Assessing yield gaps for three cash crops in Germany by applying and testing a global protocol

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Paul Schofer

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For quality of life

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Supervisor
Prof. Dr.ir. Martin K. van Ittersum

Examiner
Prof. Dr.ir. Martin K. van Ittersum
Dr.ir. Peter Leffelaar

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Summary

The demand for crop production is rising on a global scale. The increased demand must be met with increased production. The increase can be achieved by expanding crop growth areas or crop yields on current arable land on a global scale. Whether and where a yield increase is possible needs to be assessed on a global scale. van Wart et al. (in press) developed a protocol to assess the potential yield in a consistent way on a global scale. Based on land use data the major crop growth areas are selected and crop growth modeling is performed to assess the potential (Yp) and water limited (Yw) yield. Out of the average farm yield (Ya) and the potential or water-limited yield the yield gap closures (Ya/Yp or Ya/Yw) are derived. The closure can be used as a benchmark to compare different regions to each other.

The protocol of van Wart et al. (in press) involves the selection of a set of weather stations that cover at least 50% of national crop growth area in their 100 km buffer zones. The protocol is tested in an application on winter barley, winter wheat and winter rape seed in Germany. Global gridded data sets of the year 2000 and current national statistics were employed to derive the land use and yield data of all crops for the protocol. The protocol could be performed on the basis of the land use out of the national statistics for winter barley only. The land use data for winter wheat and winter rape seed out of the national statistics did not lead to a fulfillment of all criteria in the protocol of van Wart et al (in press). For the representative study area the major soil types were selected and water-limited and potential yields were assessed with two calibrated and validated crop growth models, i.e. HERMES (Kersebaum, 1995) and WOFOST (Boogaard, 1998).

The actual yields derived out of the gridded data set of 2000 were 16% lower for winter rape seed, 11% lower for winter barley and 4 % lower for winter wheat compared to the actual yields derived from the national statistics around 2008. The yield levels were estimated for multiple soil types within the buffer zones of the weather station and aggregated to the national scale. The yield gap fractions related to the water-limited yields (Yw) were 80%, 88% and 95% for winter barley, winter rape seed and winter wheat, respectively. A sensitivity analyses on the effect of buffer zone radius on the number of weather stations to cover at least 50% of the national crop growth area was performed. In addition a sensitivity analysis of the effect of the number of selected soil types within the 100 km buffer zones of the selected weather stations on the coverage of national production area was performed.

List of tables and figures

Physical units

Abbreviation	Explanation
m	meter
mm	millimeter = 10^{-3} m
cm	centimeter = 10^{-2} m
km	kilometer = 10^{3} m
ha	hectare = 10000 m^{2}
° arc	Arcminutes
Kg	Kilogram = 10^{3} g
dt	Deciton = 10^{5} g
t	tons = 10^{6} g
kJ	kilojoule =10^{3} J
d	day
s	Second
kPa	Kilopascal = 10^{3} Pa

1 Introduction

Globally, the need for crop production is estimated to increase by 70 % till the year 2050. At the same time the world population is reaching 9 billion people (Licker et al., 2010). The increased production can be achieved by expansion of arable land which is a) limited and b) not the preferred method of increasing production because of competition with other land uses. Another way to meet this demand is by increasing land productivity which means the yield per hectare of current arable land must increase.

Since crop production for a whole region or a country is managed by many farmers, one will find a certain range of managing and crop production capabilities across the group of individuals. In order to raise the average farm yield it is necessary to bridge the knowledge gap as far as possible to get the average farm yield as close as possible to the best farmers. The best farmers produce yields that are closest to the water-limited yield of the crop within rain fed conditions, or in case of irrigation the absolute potential crop yield. The potential yield is defined by van Ittersum and Rabbinge (1997), Evans (1993) and Fischer et al. (2009) as "The Maximum yield with the latest varieties, removing all constraints, including moisture, at generally prevailing solar radiation, temperature, and day length". It is therefore the theoretical maximum crop yield under optimal crop growth conditions. The water-limited yield is defined as "Maximum yield under normal rain conditions, removing all constraints as for the potential yield except for moisture". Whether it is desirable to produce at these levels depends on environmental and economic factors. The yield gap is defined as the difference between the average farm yield and the potential yield or water limited yield as derived from crop growth models suitable for the region in question. The yield gap fraction or yield gap closure is defined as the ratio of actual yields to potential yields under irrigated conditions or water-limited yields under rain-fed conditions. An overview of the concepts is provided in Table 1.

Table 1 Definitions of yield measures adjusted from van Ittersum and Rabbinge (1997), Evans (1993) and Fischer et al. (2009)

Yield	Symbol	Definition	Estimation
Average farm or on-farm yield	Ya	Average yield achieved by farmers in a defined region over several seasons	Regional statistics and global data bases
Potential yield	Yp	Maximum yield with the latest varieties, removing all constraints, including moisture, at generally prevailing solar radiation, temperature, and day length	Crop models calibrated on latest varieties
Water-limited potential yield	Yw	Maximum yield under normal rained conditions, removing all constraints as for YP except for moisture	Crop models calibrated on latest varieties
Yield gap	Yg	The difference between Yp for irrigated or Yw for rain-fed conditions and Ya (Yp-Ya=Ygp) or (Yw-Ya= Ygw)	Based on the concepts Ya, Yw, Yp
Yield gap closure	Ygc	The ratio of actual yields to potential yields in irrigated (Ya/Yp) or water-limited yields in rain-fed conditions (Ya/Yp)	Based on the concepts Ya, Yw, Yp

In order to benchmark the current production on a global scale with regional resolution, van Wart et al. (in press) developed a protocol to assess yield potential and yield gap on a regional and national scale. The protocol involves the selection of representative study areas, crop growth modeling to assess potential and water-limited yields and a method of aggregation to come to a larger spatial scale. This opens the opportunity not only to a consistent assessment of yield potential and yield gaps on a global scale but also comparing regions to one another to discover areas with large yield gaps. However it does not show why the yield gap exists at this level and how it is possible to reduce it. The diversity of actual achieved farm yields across individual farmers will not be a result of this method. The results on a global scale will give an insight where further research is necessary to explain rather large yield gaps and to develop possibilities to eliminate constraining factors like general, technical and political constraints (Fischer et al., 2009).

This report aims at testing the protocol of van Wart et al. (in press) in an application for three major land use crops in Germany. These crops cover a total of 50% of the national arable land in 2010 (BMELV, 2010). The rather dense availability of spatial data for weather, land use and actual yields in Germany is employed to test the methodology in this work. It allows comparing results of the protocol using national data or global data sets. Potential shortcomings of the protocol can be located and described.

The three major land use crops in Germany are winter wheat *Triticum aestivum* L. (27% of arable land in 2010), winter barley *Hordeum vulgare* L. (11% of arable land in 2010) and winter rape seed *Brassica napus* (12% arable land in 2010) (BMELV, 2010). The current potential and water-limited yields will be assessed using the crop growth models HERMES developed by Kersebaum (2011) and the WOFOST model out of the Wageningen crop growth model family (van Ittersum et al., 2003). The actual on-farm crop yields of three crops will be assessed out of a global grid by Monfreda et al. (2008) and the national statistics. Comparing the actual yields to the modeled potential yields will lead to the current yield gaps and yield gap closure.

The assessments of the yield potentials and yield gaps on a national scale require a representative study area for each crop. The potentially achievable yields are determined by crop growth models which require mainly weather data and crop phenology data as input for the estimation of Yp. Therefore van Wart et al. (in press) suggested using reference weather stations (RWS) for crop growth modeling to asses Yw and Yp. In order to become a RWS the weather station needs to have sufficient quality of weather data. Furthermore it needs to be located in an area with a certain harvested area of the specific crop. The sum of the harvested crop area within a 100 km buffer zone around the station will be used as the selection criterion in the process of selecting the RWS. All RWS together should cover at least 50% of the national harvested growth area of the specific crop. Their buffer zones shall not overlap. Finding the RWS' that represent the main growing area of the three crops will therefore be a primary task in this research. This process and all further processing steps that requires spatial scale were performed with the ArcMap© 10 software by ESRI©.

The necessary land use data to assess the crop growth areas will be used from the 5° arc gridded dataset MICRA (Portmann et al., 2010) and out of the national statistics. The data sets of the national statistics are available on the district level. These statistics will be linked with the spatial datasets of their political districts to provide them with a spatial reference. The first test of the methodology of van Wart et al. (in press) will be made by comparing the results of the RWS selection process for both the statistics and the Portmann et al. (2010) data sets. More details of selecting the RWS will be shown in section 2.2.2 of this report.

Furthermore the effect of the buffer zone radius on the number of RWS' will be tested. A sensitivity analysis will show how many stations and therefore how many reference points for modeling are needed to fulfill the criterion of covering 50% of the national production area of Germany.

In addition to the selection of the RWS' it is necessary to assess the soil type in the study area. The soil properties are needed as model inputs for assessing the water-limited yield. This leads to the questions what the major soil type per RWS' are and if one soil type per RWS' are covering enough crop growth area to fulfill 50% coverage of national production.

In order to benchmark the actual yields correctly, the irrigated areas of the crops need to be located as the actual yields in this area need to be compared to the potential yields (Yp) instead of the water-limited yields (Yw). Once Yw and Yp have been estimated, the actual farm yields need to be assessed in order to calculate the yield gap and yield gap closure out of two different sources for Ya, namely the 5° arc gridded data by Monfreda et al. (2008) and the national statistics with a spatial distribution over the political districts.

