned a specific K-factor, the sunflowers and rape were appointed K-factors of wheat. Vegetables were appointed the K-factor of sugar beet.

***Table 24:*** *The soil roughness factors, for the WEQ.*

| | K-factor |
|---|---|
| Summer wheat | 0.77 |
| Winter wheat | 0.77 |
| Spring barley | 0.77 |
| Winter barley | 0.77 |
| Other cereals | 0.77 |
| Potatoes | 0.66 |
| Sugar beet | 0.81 |
| Maize | 0.77 |
| Sunflower*1 | 0.77 |
| Pasture land | 0.81 |
| Switchgrass | 0.81 |
| Vegetables*2 | 0.81 |
| Rape*1 | 0.77 |

*Source:* (Kerckhoven, Riksen et al. 2009)
*1 Based on wheat
*2 Based on sugar beet

The next factor is the vegetation factor V. Although the WEQ only requires the V-factor for March, the factors of the other months were used to determine the most vulnerable period.

***Table 25:*** *The vegetation factors for the WEQ.*

| Vegetation factor (V-factor)*1 | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Okt | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corn | 0 | 0 | 0 | 0 | 0.01 | 0.16 | 0.71 | 1.56 | 4.79 | 7.40 | 0 | 0 |
| Potatoes | 0 | 0 | 0 | 0 | 0.19 | 0.85 | 6.82 | 13.5 | 0 | 0 | 0 | 0 |
| Spring barley | 0 | 0 | 0 | 0.13 | 0.50 | 1.58 | 3.96 | 4.73 | 0 | 0 | 0 | 0 |
| Summer wheat | 0 | 0 | 0 | 0.13 | 0.50 | 1.58 | 3.96 | 4.73 | 0 | 0 | 0 | 0 |
| Sugar beets | 0 | 0 | 0 | 0 | 0.13 | 0.50 | 1.58 | 3.96 | 4.73 | 4.73 | 0 | 0 |
| Sunflower | 0 | 0 | 0 | 0.01 | 0.10 | 0.37 | 0.75 | 1.15 | 2.54 | 3.98 | 0 | 0 |
| Switchgrass/pasture1st year*2 | 0 | 0 | 0 | 0.39 | 3.79 | 7.55 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 |
| Switchgrass subsequent years*2 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 |
| Pasture subsequent years*3 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 | 7.84 |
| Winter rape | 0.91 | 0.91 | 0.91 | 1.20 | 1.74 | 3.40 | 0 | 0 | 0.19 | 0.44 | 0.53 | 0.85 |
| Winter barley | 0.85 | 0.85 | 0.85 | 0.91 | 1.20 | 1.74 | 3.40 | 0 | 0 | 0.19 | 0.44 | 0.53 |
| Winter wheat | 0.85 | 0.85 | 0.85 | 0.91 | 1.20 | 1.74 | 3.40 | 0 | 0 | 0.19 | 0.44 | 0.53 |
| Other cereals | 0 | 0 | 0 | 0.13 | 0.50 | 1.58 | 3.96 | 4.73 | 0 | 0 | 0 | 0 |
| Vegetables*4 | 0 | 0 | 0.01 | 0.13 | 1.36 | 1.21 | 1.01 | 0.03 | 0.11 | 0.57 | 0 | 0 |

Source: (USDA 2006)
Notes:
*1: The V-factor is derived from the USDA and adapted to the Ukrainian situation using the planting and harvesting dates, that are described in appendix 1.1. It is assumed that the crops are planted perpendicular to the prevailing wind direction, to prevent erosion on vulnerable sites.
*2 The V-factor of switchgrass is based on the V-factor of grassland/miscanthus in (Hilst 2009). A 20-year cycle is assumed. Although the switchgrass is mowed in November, the stems are left in the soil to prevent soil erosion.
*3: Pasture land does not have a fixed mowing time. Grass can also be grazed by livestock. Similarly to Hilst 2009, grass is assumed to have the maximum value of cover (USDA 2006).
*4: The vegetables vegetation factor is build up out of 49% cabbage, 29% onion, and 22% carrots.

# 6. Water

Water quantity

The main equation that was applied to assess the water quantity is:

$$WS = \sum\left[ET_0 * K_c\right] - P$$

| | | |
|---|---|---|
| WS = | Water shortage | (mm) |
| $ET_0$ = | Monthly reference evapotranspiration | (mm/month) |
| $K_c$ = | Crop evapotranspiration coefficient | (-) |
| P = | Monthly effective precipitation | (mm/month) |

The reference evapotranspiration has been calculated according to the Penman-Monteith equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

| | |
|---|---|
| $ET_o$ | = reference evapotranspiration (mm day$^{-1}$) |
| $R_n$ | = net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$) |
| G | = soil heat flux density (MJ m$^{-2}$ day$^{-1}$) |
| T | = mean daily air temperature at 2 m height (°C) |
| $u_2$ | = wind speed at 2 m height (m s$^{-1}$) |
| $e_s$ | = saturation vapour pressure (kPa) |
| $e_a$ | = actual vapour pressure (kPa) |
| $e_s$ - $e_a$ | = saturation vapour pressure deficit (kPa) |
| D | = slope vapour pressure curve (kPa °C$^{-1}$) |
| g | = psychrometric constant (kPa °C$^{-1}$) |

The data for this equation has been taken from 12 climate stations (CLIMWAT (FAO 2010a)), that are adjacent to the Ukrainian border. The following $ET_0$ values have been derived, using CROPWAT software:

***Table 26:** Location of the CROPWAT climate stations, and the corresponding reference evapotranspiration (mm/day).*

| $ET_0$ | Country | LatDD | LongDD | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Okt | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Brest | Belarus | 52.11 | 23.68 | 0.19 | 0.37 | 0.96 | 2.19 | 3.38 | 4.01 | 4.08 | 3.50 | 2.19 | 1.11 | 0.46 | 0.21 |
| Gomel | Belarus | 52.45 | 31.00 | 0.13 | 0.32 | 0.80 | 2.16 | 3.78 | 4.31 | 4.17 | 3.63 | 2.29 | 1.11 | 0.39 | 0.22 |
| Kursk | Russia | 51.65 | 36.18 | 0.11 | 0.23 | 0.51 | 1.72 | 3.29 | 3.70 | 3.73 | 3.26 | 2.18 | 1.09 | 0.38 | 0.14 |
| Valuski | Russia | 50.21 | 38.10 | 0.20 | 0.17 | 0.63 | 1.92 | 3.62 | 4.03 | 4.13 | 3.61 | 2.40 | 1.32 | 0.51 | 0.14 |
| Certkovo | Russia | 49.38 | 40.15 | 0.12 | 0.16 | 0.51 | 1.95 | 3.73 | 4.26 | 4.62 | 4.05 | 2.73 | 1.42 | 0.44 | 0.15 |
| Rostov-na-donu | Russia | 47.25 | 39.81 | 0.33 | 0.42 | 0.78 | 2.33 | 3.76 | 4.39 | 5.06 | 4.46 | 3.12 | 1.68 | 0.74 | 0.35 |
| Primorsko-Ahtarsk | Russia | 46.03 | 38.15 | 0.40 | 0.54 | 1.03 | 2.28 | 3.59 | 4.59 | 4.99 | 4.50 | 3.07 | 1.78 | 0.95 | 0.42 |
| Sulina | Romania | 45.15 | 29.66 | 0.60 | 0.73 | 1.13 | 1.93 | 3.24 | 4.40 | 4.91 | 4.58 | 3.15 | 1.91 | 0.99 | 0.61 |
| Iasa | Romania | 47.16 | 27.63 | 0.37 | 0.56 | 1.23 | 2.85 | 4.17 | 4.68 | 4.80 | 4.44 | 3.07 | 1.75 | 0.75 | 0.42 |
| Debrecen | Hungary | 47.48 | 21.63 | 0.43 | 0.71 | 1.51 | 2.82 | 3.80 | 4.31 | 4.74 | 4.03 | 2.80 | 1.61 | 0.81 | 0.46 |
| Constanta | Romania | 44.21 | 28.63 | 0.52 | 0.74 | 1.20 | 2.13 | 3.28 | 4.39 | 4.83 | 4.46 | 3.19 | 1.87 | 0.97 | 0.6 |
| Tuapse | Russia | 44.10 | 39.06 | 1.32 | 1.42 | 1.78 | 2.10 | 2.79 | 3.67 | 4.14 | 3.95 | 3.12 | 2.23 | 1.74 | 1.34 |