The final step will be the aggregation of the potential, water-limited and actual farm yields from RWS scale to the national scale by using the method suggested in van Wart et al. (in press). The weighted average over the sum of harvested crop growth area per RWS buffer zone will be derived for Ya, Yw and Yp.

To summarize, the aims of this study are:

- Assess yield gaps for winter wheat, winter barley and winter rape seed on a national for Germany using the method by van Wart et al. (in press) by taking the steps:
    - Assessing the total amount of irrigated and non-irrigated crop growth area
    - Assessing study area by selecting RWS based on national statistics and Portmann et al. (2010) land use data
    - Assessing soil types within the buffer zones of the RWS
    - Assessing potential and water-limited yield per RWS
    - Assessing current farm yield

2 Material and Methods

This chapter has been split into two sections. The first section is describing the data and the second section the methodology to answer the questions introduced in chapter 1. Different types and sources of data that were used are described in Section 2.1. The types of data include weather, soil and land-use data for the selection of the study area as well as additional model data and the actual yields for the area.

2.1 Data

Different kinds and sources of data were needed to perform the methodology. This chapter describes the origin of the data sets and their application. Their processing will be described in the methodology part.

The weather data will be described in the first Section 2.1.1. The location of the suitable weather stations will be used as a starting point of selecting the representable RWS buffer zones. Later in the method the daily weather data will be used as an input for the crop growth modeling.

The land use data will be used in the next step of the method and will be described in Section 2.1.2. It provides the necessary information about the distribution of the crop growth areas to choose the reference weather stations for the study. A global gridded dataset by Portmann et al. (2010) and national statistics are available.

For the assessment of the water-limited yield the crop growth models not only require information about the daily weather but also about the soil properties. The soil information and data sets are described in the third Section 2.1.3.

The sources for the actual achieved farm yields are described in the fourth Section 2.1.4. One source is provided as a global grid and the second contains data only for Germany. Both data sets will be compared to each other and will be used to derive the actual farm yields Ya and the yield gap Yg.

The last Section 2.1.5 describes additional data that is required for crop growth modeling. The models need to be tested with trial yields grown under potential and water-limited crop growth conditions. The trials that were used to test the models as well as the necessary input data for dates of emergence of the crops for HERMES are described in this subchapter.

2.1.1 Weather data

The weather data was used for the crop growth modeling of the two yield levels Yp and Yw. Therefore, daily weather data for solar radiation, average minimum and maximum temperature, vapor pressure, mean wind speed and precipitation was necessary. The data was provided by the National Oceanic and Atmospheric Administration (NOAA) for a global network of weather stations. The NOAA performed quality checks with the weather data and provided this data in a database (Appendix I, 1)[1]. The source of the data for Germany in the NOAA data base was for the majority of stations the German weather service (DWD).

The NOAA data does not contain any radiation data. The radiation data was downloaded from the NASA data base (Appendix I, 2). The weather data of NOAA and NASA was statistically tested and combined to one dataset per station per year. The resulting files for the use in the WOFOST model were provided by Dr. Lenny v. Bussel (Wageningen University) (Appendix II, 19)[2]. The methodology of testing the data will be described in the methodology section 2.2.1.

Additional information about the elevation of the region and the weather stations was acquired. The elevation data of the NASA project out of the year 2000 was used. The topography of the planet was measured via radar equipment on a space shuttle. The accuracy was a vertical error of < 50 m with a grid size of 1° arc (Appendix II, 20). The elevation grids were downloaded (Appendix I, 3) and are further referred to as DEM ("digital elevation model") data (Appendix II, 21).

The resulting weather data set is containing three parts. The first part is a list of weather stations with sufficient data quality from the year 2006 till the year 2010 including their location. The second part contains a total of five files per station each containing daily values for solar radiation, average minimum and maximum temperature, vapor pressure, mean wind speed and precipitation. The last part is a 1° arc grid layer with the spatial extent over Germany containing the mean elevation of the topography.

As mentioned before, the weather data will be used as a starting point for the reference weather station selection.

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[1] Appendix I contains the overview of the web-links for data download, the number behind the comma is referring to the reference number in the table in the Appendix section

[2] Appendix II contains the overview of the raw data provided on the CD, the number behind the comma is referring to the reference number in the table in the Appendix section

2.1.2 Land use data

The spatial distribution of the land use within Germany was obtained in two ways. The first source was the MICRA grids for harvested crop areas by Portmann et al. (2010). Monthly and annual gridded data sets of the harvested area of 26 crop classes with a resolution of 5° arc were created. The land use data was based on national land use statistics around the year 2000 (Portmann et al. 2010). The gridded data sets for this study were downloaded (Appendix I,5) and contained the rain fed and irrigated grids of wheat (Appendix II,10,11), barley (Appendix II ,12,13) and rape seed (Appendix II, 14, 15).

The second source to obtain land use data for Germany was the national statistics for crop growing area (Appendix I, 6). The "Statistische Bundesamt" (Federal Statistical Office) did a partial census in the year 2010 for all farms with more than 2 ha agricultural area. The results are available per administrative unit, in this case the districts. This partial census was the first of its kind in Germany and will be executed every 10 years. Between 1975 and 1999 the land use data was collected every two years for all farms. It was used for the agricultural structure census. Since 1999 it was performed only for the farms with a minimum of 2 ha agricultural area. The data for 1999 can be found in Appendix II, 5 the data for 2010 in Appendix II, 4. In the statistics of 1999 the crop growth area values for winter wheat were obtained from the "Winterweizen" column, winter barley from the "Wintergerste" column and oil seed rape from the "Winterraps" column. The statistic of 2010 did not distinguish between spring and winter crops for wheat and barley. Therefore the "Weizen" and "Gerste" columns were obtained for wheat and barley respectively.

The shape data of the political districts was obtained in order to give the yield data out of the national statistics a spatial reference for the processing in the ArcMap software (Appendix I, 7). The so called "Verwaltungsgebiete" (administrative units) were published as a shape file for the year 2010 by the Federal Agency for Cartography and Geodesy "Bundesamt für Kartografie und Geodäsie". The data can be found in Appendix II, 9.

The two sources result in three different data sets per crop, namely the MICRA grid data of Portmann et al. (2010), the national statistics of 1999 and the national statistics of 2010. These three were used for the selection of RWS and their sum over the study area was used in the aggregation process.

2.1.3 Soil data

The assessment of the water-limited yields requires information about the soil characteristics. Two similar data sets of soil data, namely the WISE (Batjes, 2012) data set and the FAO (1995) soil map were used within the methodology. The data sets are similar in content but each data set had its own technical advantage in the processing within the method. The WISE data was used for the selection of soil types within the study area and provided input data for the crop growth models. The soil types for WOFOST were available from Dr. Lenny van Bussel (WUR). The distribution of soil types of the FAO (1995) soil data base is published in shape data format. It allowed an easier processing to derive the number of soils within the buffer zones of the RWS that were necessary to cover 50% of national crop growth area.

The WISE soil database and its description were provided by ISRIC and were used within the crop growth models (Batjes, 2012) (Appendix I, 4) (Appendix II, 22). It provides information about particle size distribution, bulk densities, soil depth and available water capacity of fixed layers. These layers are given in 20 cm intervals till 100 cm depth. The soil type distribution is based on the FAO soil map of the world (FAO, 1995). The distribution of the soil types of the WISE data is available as a grid with a resolution of 5° arc on a global scale. The major soil type per grid cell is given as a numerical code. An additional data base describes the soil properties of the different codes. The data is available for the whole globe and was favorable to be used in the protocol of van Wart et al. (in press). It provides consistent soil data for all crop growth regions on a global scale. In this study, the WOFOST soil input files for Germany were derived from the WISE data and provided by Dr. Lenny van Bussel (WUR) (Appendix II, 22).

The second source of soil data was the FAO soil map (FAO, 1995). The soil distribution of this data set was used in the separate analysis of the soil selection sensitivity analysis within the buffer zones. This analysis tested how many soils were needed per buffer zone to achieve 50% coverage of the national production area.

The distribution of soil types within the buffer zones of the RWS' was derived from the WISE data base. Also the necessary soil properties as an input for the crop growth models were derived from this data source. For easier calculation, the distribution of soil types for the separate sensitivity analysis however was derived out of the (FAO, 1995) data set.

2.1.4 Actual yields

The actual yields were available in a global grid and in the national statistics for the political districts. The global gridded data by Monfreda et al. (2008) used statistical data of national level as an input. The data for the global grid and the national statistics per political districts used the same source but were processed and presented in a different way.

The Monfreda et al. (2008) database is containing the spatial distribution of crop growth areas, yields, net primary production and physiological types on a global scale (Monfreda et al., 2008). The yield data are based on the FAO statistics as reported for Germany by the national statistics institute. This database contains averages for 1997- 2003 to derive a value for the year 2000. It can be assumed that the yields are in given standard fresh matter since Monfreda et al. (2008) states that: "yields are in metric tons per harvested hectare". The national statistics were the source of the yield data for Germany in the Monfreda et al. (2008) data set. The national yields were stated in standard fresh matter (Appendix II, 23). The standard moisture is 14% water content for wheat and barley and 9% for rape seed (Henseler, 2012). One gridded dataset per crop was created and published online (Appendix I, 8). The grids for the three crops were obtained (Appendix II, 16, 17, 18).

The second source of actual farm yields was the national statistics. The yield data values were connected with the political districts to give them spatial reference. The yields from the year 2000 till 2010 were downloaded from the web-portal of the statistical office (Appendix II, 6). The yields are given in standard fresh matter (Henseler, 2012). The standard moisture was 14% water content for wheat and barley and 9% for rape seed (Henseler, 2012). The values for winter wheat, winter barley and rape seed were obtained from the "Winterweizen", "Wintergerste" and "Winterraps" columns respectively.

Both data sets of the two sources were converted into dry matter and compared to each other. The comparison was made to verify if the yield values of the global grid of the year 2000 are still comparable to the yield values of the study time frame of 2006 to 2010. In the last steps of the methodology the actual yields were compared to the yield potentials of Yw and Yp to assess the yield gap and yield gap closure.

The next chapter will describe the trial data that is used to test the model performance and the additional data needed as an input for the HERMES model.

2.1.5 Model data

To evaluate the model performance, the modeling results needed to be compared to experimental data on potential production. In this case adequate yield data was available only for non-irrigated and therefore water-limited conditions. The Landessortenversuche (LSV) (state field trials) are non-irrigated field trials of various crops and varieties performed by the chamber of agriculture (Landwirtschaftskammer). The chambers of the different federal states performed plot size experiments on different test locations within the main growing areas of the country. The management was aiming for maximum yields. Fertilization and the plant protection measures were performed at the possible optimum level. The yield results of the trials for the three crops winter wheat, winter barley and rape seed have been published for each year from 2007 till 2010. Yields are shown in decitons fresh matter per hectare (dt/ha). The moisture contents of wheat and barley were 14% and 9% for rape seed. The published results represent average yields for multiple varieties for a certain area. Multiple trial locations were averaged in the published yield results. However the areas were characterized with the name of the region and the soil type where the trial was executed e.g. “Sandy soils North Hannover”. This example means the area is located just north of Hannover in the neighboring district on sandy soils. Additional information stated the actual districts where the trials have been performed in. The soil per trial location was briefly described. The yield results are published as an average for many varieties grown on the different locations nearby each other and on the same soil type. The relative yields of each variety in the yield result are published.

A calibration as described in Kersebaum (2011) or Wolf (2003) was not executed since no data for potential production with intermediate harvests was available. The locations of the trials suitable for model testing were selected during the process of the methodology and are described in the result section.

Besides the trial data, one of the crop growth models (HERMES) also requires crop emergence data for the different crops for the different years. This data is collected by the German weather service (DWD) for many locations over many years. Dr. Kurt-Christian Kersebaum (ZALF) purchased that data and supplied parts of the data for this research project (Appendix II, 24).

2.2 Methodology

2.2.1 Pre-processing steps

The acquired data from Section 2.1 needed to be prepared for the use in this methodology. This section describes the steps that were taken to prepare the raw data for further processing. A graphical overview of the steps is provided in Figure 1.

Crop growth models need a certain quality of weather input data. The values should be available on a daily time step without missing days. The quality check for the German weather stations was performed with the R Script provided by van Bussel (2012). It performed linear interpolation for any missing days up to a maximum of 10 consecutive days. The weather stations did not pass the test if the contained more than 10% missing data per year. The years 2006 till 2010 were tested. The outputs were five weather data files for each year from 2006 till 2010 with daily data for each station that passed the quality check. The data files were provided by van Bussel (2012) (Appendix II, 19).

The stations with an elevation exceeding plus or minus one standard deviation of the mean elevation within their 100 kilometer buffer zone were erased. In case the stations exceeded the limit, it is likely that the weather patterns will differ between the station location and the rest of the buffer zone. With differing weather patterns the crop growth model results will change. In order to verify if the elevation difference was occurring among the available weather stations, a pretest of selecting reference weather stations was performed on basis of all available weather stations in Germany. The result showed whether there were selected stations beyond this range of deviation.

In the next step, all stations beyond the range of elevation were deleted from the list of all available weather stations in Germany. The resulting list of station was imported into ArcMap (Appendix III; 1)[3] and converted into a layer (Appendix III; 2). The list was used as a starting point for the selection of reference weather stations (Figure 1).

[3] Appendix III is containing an overview table for all process models used in ArcMap© in this report. The number behind the comma is referring to the reference number in the table in the Appendix section

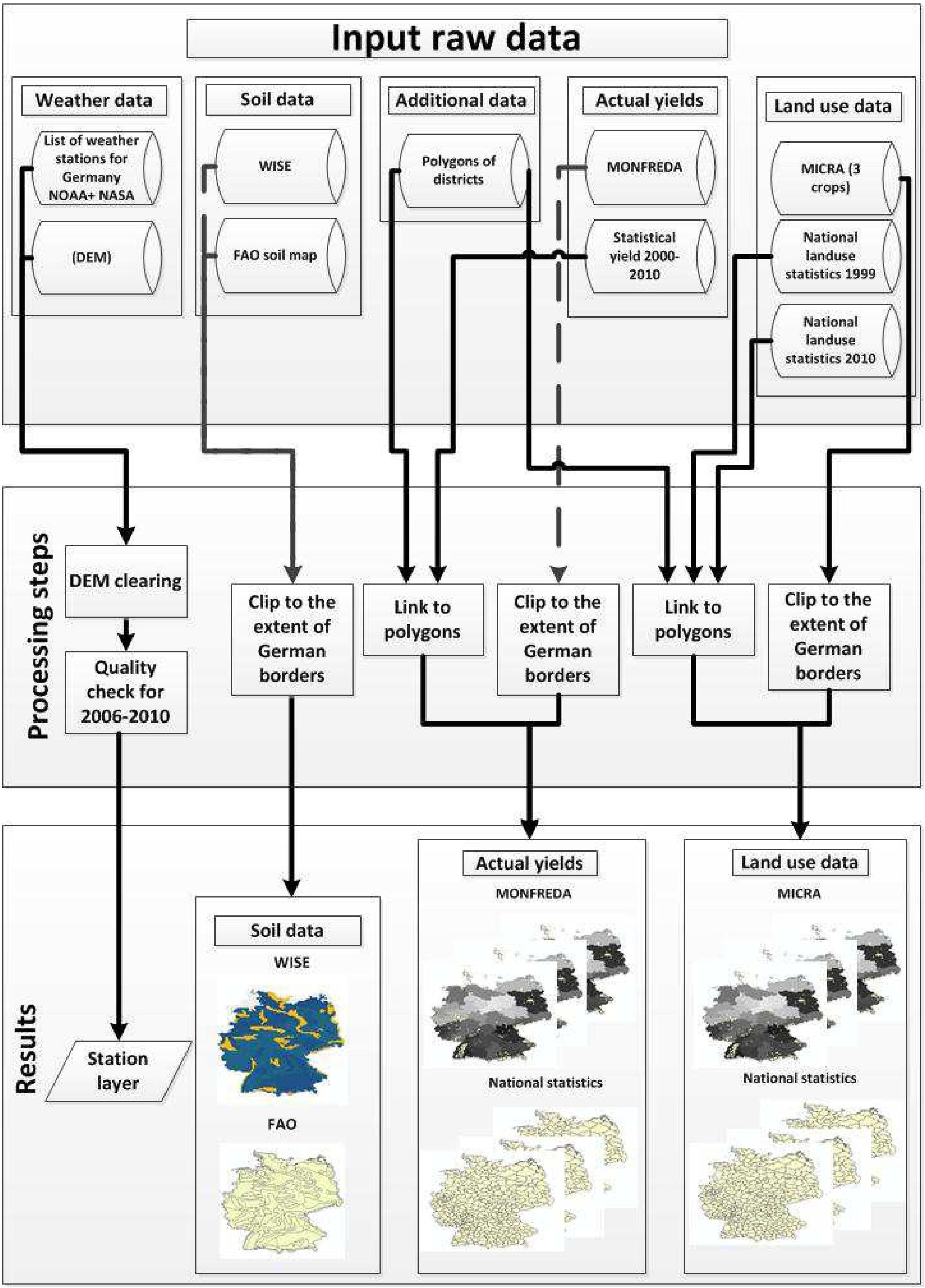


Figure 1 Scheme with the pre-processing steps of the data

All global grids and the FAO soil data needed to be clipped to the size of Germany to avoid using data of neighboring nations in the processing (Appendix III; 3, 4, 15, 16, 17, 18).

The total harvested crop growth area of all three crops under irrigated conditions for the whole country was calculated (Appendix III; 33). The grids of MICRA data containing the crop growth area for irrigated crops have been used as a source for the land use data. This step was taken to verify whether the crops are produced mainly under rain-fed or irrigated conditions. Table 5 in the result section shows that the area of irrigated crop growth for all three crops are negligible compared to the national growing areas. The further methodology of RWS selection focused on the land use data of the rain-fed crops.