*Source:* (FAO 2010a, FAO 2010b)

The crop evaporation coefficient (Kc) was calculated on a basis of FAO data. The main input parameter that determines the Kc value is the stage of development. Using FAO data, combined with data on the planting dates of the crops, the following stages of development were used:

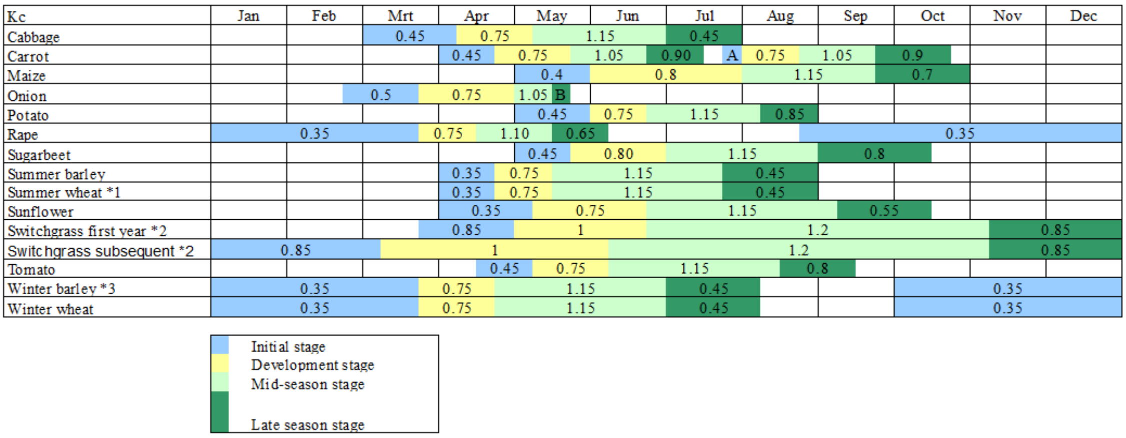


***Figure 9:*** *Kc-value on arable land per development stage per crop type. A=0.45 B=0.85*
*Source: {{184 Brouwer, C 1996;}}*
*[*1]: based on the value for spring barley.*
*[*2]:Source: Specific values for switchgrass are unavailable. Consequently, the Kc value per development stage are based on the Kc of miscanthus* (Hilst 2009, KNMI 2002). *Also the development stages are derived from {{92 Hilst, van der, F. 2009; 254 KNMI 2002}}.*
*[*3]: based on value for winter wheat.*

According to the planting dates, growth stages and stage specific Kc-values, a monthly Kc value could be allocated to the various crop types. Within the group 'vegetables', only cabbage, onion, tomato and carrot could be assigned Kc-values. By taking the relative cropping areas of these vegetables, an average Kc-value could be determined. It was assumed that this value was also relevant for the other vegetables.

Combining the crop specific Kc-values with the oblast-specific crop fractions, the following Kc coefficients for arable land were derived:

***Table 27:*** *Crop evapotranspiration coefficients per month per oblast.*

| $K_c$ coëfficiënts per oblast | Jan | Feb | Mrt | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crimea | 0.19 | 0.19 | 0.25 | 0.68 | 0.96 | 1.02 | 0.63 | 0.30 | 0.06 | 0.21 | 0.19 | 0.19 |
| Vinnytsya | 0.14 | 0.14 | 0.19 | 0.50 | 0.78 | 0.87 | 0.68 | 0.52 | 0.28 | 0.28 | 0.14 | 0.14 |
| Volyn | 0.13 | 0.14 | 0.18 | 0.43 | 0.68 | 0.77 | 0.55 | 0.34 | 0.07 | 0.17 | 0.13 | 0.13 |
| Dnipropetrovs'k | 0.11 | 0.11 | 0.15 | 0.50 | 0.78 | 0.94 | 0.80 | 0.64 | 0.35 | 0.28 | 0.11 | 0.11 |
| Donets'k | 0.10 | 0.10 | 0.14 | 0.49 | 0.76 | 0.94 | 0.82 | 0.64 | 0.32 | 0.25 | 0.10 | 0.10 |
| Zhytomyr | 0.10 | 0.10 | 0.13 | 0.34 | 0.58 | 0.67 | 0.52 | 0.40 | 0.20 | 0.21 | 0.10 | 0.10 |
| Transcarpathia | 0.08 | 0.08 | 0.13 | 0.31 | 0.66 | 0.89 | 0.77 | 0.67 | 0.32 | 0.29 | 0.08 | 0.08 |
| Zaporizhzhya | 0.12 | 0.12 | 0.16 | 0.55 | 0.80 | 0.96 | 0.81 | 0.62 | 0.31 | 0.25 | 0.12 | 0.12 |
| Ivano-Frankivs'k | 0.10 | 0.10 | 0.14 | 0.34 | 0.66 | 0.83 | 0.71 | 0.56 | 0.21 | 0.22 | 0.10 | 0.10 |
| Kiev | 0.13 | 0.13 | 0.17 | 0.45 | 0.73 | 0.85 | 0.66 | 0.51 | 0.27 | 0.27 | 0.13 | 0.13 |
| Kirovohrad | 0.12 | 0.12 | 0.16 | 0.52 | 0.78 | 0.88 | 0.75 | 0.60 | 0.33 | 0.26 | 0.12 | 0.12 |
| Luhans'k | 0.11 | 0.11 | 0.14 | 0.48 | 0.73 | 0.90 | 0.78 | 0.63 | 0.33 | 0.26 | 0.11 | 0.11 |
| L'viv | 0.14 | 0.14 | 0.19 | 0.45 | 0.73 | 0.84 | 0.65 | 0.45 | 0.14 | 0.21 | 0.14 | 0.14 |
| Mykolayiv | 0.14 | 0.14 | 0.18 | 0.59 | 0.84 | 0.93 | 0.75 | 0.54 | 0.27 | 0.24 | 0.14 | 0.14 |
| Odessa | 0.15 | 0.15 | 0.20 | 0.58 | 0.85 | 0.91 | 0.66 | 0.43 | 0.21 | 0.23 | 0.15 | 0.15 |
| Poltava | 0.10 | 0.10 | 0.13 | 0.41 | 0.72 | 0.90 | 0.76 | 0.65 | 0.39 | 0.32 | 0.10 | 0.10 |
| Rivne | 0.12 | 0.13 | 0.17 | 0.42 | 0.69 | 0.77 | 0.60 | 0.41 | 0.14 | 0.19 | 0.12 | 0.12 |
| Sumy | 0.11 | 0.11 | 0.14 | 0.40 | 0.67 | 0.81 | 0.63 | 0.49 | 0.25 | 0.25 | 0.11 | 0.11 |
| Ternopil' | 0.16 | 0.16 | 0.20 | 0.53 | 0.81 | 0.88 | 0.63 | 0.43 | 0.20 | 0.25 | 0.16 | 0.16 |
| Kharkiv | 0.12 | 0.12 | 0.15 | 0.49 | 0.78 | 0.94 | 0.77 | 0.58 | 0.29 | 0.26 | 0.12 | 0.12 |
| Kherson | 0.15 | 0.15 | 0.20 | 0.60 | 0.84 | 0.92 | 0.72 | 0.52 | 0.26 | 0.25 | 0.15 | 0.15 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Khmel'nyts'kyy | 0.15 | 0.15 | 0.19 | 0.50 | 0.75 | 0.78 | 0.57 | 0.39 | 0.19 | 0.23 | 0.15 | 0.15 |
| Cherkasy | 0.12 | 0.12 | 0.16 | 0.47 | 0.75 | 0.86 | 0.69 | 0.57 | 0.34 | 0.30 | 0.12 | 0.12 |
| Chernivtsi | 0.08 | 0.08 | 0.11 | 0.31 | 0.65 | 0.86 | 0.76 | 0.71 | 0.42 | 0.34 | 0.08 | 0.08 |
| Chernihiv | 0.08 | 0.08 | 0.11 | 0.29 | 0.53 | 0.67 | 0.55 | 0.48 | 0.28 | 0.25 | 0.08 | 0.08 |

On pasture land, the reference evapotranspiration is dependant on the climate:

***Table 28:*** *Kc values on pasture land.*

| **Pasture land** | **$K_c$-value** |
|---|---|
| Moist climate | 1.0 |
| Dry climate | 0.95 |

*Source:* (Brouwer, Heibloem et al. 1996)

Together with the precipitation data from the NOAA, the water shortage can be spatially calculated, according to the above formula. The following graph depicts the water shortage for three Ukrainian oblasts. The oblasts represent respectively, the Southern oblasts (Crimea), the Northern oblasts (Sumy), and the Carpathian oblasts (Ivano-Frankivs'k).

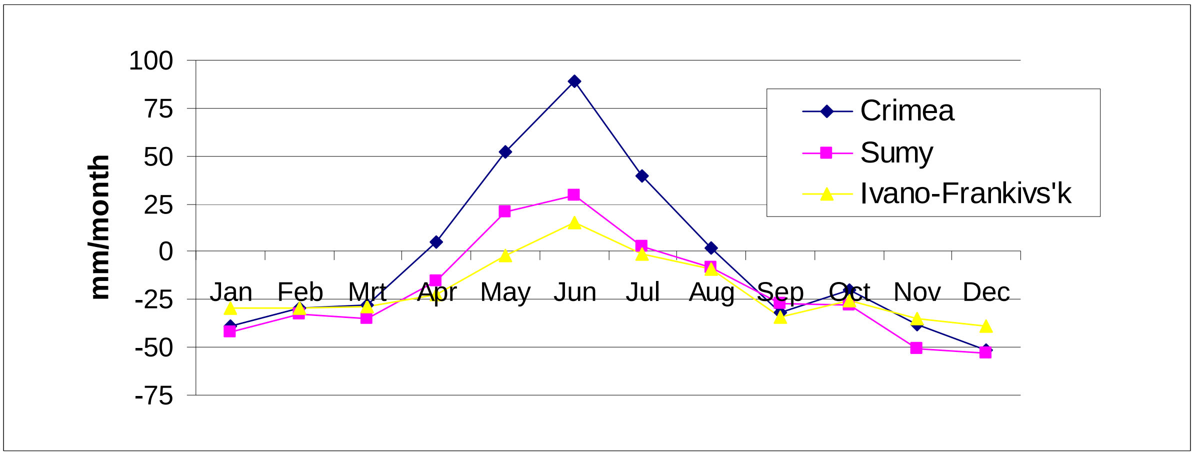


***Figure 10:*** *Water shortage on arable land of three oblasts per month.*

From the graph it can be derived that the water shortage is largest from the end of July to the beginning of August. The spatial comparison between the current situation and the two bioenergy chains will be done when the water shortage per grid cell is largest.

From the analysis it can be concluded that switchgrass leads to larger water shortages then wheat. The water use efficiency is however larger for switchgrass, as can be seen from table 29.

***Table 29:*** *Water use efficiency.*

| **Crop** | **Source** | |
|---|---|---|
| | *Berndes* | *FAO* |
| Maize | 0.7-2.1 | 0.7-1.41 |
| Miscanthus | 9.5 | 4.1-22.0 |
| Potato | | 1.08-1.89 |
| Rapeseed | 0.9-1.2 | |
| Sugar beet | 0.9-2.4 | 1.02-1.54 |
| Wheat (summer, winter) | 0.6-3.6 | 0.69-0.86 |

Source: (Berndes 2002)

# Appendix 2: Climate data

<u>Temperature and precipitation</u>

The precipitation data used in this study, has been provided by 45 Ukrainian weather stations (NOAA ESRL physical science division 2008). Also 4 non-Ukrainian weather stations were used, to provide accurate data on border areas. The data can be found in table 1a-1b.