The land use data out of the national statistics was linked to the political districts to give it spatial reference (Appendix III, 18-20). In the mid-2000s some changes in the political area did occur. The "Kreisreform" was applied in Saxony-Anhalt and Mecklenburg-Vorpommern. Administrative districts were split and or merged into larger units. The statistical data before the "Kreisreform" could not be linked to the shape area of the districts of the year 2010 anymore. In Mecklenburg-Vorpommern the districts were merged as a whole unit without splitting them. The data for land use out of the statistics of 1999 could be summed up and linked to the shape areas of the districts of the year 2010. The yield data could be averaged over the growing area of the districts merged and also be linked. In Saxony-Anhalt no yield data was available for the city district of Magdeburg. The value of the bordering district "Börde" was used for Magdeburg since soil types are similar and the crop production conditions can be assumed to be similar.

The results of the preprocessing were the layer of weather stations suitable for the use in the crop growth models WOFOST and HERMES, two types of soil data, two layers of actual yields per crop from two different data sources and two layers of land use data per crop from two sources for land use. All datasets were clipped to the spatial extent of the German borders (Figure 1).

2.2.2 Land use and selection of RWS

This chapter describes the method of how the reference weather stations were chosen according to van Wart et al. (in press). The list of weather stations that passed the prescreening was used as a starting point of selecting the RWS. The selection process was done for three crops and three data sets per crop resulting in nine different selections of reference weather stations. The resulting selections of RWS per crop with their buffer zones were compared to each other in pairs. This showed the overlaps between the data sets of Portmann et al. (2010), the national statistics of 1999 and of 2010. A high overlap in buffer zone areas between the data sets was the result of a similar land use distribution. A sensitivity analysis of the buffer zone radius on the amount of RWS was carried out as the last step of the subchapter.

The work flow of the RWS selection is visualized in Figure 2. As input all weather stations that passed the pre-screening were selected. A 100 kilometer buffer zone was created around all the weather stations. Within each zone the sum of the harvested crop area was calculated. The land use data from Portmann et al. (2010) and the statistics of 1999 and 2010 were used (Figure 2). This selection resulted in three sets of RWS selections per crop, a total of 9 data sets (Appendix III, 9-10, 21-27).

Per land use data set, the stations and their buffer zones were ranked in order of descending harvested crop growth area. All stations with an area smaller than 2% of national harvest crop growth area were deleted. The total national harvested area was used from the respective land use data set. The station with the largest growing area per data set was selected and all stations in a 200 km circle were deleted to avoid overlap. The station with the largest area of the list of remaining stations was selected and again all stations 200 km around this station were deleted. This process was repeated till the sum of crop growth area over all selected stations reached at least 50% of the national harvested crop growth. One RWS data set per crop and per land use data set was created. A total of nine selections were made. In the final step of this section the RWS selections per crop were compared to each other. In the first comparison the RWS selection and their buffer zones based on the land use data of Portmann et al. (2010) was intersected with the RWS selection and their buffer zones based on the statistical land use data of 1999. In the second comparison the RWS selection and their buffer zones based on the land use data of Portmann et al. (2010) was intersected with the RWS selection and their buffer zones based on the statistical land use data of 2010. The harvested crop growth area in the resulting overlaps of the intersections was calculated and compared to the national growing area (Figure 2).

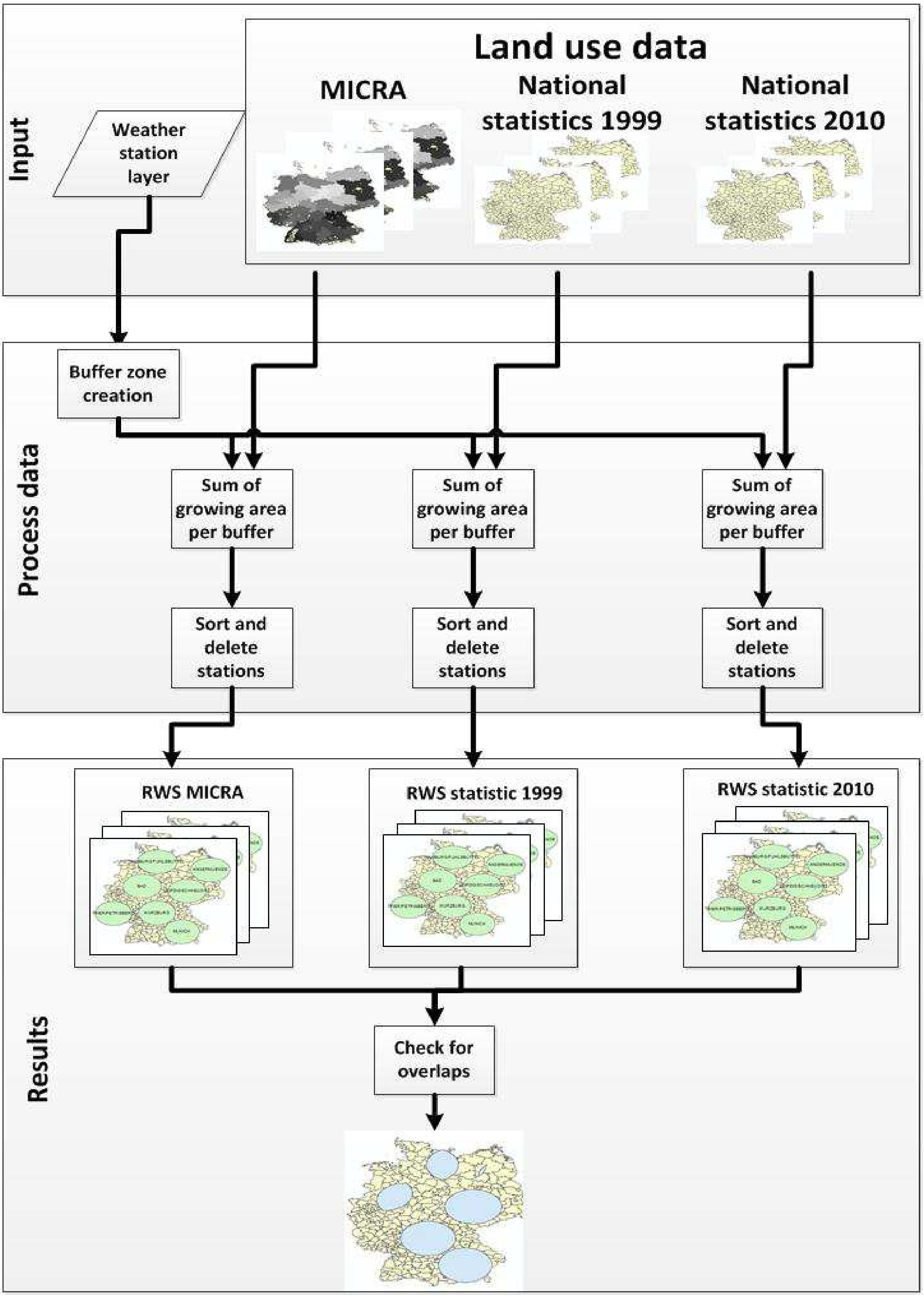


Figure 2 Scheme of selection methods of RWS choosing different land use data sets and comparing the results by overlapping their buffer zones

A closer location of the reference weather station to the growing area might improve yield level assessment at the crop growing area. A closer location can be achieved by a smaller radius of the buffer zones of the RWS. Therefore a sensitivity analysis for the buffer zone radius was carried out to find out how many RWS are required to cover at least 50% of the national crop production. The buffer zones were created around all available weather stations within Germany. The buffer zone radius was changed from 25 km to 150 km in 5 km increments and for each step the RWS were selected. The sensitivity analysis showed how many stations were at least required to fulfill the methodology requirements of covering at least 50% of the national growing area.

As shown in the result section, the RWS selection based on the national statistics does not fulfill the method requirement of at least 50% coverage of national crop growth area. In order to be consistent, all further steps in the methodology requiring land use data are based on the Portmann et al. (2010) data set.

2.2.3 Soil type selection and sensitivity analysis

The assessment of the water limited yield (Yw) required information about the soil. The crop growth modeling was performed for the locations of the RWS's. The main soil type within the buffer zones of the RWS's was required. For each buffer zone of the RWS' the major soil type was selected out of the WISE data base (Appendix III, 14). Only The RWS's selected based on the Portmann et al. (2010) land use data were used in this process. As shown later the other data sets do not lead to a fulfillment of the selection criterion of a total of at least 50% coverage of harvested national crop growth area. The process of selecting the soil types is shown in Figure 3.

van Wart et al. (in press) suggested selecting only the major soil type per RWS buffer zone to assess the water-limited yield (Left column in Figure 3). However choosing only one soil type might not fulfill the criterion of at least 50% coverage of national harvested crop growth area anymore. Therefore a sensitivity analysis for the number of soils selected over the coverage on national harvested crop growth area was carried out. The RWS buffer zone areas were intersected with the FAO (1995) data. This soil data is available as polygon data and a different intersection method in ArcMap than the grid data out of the Batjes (2012) data set can be performed. The selected RWS's per crop cover at least 50 % of the national growing area of the specific crop in their 100 km buffer zones. The total crop growth area within the

RWS' buffer zones was defined as a 100% filling in the following sensitivity analysis. In other words 100% filling within all buffer zones was equal to at least 50% coverage of total national production. The land use data for the analysis was used out of the Portmann et al. (2010) data set.