**Table 1a:** Average long-term precipitation data (mm/month).

| Name: | LATDD | LONGDD | Jan | Feb | Mrt | Apr | Mei | Jun | Jul | Aug | Sep | Okt | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Al-Petri* | 44 | 34 | 54 | 123 | 81 | 61 | 68 | 71 | 55 | 56 | 64 | 62 | 107 | 173 |
| *Askaniia-Nova* | 46 | 34 | 30 | 28 | 25 | 27 | 38 | 46 | 42 | 35 | 28 | 26 | 34 | 37 |
| *Chernihiv* | 51 | 31 | 42 | 36 | 35 | 42 | 45 | 79 | 83 | 67 | 42 | 35 | 48 | 47 |
| *Chernivetsi* | 48 | 26 | 32 | 32 | 36 | 58 | 77 | 105 | 103 | 61 | 51 | 33 | 36 | 37 |
| *Dnipropetrovsk* | 49 | 35 | 45 | 36 | 34 | 38 | 46 | 59 | 56 | 37 | 36 | 32 | 42 | 52 |
| *Donetsk* | 48 | 38 | 43 | 34 | 33 | 41 | 52 | 62 | 48 | 41 | 40 | 27 | 42 | 52 |
| *Feodosiia* | 45 | 35 | 36 | 34 | 31 | 33 | 35 | 44 | 35 | 51 | 38 | 24 | 38 | 46 |
| *Gajvoron* | 48 | 30 | 36 | 34 | 31 | 33 | 35 | 44 | 35 | 51 | 38 | 24 | 38 | 46 |
| *Heniches'k* | 46 | 35 | 35 | 32 | 31 | 29 | 34 | 41 | 39 | 26 | 31 | 25 | 31 | 37 |
| *Ivano-Frankivsk* | 49 | 25 | 30 | 31 | 34 | 53 | 87 | 97 | 103 | 81 | 52 | 36 | 37 | 40 |
| *Izmail* | 45 | 29 | 36 | 42 | 32 | 34 | 47 | 57 | 51 | 38 | 46 | 25 | 37 | 41 |
| *Kharkiv* | 50 | 36 | 44 | 32 | 27 | 36 | 47 | 58 | 60 | 50 | 41 | 35 | 44 | 45 |
| *Kherson* | 47 | 33 | 33 | 30 | 26 | 33 | 43 | 45 | 49 | 38 | 40 | 28 | 36 | 40 |
| *Khmelnytskyi* | 49 | 27 | 38 | 40 | 32 | 48 | 64 | 105 | 107 | 69 | 51 | 30 | 42 | 43 |
| *Kirovorad* | 49 | 32 | 32 | 31 | 27 | 36 | 45 | 66 | 72 | 48 | 38 | 27 | 35 | 42 |
| *Klepinino* | 46 | 34 | 31 | 29 | 30 | 28 | 42 | 59 | 42 | 32 | 33 | 27 | 32 | 38 |
| *Komisarivka* | 48 | 34 | 40 | 30 | 27 | 38 | 47 | 64 | 56 | 45 | 34 | 34 | 39 | 44 |
| *Kovel* | 51 | 25 | 33 | 31 | 30 | 39 | 62 | 75 | 81 | 63 | 52 | 37 | 42 | 40 |
| *Kyiv* | 50 | 31 | 47 | 46 | 39 | 49 | 53 | 73 | 88 | 69 | 47 | 35 | 51 | 52 |
| *Kyrylivka* | 47 | 36 | 51 | 39 | 37 | 41 | 54 | 68 | 74 | 40 | 44 | 26 | 48 | 62 |
| *Lviv* | 50 | 24 | 42 | 43 | 43 | 51 | 77 | 98 | 102 | 76 | 58 | 47 | 46 | 57 |
| *Liubashivka* | 48 | 30 | 40 | 38 | 33 | 39 | 51 | 62 | 81 | 55 | 42 | 28 | 42 | 41 |
| *Lozova* | 49 | 36 | 55 | 38 | 35 | 41 | 50 | 67 | 58 | 44 | 45 | 30 | 46 | 56 |
| *Lubny* | 50 | 33 | 49 | 43 | 42 | 44 | 41 | 68 | 75 | 62 | 44 | 37 | 53 | 60 |
| *Luhansk* | 49 | 39 | 36 | 29 | 29 | 39 | 44 | 62 | 51 | 39 | 32 | 27 | 42 | 43 |
| *Luts'k* | 51 | 25 | 31 | 30 | 27 | 39 | 60 | 68 | 76 | 61 | 56 | 37 | 36 | 38 |
| *Nikopol* | 48 | 34 | 35 | 35 | 29 | 32 | 43 | 52 | 58 | 41 | 39 | 22 | 36 | 43 |
| *Odesa* | 46 | 31 | 42 | 41 | 31 | 34 | 39 | 42 | 49 | 34 | 36 | 26 | 42 | 48 |
| *Ovruch* | 51 | 29 | 40 | 35 | 34 | 45 | 52 | 81 | 96 | 71 | 52 | 39 | 50 | 46 |
| *Poltava* | 50 | 35 | 43 | 37 | 35 | 40 | 51 | 60 | 71 | 46 | 44 | 42 | 49 | 51 |
| *Rivne* | 51 | 26 | 30 | 28 | 26 | 41 | 56 | 81 | 84 | 63 | 48 | 38 | 36 | 37 |
| *Romny* | 51 | 33 | 48 | 39 | 42 | 43 | 49 | 65 | 83 | 64 | 44 | 37 | 50 | 58 |
| *Rozdil'na* | 47 | 30 | 36 | 36 | 29 | 35 | 46 | 69 | 69 | 40 | 42 | 26 | 38 | 39 |
| *Sarata* | 46 | 29 | 32 | 33 | 26 | 32 | 48 | 63 | 61 | 42 | 43 | 25 | 34 | 38 |
| *Sarny* | 51 | 27 | 38 | 32 | 29 | 44 | 59 | 93 | 80 | 62 | 58 | 43 | 41 | 42 |
| *Simferopol* | 45 | 34 | 42 | 33 | 37 | 33 | 44 | 53 | 55 | 41 | 37 | 32 | 44 | 54 |
| *Sumy* | 51 | 35 | 43 | 33 | 38 | 39 | 55 | 69 | 77 | 62 | 45 | 38 | 52 | 54 |
| *Ternopil* | 50 | 26 | 34 | 34 | 32 | 47 | 68 | 81 | 92 | 63 | 52 | 33 | 36 | 39 |
| *Uman* | 49 | 30 | 47 | 44 | 38 | 48 | 55 | 87 | 87 | 59 | 43 | 33 | 43 | 48 |
| *Uzhhorod* | 49 | 22 | 57 | 46 | 48 | 45 | 70 | 88 | 85 | 71 | 53 | 50 | 58 | 69 |
| *Vinnytsia* | 49 | 29 | 39 | 37 | 34 | 48 | 62 | 87 | 93 | 67 | 46 | 33 | 41 | 43 |
| *Yalta* | 45 | 34 | 83 | 64 | 45 | 35 | 35 | 45 | 36 | 35 | 43 | 38 | 68 | 95 |
| *Zaporizhzhia* | 48 | 35 | 49 | 39 | 36 | 38 | 46 | 60 | 48 | 40 | 32 | 27 | 43 | 52 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Zhytomir* | 50 | 29 | 33 | 28 | 31 | 43 | 59 | 76 | 94 | 75 | 51 | 34 | 44 | 38 |
| *Znamianka* | 49 | 32 | 40 | 35 | 32 | 41 | 49 | 72 | 75 | 51 | 40 | 33 | 43 | 50 |
| *Zolotonosha* | 50 | 32 | 40 | 38 | 31 | 41 | 42 | 71 | 81 | 55 | 40 | 32 | 42 | 54 |
| *Brest (Belarus)* | 52 | 24 | 37 | 33 | 31 | 39 | 59 | 72 | 80 | 76 | 51 | 42 | 47 | 44 |
| *Gomel (Belarus)* | 52 | 31 | 36 | 28 | 32 | 39 | 48 | 84 | 82 | 59 | 48 | 43 | 45 | 44 |
| *Kursk (Russia)* | 52 | 36 | 42 | 33 | 37 | 42 | 52 | 72 | 78 | 55 | 51 | 43 | 52 | 52 |
| *Rostov na donu (Russia)* | 47 | 40 | 56 | 44 | 38 | 47 | 55 | 59 | 56 | 38 | 38 | 33 | 55 | 77 |
| *Luhansk II*[*1] | 49 | 40 | 36 | 29 | 29 | 39 | 44 | 62 | 51 | 39 | 32 | 27 | 42 | 43 |

*Source:* (NOAA ESRL physical science division 2008).