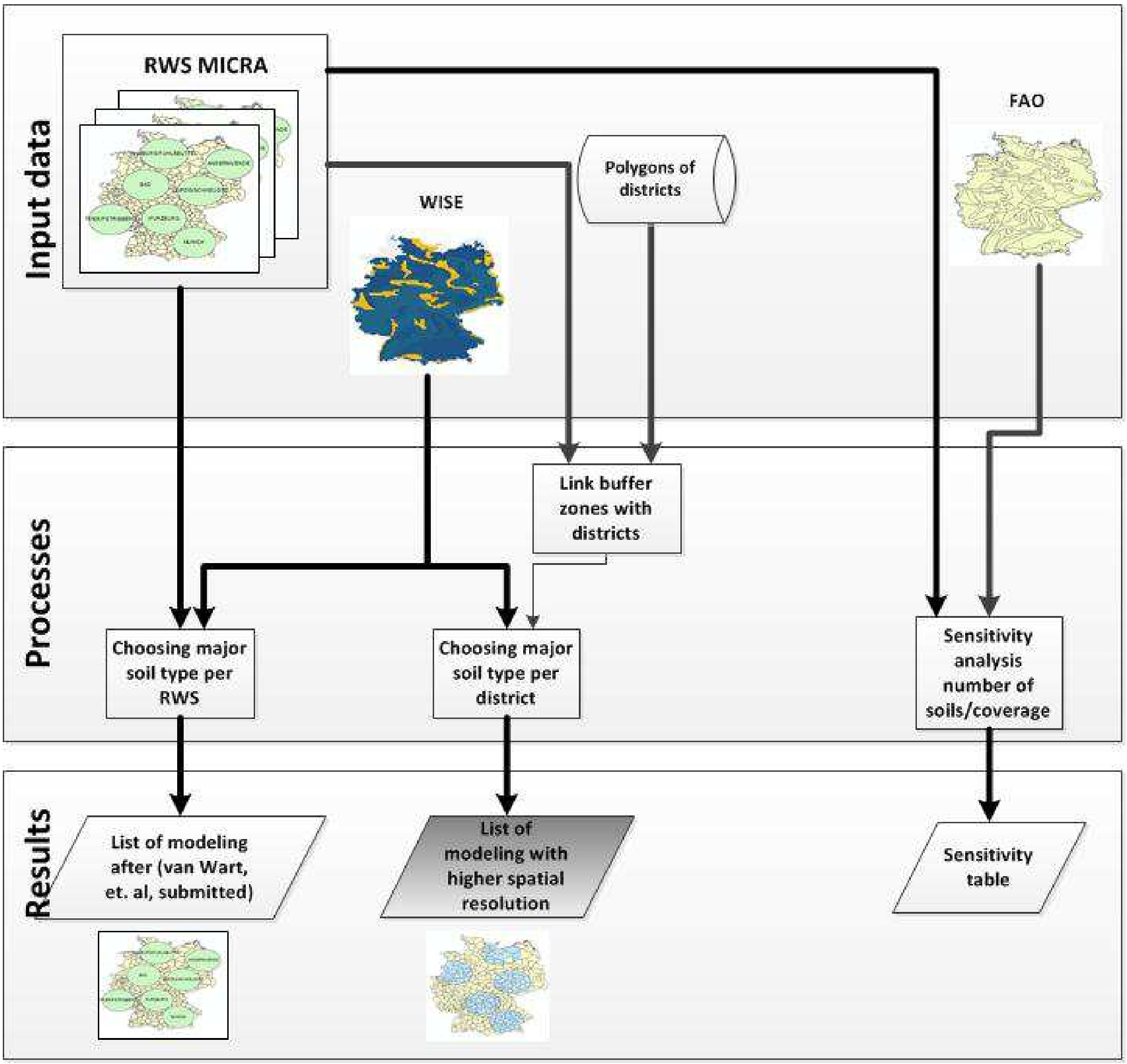


Figure 3 Scheme of soil type selection within the RWS buffer zones and the sensitivity of selected number of soils types as to coverage of national crop growth area

The question is how many model units are necessary to reach how much coverage of the total national crop growth area? A model unit was defined as the unique combination of RWS and soil type. The percentage coverage within the buffer zone was introduced as a simplification. This was done since the total number and the distributions of soil types within one buffer zone differ between the different buffer zones. This percentage coverage is defined as the minimum area of crop growth within the buffer zone that needs to be covered by selecting one or several soil types. According to the protocol of van Wart, et al (in press) a soil type is dominant when he is most present on the arable land within the buffer zone. This example will select the most dominant soil type per RWS by selecting the soil type with the largest crop growth area. For example, a buffer zone contains 1000 ha of wheat. The crop growth area is located on two soil types; 800 ha of wheat are grown on the most dominant soil type within the buffer zone; 200 ha are grown on the least dominant soil type within the buffer zone. 1000 ha is defined as 100 % coverage. A selection of at least 10% coverage means that the most dominant soil is selected and the fraction of its crop growth area of the total area is calculated (800ha/1000ha = 80%). The result will be one model unit and 80% coverage. A selection of at least 90% coverage would lead to the selection of both soil types. The results will be two model units and a fraction of 100% (200ha+800ha/ 1000ha).

The soils were selected with priority over dominance. The most dominant soil type for each buffer zone was selected first, followed by the second most dominant per buffer zone. In case of 10% coverage at least one soil per buffer zone was selected. In case of 100% coverage all the soil types in the buffer zone were selected. This process was done for all three crops. The results showed how many model units were necessary to achieve certain amounts of coverage of national harvested crop growth area (Right column in Figure 3).

In order to assess the Yw with higher spatial resolution, the RWS buffer zones were intersected with the political districts. The layer of the political district did contain the yield data from 2006 to 2010 out of the national statistics. The higher spatial details allowed the comparison to the Monfreda et al. (2008) data on the district level (Appendix III, 34, 35). The major soil type for each district within each buffer zone was selected out of the WISE data. In case the district is located partly in the buffer zone only the area of the district inside the buffer zone was used for the selection of the major soil type for this district. The combination out of weather data from the RWS and the major soil type was selected as a model unit. The crop growth modeling was made for these model units and later linked back to the districts to compare Yw, Yp and Ya to each other. In Figure 3 this is named the “list of modeling with higher spatial resolution”.

2.2.4 Assessment of Yp and Yw

The assessments of Yp and Yw were performed by using crop growth models that were pre-calibrated on trial data. The advantages of these models are that they are applicable over a wide range of environmental conditions (Boogaard, 1998) (Palosuo et al., 2011). Two different crop growth models where used in this study. WOFOST developed in Wageningen (van Ittersum et al., 2003) and HERMES developed and calibrated by Kersebaum (2011). Both models are based on the SUCROS approach of van Keulen et al. (1997) for crop growth (van Ittersum et al., 2003) (Kersebaum, 1995). HERMES was developed for the simulation of N-dynamics in crop growth systems (Kersebaum, 2010). Section 2.2.4.1 describes the SUCROS approach used by WOFOST and HERMES, Section 2.2.4.2 describes the differences between the WOFOST and the HERMES model.

2.2.4.1 SUCROS approach

The SUCROS approach is split in two parts. SUCROS1 is modeling the potential crop growth situations and SUCROS2 is modeling water-limited crop growth situations. SUCROS2 is based on SUCROS1 and includes the Penman equation plus a crop factor for the water-limited production (van Keulen et al., 1997).

The relational diagram of the system in SUCROS1 is given in Figure 4. In SUCROS1 the daily rate of CO_2 canopy assimilation is calculated from incoming radiation, leaf area index (LAI), leaf CO_2 assimilation light response and temperature (Goudriaan & Van Laar, 1994). Losses from maintenance respiration are subtracted from the assimilate pool. The maintenance respiration is determined by the crop biomass. The remaining assimilates in the pool are converted into structural biomass. The losses due to growth respiration are subtracted within this conversion process. The resulting structural biomass is partitioned among the plant organs. The partitioning changes over the various development stages of the crop.

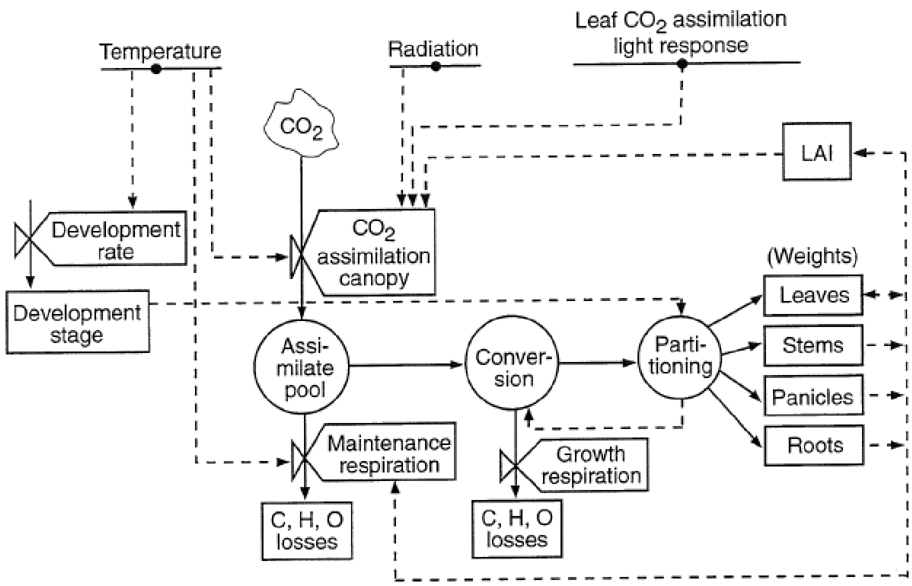


Figure 4 Relational diagram of SUCROS1. Boxes are state variables, valves are rate variables, circles are intermediate variables. Solid lines are flows of material, dotted lines are flows of information (van Keulen et al., 1997).

SUCROS 2 is based on SUCROS1 and includes water-limitation as a yield limiting factor. Limited supply of water has an influence on photosynthesis and the root/shoot partitioning within the model (van Laar, Goudriaan van Keulen, 1997). The relational diagram of the system is shown in Figure 5. The system has been extended and includes the soil water balance. The soil is split into four soil layers that are filled by rainfall (Figure 5). Transpiration, evaporation and drainage are subtracting water from the soil water content. The water loss by transpiration is caused by the crop. The amount of transpiration is subtracted from the rooted soil layers. The transpiration is influenced by the leaf area index, the soil water content and the weather. Evaporation is water loss from bare soil. Drainage occurs for all water that enters the deepest soil layer when this layer is at field capacity. All rain water exceeding the field capacity of the soil layers is drained. This concept is called "tipping bucket" (van Keulen, 1975).

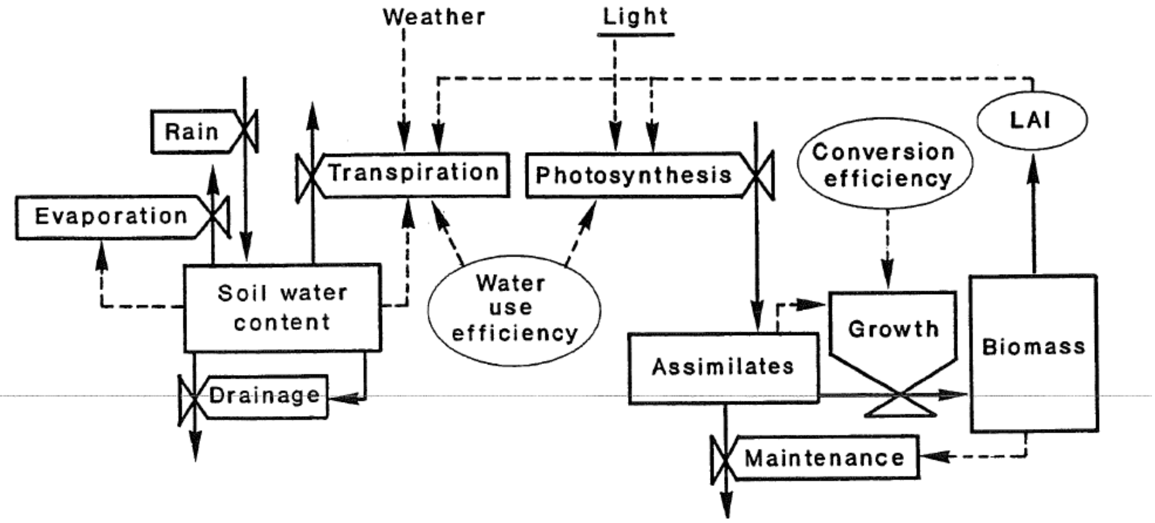


Figure 5 Relational diagram of a system where water is limiting crop growth (van Keulen et al., 1997)

Water-limited crop growth situations occur when the soil water content in the rooting zone is at the critical level. The critical level is met when the water demand by transpiration of the plant cannot be met by the available water in the soil anymore. The critical level is therefore not fixed. It can be derived by the following equations in Equation 1 and Equation 2.

Equation 1 WOFOST for critical water content (van Diepen et al., 1988)

$$\theta_{ws} = (1-p)(\theta_{fc} - \theta_{wp}) + \theta_{wp} \qquad (6.9)$$

Where θ_{ws}	:	Critical soil moisture content	[cm^3 cm^{-3}]
p	:	Soil water depletion fraction as a function of pot. evapotranspiration	[cm^3 cm^{-3}]
θ_{fc}	:	Soil moisture content at field capacity	[cm^3 cm^{-3}]
θ_{wp}	:	Soil moisture content at wilting point	[cm^3 cm^{-3}]

Equation 2 WOFOST for fraction of easy available soil water (van Diepen et al., 1988)

$$p = \frac{1}{\alpha_p + \beta_p\, ETO} - 0.10(5 - No_{cg}) \qquad (6.10)$$

where p	:	Fraction of easily available soil water	[cm^3 cm^{-3}]
α_p	:	Regression constant (=0.76 van Diepen et al., 1988)	[-]
β_p	:	Regression constant (=1.5 van Diepen et al., 1988)	[d cm-^{1}]
ETO	:	Potential evapotranspiration rate	[cm d^{-1}]
No_{cg}	:	Crop Group number (=1 to 5, Doorenbos et al., 1978)	[-]

In case the critical level is met the assimilation rate is reduced and the partitioning is changed in favor of the roots. Up to 50% of the amount of assimilates that would have been located to the shoots are located to the roots (van Keulen et al., 1997). The CO_2 assimilation is reduced by the ratio between actual transpiration and potential transpiration (van Keulen et al., 1997).

2.2.4.2 Crop growth models WOFOST and HERMES

The crop growth model WOFOST is described by Boogaard (1998). It has been used in many applications ranging from yield risk assessment to regional yield forecasting Boogaard (1998). In this study it is used to assess potential and water limited yields for various locations and soil types over Germany. The WOFOST crop files were calibrated at the Centre for Agrobiological Research (CABO-DLO) for the simulation of crop growth and yield. The calibration procedure can be found in Wolf (2003). The model and the crop files are available online under: http://www.wofost.wur.nl/UK/

HERMES and its follow up version MONICA have been used in many applications in Germany (Nendel et al., 2011) (Palosuo et al., 2011). HERMES was provided by Dr. Kurt-Christian Kersebaum (ZALF). Besides the model software it included the calibrated crop parameter files for winter wheat, winter barley and winter rape seed. Winter wheat and winter barley have been calibrated in Germany (Kersebaum, 2011). The winter rape seed parameters where calibrated on trials performed in the Czech Republic.

Both crop growth models are using the SUCROS approach. The crop phenology is separated into two development stages (DVS) in WOFOST and into five development stages in HERMES. WOFOST distinguishes between pre- (DVS<1) and post-flowering (DVS>1) growth, whereas HERMES distinguishes between emergence till double ring, double ring to ear emergence, ear emergence to flowering, grain filling and senescence. The duration of each of these stages in WOFOST and HERMES are determined by a temperature sum and a minimum photoperiod requirement. Sensitivity to water stress and allocation patterns of assimilates change over the different development stages. In WOFOST the temperature sums determining the pre-flowering stage (TSUM1) and the post-flowering stage (TSUM2) will be slightly adjusted to fit the model yield results to the trial yield results. The HERMES original calibrated crop files fitted better to the trial results and the minor adjustments were done based on the consulting of the model expert Dr. Kurt-Christian Kersebaum and will be shown in the result section.

HERMES and WOFOST both need soil data and daily weather data as an input. The necessary inputs files for WOFOST for the weather data from 2006 till 2010 and the soil data files for the different RWS and buffer zones were provided by Dr. Lenny van Bussel (WUR). The soil parameters for WOFOST include soil water retention and percolation. HERMES requires information about the texture class, bulk density and stone content. The texture classes were derived by using the ratios of sand, silt and clay out of the WISE data base and selecting the corresponding texture class from the conversion table provided in Kersebaum (2010).

An overview of the daily weather data input for both models in provided in Table 2.

Table 2 Overview of daily weather data input for WOFOST and HERMES. An empty cell in the table means that the model is not using that input

Weather data model input	unit in HERMES	unit in WOFOST
solar radiation at surface	J cm^{-2} d^{-1}	KJ m^{-2} d^{-1}
minimum temperature	°C	°C
maximum temperature	°C	°C
average temperature	°C	
vapor pressure		kPa d^{-1}
mean wind speed	m s^{-1}	m s^{-1}
precipitation	mm d^{-1}	mm d^{-1}
relative humidity	ratio	

The relative humidity for HERMES was derived by dividing the vapor pressure of the WOFOST file by the saturated vapor pressure. The saturated vapor pressure is a function of temperature. The empirical converting equation was tested by Wexler (1976) and compared to other equations in Buck (1981).

In HERMES and WOFOST each model run was performed for 5 consecutive years, starting with year 2006. HERMES is modeling the water content in the soil continuously for all years, whereas WOFOST starts with soil water contents at field capacity every first day of the year. Germany is located in a humid climate zone with a surplus of rain over evapotranspiration in the winter. Therefore the soil water content for the first day of simulation could be assumed at field capacity (Wolf, 2003). HERMES needs to derive the initial conditions through one model year. The weather data of the year 2006 was copied and provided as weather input data for the year 2005 in HERMES.

HERMES uses emergence dates of the crop as a model start. The necessary input dates of emergence for each crop were selected out of the data base provided from Dr. Kurt-Christian Kersebaum (ZALF). Linear interpolation over the years was executed for all missing data points. WOFOST assumes that the crop is already established and starts with the model run at the first day of a year with a certain initial amount of dry matter (Table 8). No initial ground water table was used for both models as an input since this information was not available. The ground water influence will be discussed in the discussion section. Both models allow simulating capillary rise.