[*]1: In order to include the area to the West of Luhansk , an extra weather station was manually added at 1 DD to the West of Luhank. The station was appointed identical data as the Luhansk station.

Also the temperature has been taken from the weather stations:

***Table 1b:*** *Average long-term temperature data (℃).*

| Name | LATDD | LONGDD | Jan | Feb | Mrt | Apr | Mei | Jun | Jul | Aug | Sep | Okt | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Al-Petri* | 44 | 34 | -4 | -3 | -1 | 5 | 10 | 13 | 15 | 15 | 11 | 7 | 3 | -2 |
| *Askaniia-Nova* | 46 | 34 | -3 | -2 | 2 | 10 | 16 | 20 | 22 | 22 | 17 | 10 | 4 | 0 |
| *Chernihiv* | 51 | 31 | -7 | -6 | -1 | 8 | 14 | 18 | 19 | 18 | 13 | 7 | 1 | -3 |
| *Chernivetsi* | 48 | 26 | -5 | -3 | 2 | 9 | 14 | 17 | 19 | 18 | 14 | 9 | 3 | -2 |
| *Dnipropetrovsk* | 49 | 35 | -6 | -4 | 1 | 10 | 16 | 20 | 21 | 21 | 16 | 9 | 3 | -2 |
| *Donetsk* | 48 | 38 | -6 | -5 | 0 | 9 | 16 | 19 | 21 | 20 | 15 | 8 | 2 | -3 |
| *Feodosiia* | 45 | 35 | 1 | 1 | 4 | 11 | 16 | 21 | 23 | 23 | 18 | 12 | 8 | 4 |
| *Gajvoron* | 48 | 30 | -5 | -4 | 1 | 9 | 15 | 18 | 20 | 19 | 15 | 8 | 3 | -2 |
| *Heniches'k* | 46 | 35 | -2 | -2 | 2 | 9 | 16 | 21 | 23 | 22 | 17 | 11 | 5 | 1 |
| *Ivano-Frankivsk* | 49 | 25 | -5 | -3 | 1 | 8 | 14 | 17 | 18 | 17 | 14 | 8 | 3 | -2 |
| *Izmail* | 45 | 29 | -2 | 0 | 4 | 11 | 16 | 20 | 22 | 21 | 17 | 11 | 6 | 1 |
| *Kharkiv* | 50 | 36 | -7 | -6 | 0 | 9 | 16 | 19 | 20 | 20 | 14 | 7 | 1 | -3 |
| *Kherson* | 47 | 33 | -3 | -2 | 3 | 10 | 16 | 20 | 22 | 21 | 16 | 10 | 4 | 0 |
| *Khmelnytskyi* | 49 | 27 | -6 | -4 | 0 | 8 | 14 | 17 | 18 | 17 | 13 | 8 | 2 | -3 |
| *Kirovorad* | 49 | 32 | -6 | -4 | 1 | 9 | 15 | 19 | 20 | 19 | 15 | 8 | 2 | -2 |
| *Klepinino* | 46 | 34 | -1 | -1 | 3 | 10 | 16 | 20 | 22 | 22 | 17 | 10 | 6 | 2 |
| *Komisarivka* | 48 | 34 | -6 | -4 | 1 | 9 | 16 | 19 | 21 | 20 | 15 | 8 | 2 | -2 |
| *Kovel* | 51 | 25 | -5 | -3 | 1 | 8 | 14 | 17 | 18 | 17 | 13 | 8 | 3 | -2 |
| *Kyiv* | 50 | 31 | -6 | -4 | 1 | 9 | 15 | 18 | 19 | 19 | 14 | 8 | 2 | -2 |
| *Kyrylivka* | 47 | 36 | -5 | -4 | 1 | 9 | 15 | 19 | 21 | 20 | 15 | 8 | 3 | -2 |
| *Lviv* | 50 | 24 | -5 | -3 | 1 | 8 | 13 | 16 | 17 | 17 | 13 | 8 | 3 | -2 |
| *Liubashivka* | 48 | 30 | -5 | -4 | 1 | 9 | 15 | 19 | 20 | 20 | 15 | 9 | 3 | -2 |
| *Lozova* | 49 | 36 | -7 | -5 | 0 | 9 | 16 | 19 | 21 | 20 | 15 | 8 | 2 | -3 |
| *Lubny* | 50 | 33 | -6 | -5 | 0 | 9 | 15 | 19 | 20 | 19 | 14 | 8 | 1 | -3 |
| *Luhansk* | 49 | 39 | -6 | -5 | 1 | 10 | 16 | 20 | 22 | 21 | 15 | 8 | 2 | -2 |
| *Luts'k* | 51 | 25 | -5 | -4 | 1 | 8 | 14 | 17 | 18 | 17 | 13 | 8 | 3 | -2 |
| *Nikopol* | 48 | 34 | -3 | -2 | 3 | 10 | 17 | 20 | 22 | 22 | 17 | 10 | 5 | 0 |
| *Odesa* | 46 | 31 | -2 | -1 | 3 | 9 | 15 | 19 | 22 | 21 | 17 | 11 | 6 | 1 |
| *Ovruch* | 51 | 29 | -6 | -5 | 0 | 8 | 14 | 17 | 18 | 17 | 13 | 7 | 2 | -3 |
| *Poltava* | 50 | 35 | -7 | -5 | 0 | 9 | 15 | 19 | 20 | 19 | 14 | 8 | 2 | -3 |
| *Rivne* | 51 | 26 | -5 | -4 | 0 | 8 | 14 | 17 | 18 | 17 | 13 | 8 | 2 | -3 |
| *Romny* | 51 | 33 | -7 | -6 | -1 | 8 | 15 | 18 | 19 | 18 | 13 | 7 | 1 | -4 |
| *Rozdil'na* | 47 | 30 | -4 | -2 | 2 | 10 | 16 | 19 | 21 | 21 | 16 | 10 | 4 | -1 |
| *Sarata* | 46 | 29 | -2 | -1 | 3 | 10 | 16 | 20 | 22 | 21 | 17 | 10 | 5 | 1 |
| *Sarny* | 51 | 27 | -5 | -4 | 1 | 8 | 14 | 17 | 18 | 18 | 13 | 8 | 2 | -2 |
| *Simferopol* | 45 | 34 | 0 | 0 | 4 | 10 | 15 | 19 | 21 | 21 | 17 | 11 | 6 | 2 |
| *Sumy* | 51 | 35 | -8 | -6 | -1 | 8 | 15 | 18 | 19 | 18 | 13 | 7 | 1 | -4 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Ternopil* | 50 | 26 | -6 | -4 | 0 | 7 | 13 | 16 | 17 | 17 | 13 | 7 | 2 | -3 |
| *Wind velocityUman* | 49 | 30 | -6 | -4 | 0 | 9 | 15 | 18 | 19 | 18 | 14 | 8 | 2 | -2 |
| *Uzhhorod* | 49 | 22 | -3 | 0 | 5 | 11 | 16 | 18 | 20 | 19 | 16 | 10 | 5 | 0 |
| *Vinnytsia* | 49 | 29 | -6 | -4 | 0 | 8 | 14 | 17 | 18 | 18 | 13 | 8 | 2 | -3 |
| *Yalta* | 45 | 34 | 4 | 4 | 6 | 11 | 16 | 20 | 23 | 23 | 19 | 14 | 10 | 6 |
| *Zaporizhzhia* | 48 | 35 | -4 | -3 | 2 | 10 | 16 | 20 | 22 | 21 | 16 | 10 | 4 | -1 |
| *Zhytomir* | 50 | 29 | -6 | -5 | 0 | 8 | 14 | 17 | 18 | 17 | 13 | 7 | 2 | -3 |
| *Znamianka* | 49 | 32 | -6 | -5 | 0 | 9 | 15 | 19 | 20 | 19 | 15 | 8 | 2 | -3 |
| *Zolotonosha* | 50 | 32 | -6 | -5 | 1 | 9 | 15 | 19 | 20 | 19 | 14 | 8 | 2 | -3 |
| *Brest (Belarus)* | 52 | 24 | -5 | -3 | 1 | 8 | 14 | 17 | 18 | 17 | 13 | 8 | 3 | -2 |
| *Gomel (Belarus)* | 52 | 31 | -7 | -6 | -1 | 7 | 14 | 17 | 18 | 18 | 13 | 7 | 1 | -4 |
| *Kursk (Russia)* | 52 | 36 | -9 | -8 | -2 | 7 | 14 | 17 | 19 | 18 | 12 | 6 | -1 | -5 |
| *Rostov na donu (Russia)* | 47 | 40 | -5 | -3 | 2 | 11 | 17 | 21 | 23 | 22 | 17 | 9 | 4 | -1 |
| *Luhansk II* | 49 | 40 | -6 | -5 | 1 | 10 | 16 | 20 | 22 | 21 | 15 | 8 | 2 | -2 |

*Source:* (NOAA ESRL physical science division 2008).

Wind velocity

Data on the wind velocity, has been taken from the physical sciences division of (NOAA ESRL physical science division 2010). Although the resolution of this data is low (200 x 280 km.), other weather databases do not provide monthly data, do not include Ukraine, or cannot provide long term data. Some climate databases, such as ECA&D or E-OBS, are to detailed, and could not be analysed within the timeframe of this study. To use the data from the NOAA physical sciences division, the data was interpolated, according to the bilinear interpolation method.

***Table 2:*** *Average long-term wind velocity (m/s).*

| **Latitude** | **Longitude** | | | | | | |
|---|---|---|---|---|---|---|---|
| *January* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 6,3 | 5,4 | 5,1 | 5,3 | 5,4 | 5,0 | 4,7 |
| 52,500 | 5,4 | 5,2 | 4,8 | 4,7 | 4,8 | 4,8 | 5,0 |
| 50,000 | 4,5 | 5,2 | 5,4 | 4,9 | 4,7 | 5,1 | 5,7 |
| 47,500 | 3,6 | 3,8 | 4,6 | 5,2 | 5,4 | 6,1 | 7,1 |
| 45,000 | 3,9 | 3,7 | 5,0 | 6,5 | 6,8 | 6,7 | 7,0 |
| *February* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 5,8 | 5,0 | 4,8 | 5,1 | 5,2 | 4,8 | 4,6 |
| 52,500 | 4,9 | 4,8 | 4,7 | 4,7 | 4,8 | 4,8 | 5,0 |
| 50,000 | 4,3 | 4,9 | 5,0 | 4,7 | 4,7 | 5,3 | 5,9 |
| 47,500 | 3,5 | 3,8 | 4,6 | 5,2 | 5,6 | 6,3 | 7,3 |
| 45,000 | 3,7 | 3,6 | 4,9 | 6,4 | 6,5 | 6,5 | 6,9 |
| *March* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 5,7 | 4,9 | 4,7 | 4,9 | 4,9 | 4,5 | 4,3 |
| 52,500 | 4,8 | 4,6 | 4,3 | 4,3 | 4,5 | 4,5 | 4,7 |
| 50,000 | 4,3 | 4,7 | 4,6 | 4,4 | 4,5 | 4,9 | 5,6 |
| 47,500 | 3,5 | 3,7 | 4,2 | 4,8 | 5,2 | 5,9 | 6,8 |
| 45,000 | 3,5 | 3,4 | 4,4 | 5,8 | 6,0 | 5,8 | 6,1 |
| *April* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 4,8 | 4,3 | 4,2 | 4,4 | 4,5 | 4,2 | 4,0 |
| 52,500 | 4,2 | 4,0 | 3,8 | 3,9 | 4,1 | 4,1 | 4,3 |
| 50,000 | 3,8 | 4,1 | 4,2 | 4,0 | 4,2 | 4,6 | 5,0 |
| 47,500 | 3,2 | 3,5 | 4,0 | 4,5 | 4,6 | 5,0 | 5,7 |
| 45,000 | 3,2 | 3,2 | 4,1 | 5,1 | 4,9 | 4,7 | 4,9 |
| *May* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 4,5 | 4,0 | 3,9 | 4,1 | 4,1 | 3,7 | 3,5 |
| 52,500 | 3,8 | 3,7 | 3,5 | 3,6 | 3,6 | 3,6 | 3,8 |