In WOFOST for the water limited conditions the effect of drought only was used. No effect of oxygen shortage was used under the assumption that soils had sufficient drainage capacity. WOFOST could model potential and water-limited growth conditions in the same software, whereas HERMES uses two different versions for modeling potential and water limited growth. The program version for water-limited yield was not using any stress factors of nitrogen limitation on the crop growth. The version for potential yield was not using the stress factors for water shortage and nitrogen shortage.

2.2.4.3 Model calibration

The yield gap assessment is based on the calculated potential and water limited yields of the crop growth models. Since they are a simplification of the reality they need to be calibrated and tested. Both models came with pre-calibrated parameters for all three crops in this research. The model results were compared to actual water-limited trial yields to test these calibrations. The LSV data (Section 2.1.5) on sandy and on clay soils was used to compare the model results of Yw to actual water-limited yields. The information about the LSVs contained the district and soil type they were performed on. Additional background information was provided for all trial years. The information included fertilization rates, seeding densities and disease pressure of the trial year. Based on this description, the trials with the lowest amount of disease pressure and the best crop growth conditions were chosen to compare the performance of the crop growth models. The soil type for the modeling was selected out of the WISE database by using the information about trial location and the soil type out of the trial description.

The weather data for crop growth modeling was used from the weather station that was located closest to the trial location. The weather station had passed the data quality screening. The trials for all three crops on sandy soils were in the middle of three weather stations. In these cases one model run per station with the soil type of the trial location was executed. The results of all model runs were averaged and compared to the trial location.

The water limited yields of both models were compared to trial yields for each year available (2007-2010). Also the average yields of trials and models over the years were derived and compared to each other for sandy and clay soils. When large differences occurred the results of the single years were checked and the problem was located. More information about the trial was acquired in order to locate potential shortcomings in the trial set up or environmental conditions of the trials. In case shortcomings within the trial setup could be excluded the intermediate results of the models were checked. Model experts were consulted to identify for the most suitable change in parameters to achieve the goal of fitting the model closer to reality. This adjustment was done carefully since there was only limited experimental data available. In the case of rape seed the breeding expert Dr. Örtel (Deutsche Saatenveredlung) was consulted since the parameter identification was not clear.

The processes of selecting the trails and the model adjustment are shown in Figure 6.

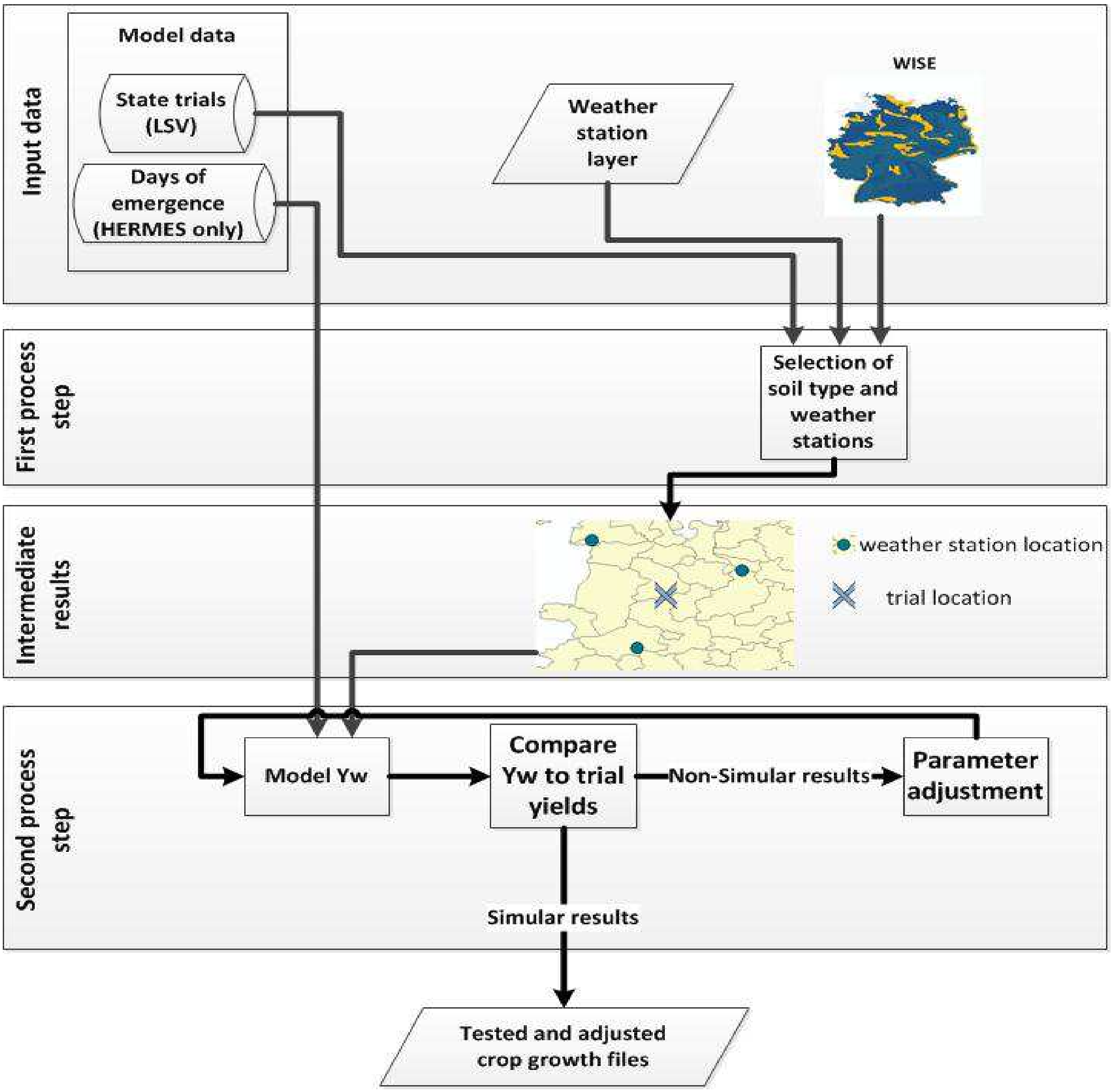


Figure 6 Scheme of model validation

In WOFOST mainly the temperature sums TSUM1 and TSUM2 for the vegetative and generative stage, respectively, were changed to achieve a longer filling of the grains and therefore a higher yield. In HERMES the yield for canola was adjusted by changing the factor of seed fraction in the storage organ.

The crop growth models could produce outliers in the yield results for many reasons. The outliers in the modeled yield levels needed to be erased. Outliers in the WOFOST model results were erased by using a frame of criteria for the model results of total biomass at maturity, leaf area index and harvest index suggested by the model expert Joost Wolff (Wageningen University). Any result of the model run where one or more of these parameters were out of the range mentioned in Table 3 were deleted.

Table 3 Parameter values that are considered outliers in WOFOST (estimated by Joost Wolf, Wageningen University)

	LAI in m^2/m^2		**Harvest index**		**Total biomass in kg DM[4]/ha**	
	min	max	Min	max	min	max
Barley	3	8	0.35	0.55	11000	21000
rape seed	2.5	6	0.25	0.40	10000	16000
Wheat	3	8	0.35	0.55	12000	22000

For the yield results of Hermes a less complex approach was used since the model performance compared to the water-limited trials was good even though the model parameters of Table 3 were out of range. Minimum yields per crop were used to single out extreme outliers (Table 4).

Table 4 Outlier criterion for all three crops in HERMES

	minimum yield in t DM/ha
Barley	2
rape seed	1
Wheat	2

[4] Dry matter

2.2.5 Aggregation

The aggregation process brought the simulated and actual yield levels from the small spatial units of the districts in the RWS buffer zones up to the national scale. The aggregation equation suggested by van Wart et al. (in press) will be used in this process. The equation involves building the production weighted average of the yield levels.