| **Latitude** | **Longitude** | | | | | | |
|---|---|---|---|---|---|---|---|
| *July* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 4,5 | 4,0 | 3,9 | 4,1 | 4,1 | 3,7 | 3,4 |
| 52,500 | 3,6 | 3,6 | 3,6 | 3,5 | 3,6 | 3,5 | 3,6 |
| 50,000 | 3,3 | 3,6 | 3,7 | 3,4 | 3,4 | 3,6 | 3,9 |
| 47,500 | 2,8 | 3,0 | 3,4 | 3,9 | 3,9 | 4,1 | 4,5 |
| 45,000 | 2,6 | 2,5 | 3,3 | 4,3 | 4,3 | 4,1 | 4,3 |
| *August* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 4,3 | 3,8 | 3,7 | 3,9 | 4,0 | 3,7 | 3,4 |
| 52,500 | 3,5 | 3,4 | 3,4 | 3,4 | 3,4 | 3,4 | 3,5 |
| 50,000 | 3,0 | 3,3 | 3,4 | 3,2 | 3,3 | 3,6 | 3,9 |
| 47,500 | 2,5 | 2,7 | 3,1 | 3,7 | 3,9 | 4,2 | 4,7 |
| 45,000 | 2,4 | 2,5 | 3,1 | 4,2 | 4,3 | 4,1 | 4,2 |
| *September* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 5,0 | 4,4 | 4,2 | 4,5 | 4,5 | 4,1 | 3,9 |
| 52,500 | 4,0 | 4,0 | 3,9 | 3,9 | 3,9 | 3,9 | 4,1 |
| 50,000 | 3,5 | 3,8 | 3,9 | 3,7 | 3,7 | 4,0 | 4,4 |
| 47,500 | 2,8 | 3,0 | 3,5 | 4,0 | 4,2 | 4,5 | 5,0 |
| 45,000 | 2,7 | 2,9 | 3,5 | 4,5 | 4,7 | 4,5 | 4,5 |
| *October* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 5,8 | 5,0 | 4,8 | 5,0 | 5,1 | 4,8 | 4,4 |
| 52,500 | 4,7 | 4,5 | 4,3 | 4,3 | 4,4 | 4,4 | 4,7 |
| 50,000 | 4,0 | 4,4 | 4,4 | 4,1 | 4,2 | 4,5 | 5,1 |
| 47,500 | 3,1 | 3,4 | 3,9 | 4,4 | 4,7 | 5,1 | 5,8 |
| 45,000 | 3,1 | 2,9 | 4,0 | 5,4 | 5,6 | 5,4 | 5,4 |
| *November* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 6,2 | 5,3 | 5,0 | 5,2 | 5,2 | 4,7 | 4,5 |
| 52,500 | 5,3 | 5,0 | 4,7 | 4,6 | 4,6 | 4,6 | 4,9 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 50,000 | 3,4 | 3,6 | 3,6 | 3,5 | 3,7 | 4,0 | 4,3 |
| 47,500 | 2,9 | 3,1 | 3,6 | 3,9 | 4,0 | 4,3 | 4,9 |
| 45,000 | 2,9 | 2,9 | 3,6 | 4,4 | 4,3 | 4,1 | 4,1 |
| *June* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 4,4 | 4,0 | 3,8 | 3,9 | 3,9 | 3,6 | 3,3 |
| 52,500 | 3,6 | 3,6 | 3,5 | 3,5 | 3,6 | 3,5 | 3,6 |
| 50,000 | 3,3 | 3,6 | 3,6 | 3,3 | 3,4 | 3,7 | 3,9 |
| 47,500 | 2,7 | 3,0 | 3,4 | 3,7 | 3,9 | 4,0 | 4,3 |
| 45,000 | 2,7 | 2,8 | 3,5 | 4,3 | 4,2 | 4,0 | 4,0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 50,000 | 4,4 | 4,9 | 5,0 | 4,5 | 4,4 | 4,8 | 5,3 |
| 47,500 | 3,5 | 3,8 | 4,4 | 4,9 | 5,1 | 5,5 | 6,3 |
| 45,000 | 3,6 | 3,5 | 4,6 | 6,0 | 6,2 | 6,0 | 6,2 |
| *December* | 22,500 | 25,000 | 27,500 | 30,000 | 32,500 | 35,000 | 37,500 |
| 55,000 | 6,0 | 5,1 | 4,8 | 5,1 | 5,3 | 5,0 | 4,7 |
| 52,500 | 5,1 | 4,8 | 4,5 | 4,6 | 4,8 | 4,8 | 5,1 |
| 50,000 | 4,4 | 4,9 | 5,1 | 4,7 | 4,6 | 5,0 | 5,6 |
| 47,500 | 3,6 | 3,8 | 4,5 | 5,0 | 5,2 | 5,8 | 6,7 |
| 45,000 | 3,9 | 3,6 | 4,9 | 6,3 | 6,6 | 6,4 | 6,6 |

*Source:* (NOAA ESRL physical science division 2010)

<u>Climate zoning</u>

Ukraine has been divided into four climate regions. To determine the climate region, a classification system has been followed from the IPCC. It depends on the mean annual temperature (MAT), precipitation (MAP) potential evaporation (PET), and the frost days per year.

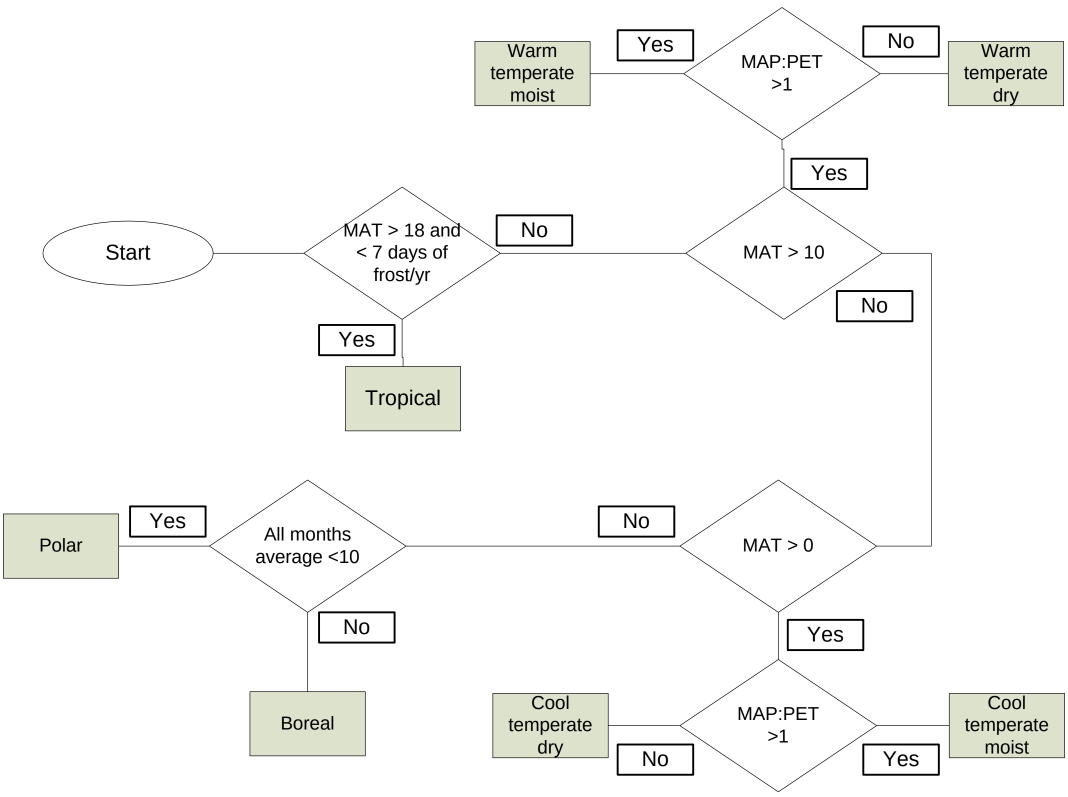


***Figure 1:*** *Climate zone classification rules, according to IPCC (IPCC, 2006).*

If these rules are applied to the climate data that is indicated above, several climate zones can be derived and applied to Ukraine.

Although the original climate zones are not hindered by administrative borders, in this study they are applied per oblast. This has been done to prevent climate zones from creating artificial borders in the results. The oblasts borders are the most appropriate perimeter, as many other parameters are also differentiated per oblast. Although climate zoning is an inaccurate way to define climate parameters, the IPCC prescribes the methodology, because of reasons of consistent data representation (IPCC 2006a). The zones were allocated as indicated in figure 2.

As the climate zones are determined with data from 41 weather stations, the uncertainty should be minimized.

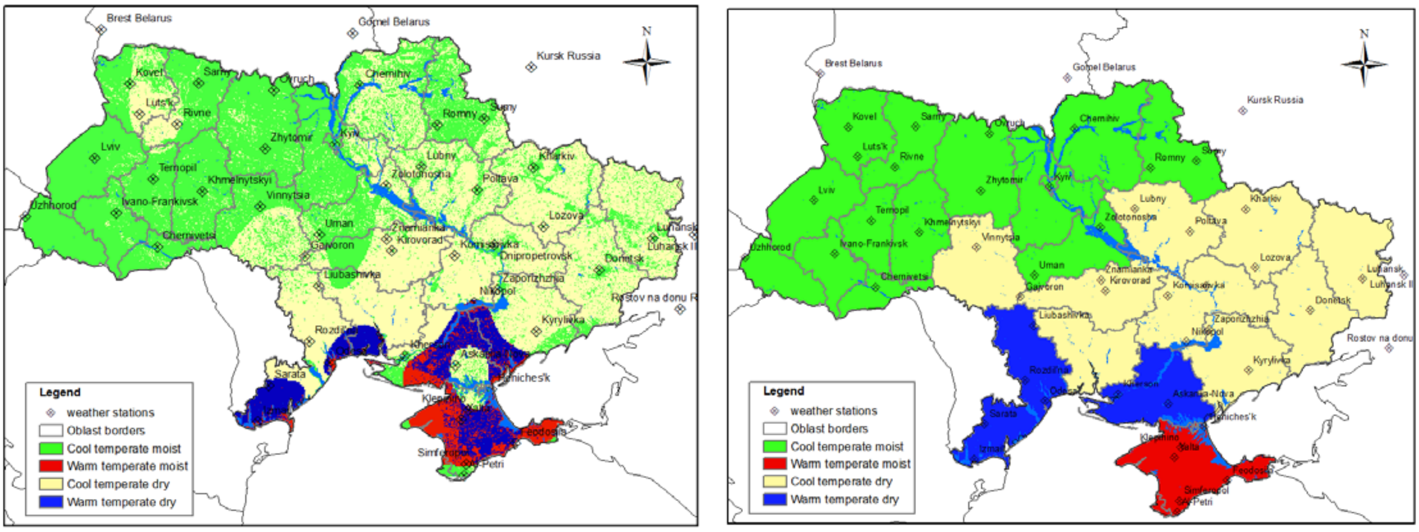

**Figure 2:** *Left: Climate zones as derived from the model. Right: Climate zones applied per oblast.*

Reference evapotranspiration

The reference evapotranspiration has been determined on the basis of CROPWAT weather stations. The cropwat weather stations are distributed according to the following figure:

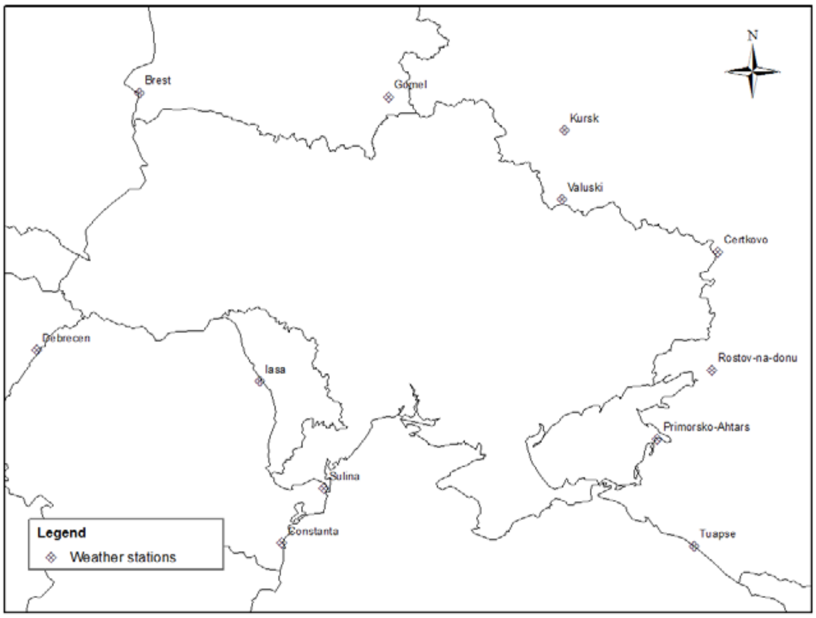

**Figure 3:** *CROPWAT weather stations.*

# Appendix 3: GIS metadata

The table below summarises the origin and size of the spatial data that was used during this research. The data can be both polygon or raster based. Some data was only available on oblast level. This oblast level data has been included as raster data, with a grid size of 863m, to match with the land use data from Globcover.

***Table 1:*** *GIS sources and data characteristics.*

| Name/Subject | Grid Size | Year | Source |
|---|---|---|---|
| Administrative overlay (countries, oblasts, regions, labels, rivers, lakes) | Polygon | 2009 | (GADM 2010) |
| Infrastructure (rail, road) | Polyline | 2009 | (Pennsylvania state University Libraries 1997) |
| Digital elevation model (DEM) | 50 x 100m | 2010 | (NASA, Japan's Ministry of Economy, Trade and Industry (METI) et al. 2010) |
| Production potential wheat and switchgrass | Oblast level | 2009 | (Refuel 2008) |
| Current land cover | 863 x 863m | 2009 | Corine (EEA 2009) |
| Current crops on agri. land | Oblast | 2008 | (State Statistics Committee of Ukraine, Ostapchuk et al. 2009) |
| Livestock (number per species) | Oblast | 2008 | (State Statistics Committee of Ukraine, Ostapchuk et al. 2009) |
| National parks | Polygon | 2005 | (WDPA 2010);(UNEP-WCMC, Bubb et al. 2005) |
| Chernobyl exclusion zone | Polygon | 2010 | Digitalised on the basis of literature. |
| Precipitation (monthly) | Point data: 49 weather stations | Long term data | (NOAA ESRL physical science division 2008) |
| Surface temperature (monthly) | Point data: 49 weather stations | Long term data | (NOAA ESRL physical science division 2008) |
| Wind speed | 180 x 280 km | Long term data | {{144 US Department of Commerce, National Oceanic and Atmospheric Administration, earth system research laboratory, physical sciences division. 2010;}} CDC Derived NCEP Reanalysis Products Pressure Level GrADS image. |
| Reference evapotranspiration | Point data: 12 weather stations | Long term data | Cropwat: (FAO 2010a, FAO 2010b) |
| Soil type | Polygon | 2004 | (EU Commission, European Soil Bureau Network 2004) |
| Harvested area | Oblast | 2008 | (State Statistics Committee of Ukraine, Ostapchuk et al. 2009) |
| Slope | 50 x 50 m | 2010 | Created from DEM |
| Aspect | 50 x 50 m | 2010 | Created from DEM |
| Slope length | 50 x 50 m | 2010 | Created from DEM |
| $NO_3$ concentration | Oblast | 2010 | Output of theMiterra model: (Alterra 2010) |