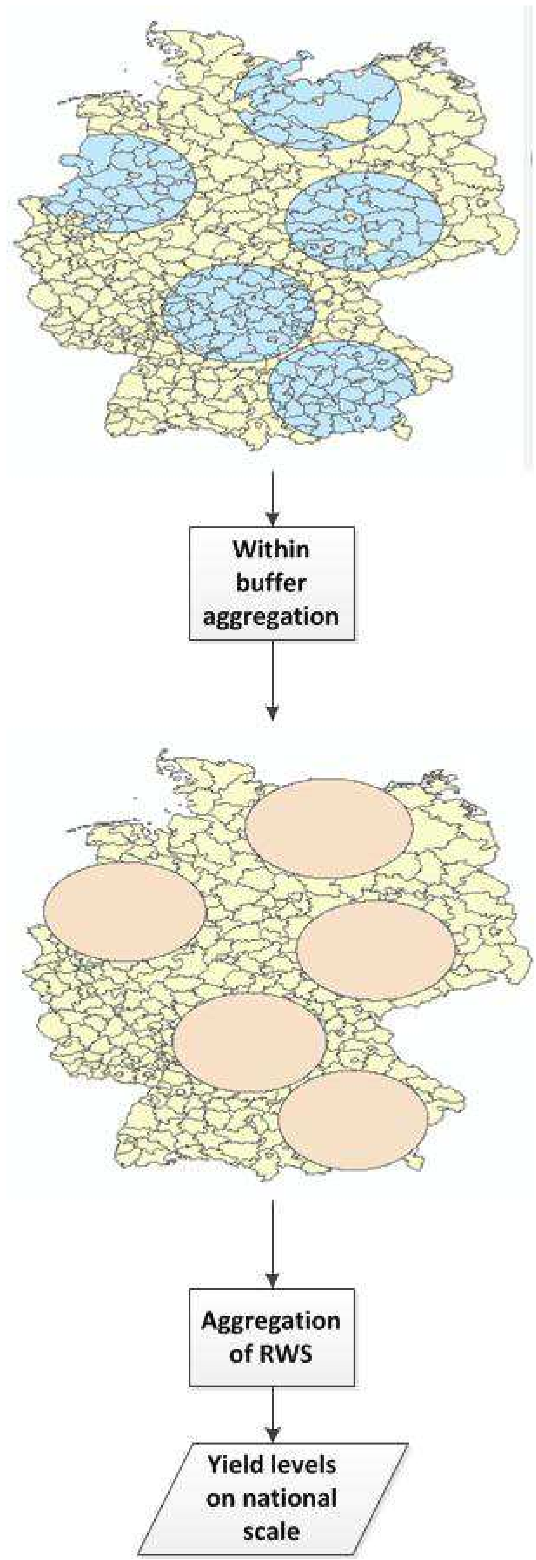


Figure 7 Scheme of the method of aggregation

In the first step all actual yields Ya out of the statistics and the estimated Yw of both crop growth models per districts in the RWS buffer zones needed to be averaged to one value per year per RWS buffer zone. As suggested in van Wart et al. (in press) the crop growth area based on Portmann et al. (2010) within the districts in the buffer zones will be used as a basis for the weighted production.

In the next step the average over the years within each RWS buffer zone will be computed. In the last step the different yield levels for the different RWS will be merged to one national average for Ya, Yw and Yp by using the equation suggested by van Wart et al. (in press). The basis for the production weighted average will be the crop growth area by Portmann et al. (2010) within each buffer zone.

Results for yield gaps will be presented for each district within the RWS buffer zones and on national scale.

3 Results

This chapter presents the results of the data process described in the methodology Section 2.2. It will be split into six parts.

Section 3.1 presents the results of the preprocessing steps. This includes the national crop growth areas for all three crops that have been produced under irrigated conditions. Section 3.2 shows the selection of the reference weather stations for all three crops based on land use data of Portmann et al. (2010) and the national statistics, followed by Section 3.3 showing the results of the sensitivity analysis of soil selection. Section 3.4 presents the results of the crop growth model validation, followed by Section 3.5 describing the comparison of the yield data by Monfreda et al. (2008) and the national statistics. The last Section 3.6 shows the aggregated results of all yield levels.

3.1 Preprocessing steps

The first step of the preprocessing was the correct selection the gridded data sets of Portmann et al. (2010) for irrigated or rain-fed crops. The land use data sets are available for irrigated and rain fed crops. In order to compare the actual yields with the appropriate yield level (Yw, Yp) one needed to determine whether the crop was produced mainly under rain-fed or irrigated conditions. The sums of irrigated harvested crop growth area from Portmann et al. (2010) for all three crops for Germany were calculated (Table 5).

Table 5 National sum of irrigated crop growth area according to Portmann et al. (2010)

Crop MICRA	Area in ha
Barley	13
Canola	11
Wheat	19

According to Portmann et al. (2010) none of the three crops is grown on more than 20 ha under irrigated conditions (Table 5). The explanation can be found in the data description of Portmann et al. (2010). The assumption was made that only tuber and root crops are irrigated in Germany. The arable land equipped with irrigation equipment was distributed among these crops. Additional information showed that there are 560 000 hectare, or 3.3 % of the total German arable land are equipped with irrigation infrastructure (Umwelt Bundesamt, 2011).

Since the land use data determines whether the yield gap is derived based on Yp or Yw, one might conclude at this point that the yield gap and the yield gap closure are derived from Yw. Even though the additional information shows a rather large amount of arable land equipped with irrigation, one might assume that this won't be used only for one of the crops in question but rather in a crop rotation. The amount of crop growth area under irrigation of wheat, barley and rape seed can only be a minor fraction of the national crop growth area. The yield gap closures and yield gaps are derived from Yw. The yield gap closures and yield gaps based on Yp are shown for additional information.

The next step of preprocessing was to verify whether the selection procedure of RWS will select stations which are located on significantly higher or lower elevation compared to their surrounding area. Figure 8 shows that at least two of the six stations selected are located on higher or lower elevation compared to the mean elevation of their buffer zone.

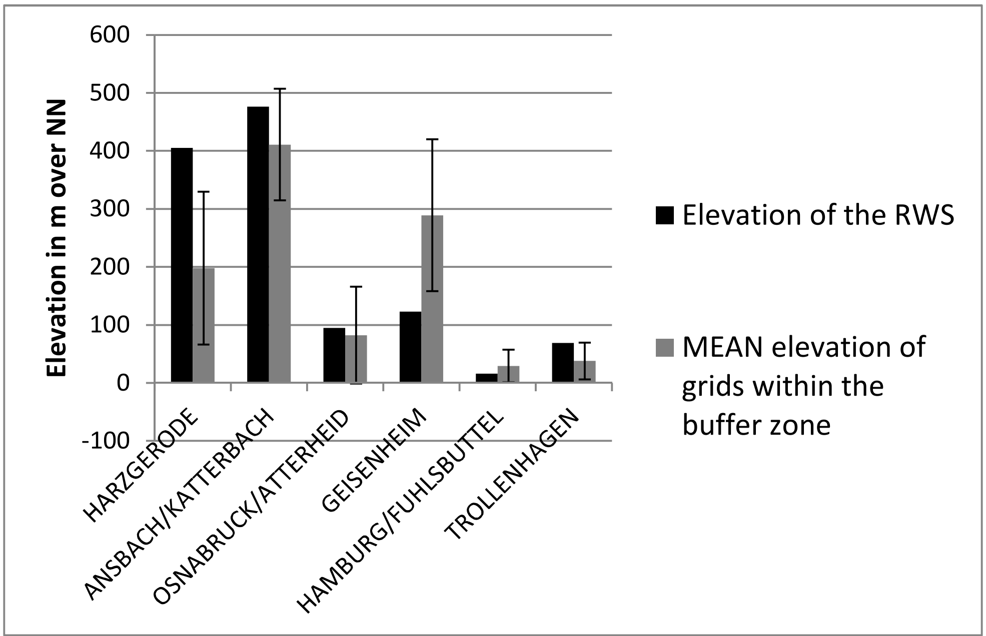


Figure 8 Elevation of the RWS and their 100 km buffer zones

As discussed later, the difference in elevation can lead to a false estimation of Yw and Yp. Therefore all further process steps will be performed for weather stations that passed the elevation prescreening.

3.2 Reference weather station and land use selection

This Section presents the results of the reference weather station selection based on the land use data of Portmann et al. (2010) and the national data.

Calculation of the total national growing area of all the crops was the first step to process the methodology. The Portmann et al. (2010) data set is based on "the harvested area of the years around the year 2000", whereas the national statistics are available for the years 1999 and 2010. The national sums of harvested crop growth area for all three crops in Germany from Portmann et al. (2010) and the national statistics are shown in Table 6. The Portmann et al. (2010) shows the crop growth areas for rain-fed crops, the national statistics does not distinguish between irrigated and non-irrigated crop growth area.

Table 6 Total national growing areas in ha for all three crops in Germany

	Total national growing areas in 10^6 ha		
crop	**Portmann et al. (2010)**	**German Statistics 1999**	**German Statistics 2010**
barley	1.87	1.37	1.64
rape seed	0.98	1.15	1.46
wheat	2.48	2.60	3.30

For the barley crop, Portmann et al. (2010) estimates approximately 1.87 million ha whereas the national statistics estimate 1.37 million ha for 1999 and 1.64 million ha for 2010. The statistic of 2010 includes spring and winter barley for the crop growth area for barley. The statistics of 1999 distinguishes between spring and winter barley; the crop growth area for barley of the German statistics of 1999 in Table 6 represents the crop growth area for winter barley. Including spring barley for 1999 the total national crop growth area would be 2.22 million ha. For the rape seed crop the statistics of 1999 and 2010 publish the crop growth areas only for the winter crop. The national rape seed crop growth area is estimated with 0.98 million ha by Portmann et al. (2010), 1.15 million ha by the statistics of 1999 and 1.46 million ha by the statistics of 2010. For the wheat crop Portmann et al. (2010) estimates the total national crop growth area at 2.48 million ha, the statistics of 1999 at 2.60 million ha and the statistics of 2010 at 3.30 million ha.

The results for the total crop growth area differ from each other for all crops. The data in Table 6 shows a strong increase in crop growth area for rape seed and wheat, comparing the data of Portmann et al. (2010) and the statistics of 1999 to the statistics of 2010 .The Portmann et al. (2010) data shows a slightly smaller total growing area for wheat and rape seed than the statistics of 1999. For the barley crop the Portmann et al. (2010) data shows a larger crop growing area of 0.50 million or 39 % compared to the statistics of 1999.

In the second part a sensitivity analysis was carried out. The number of RWS to fulfill the methodology requirements of 50% national coverage of van Wart et al. (in press) was in question. Based on the Portmann et al. (2010) land use data, Figure 9 shows that at a buffer zone radius of at least 35 kilometers in wheat and 40 kilometers in barley and rape seed is needed to fulfill the methodology requirements.

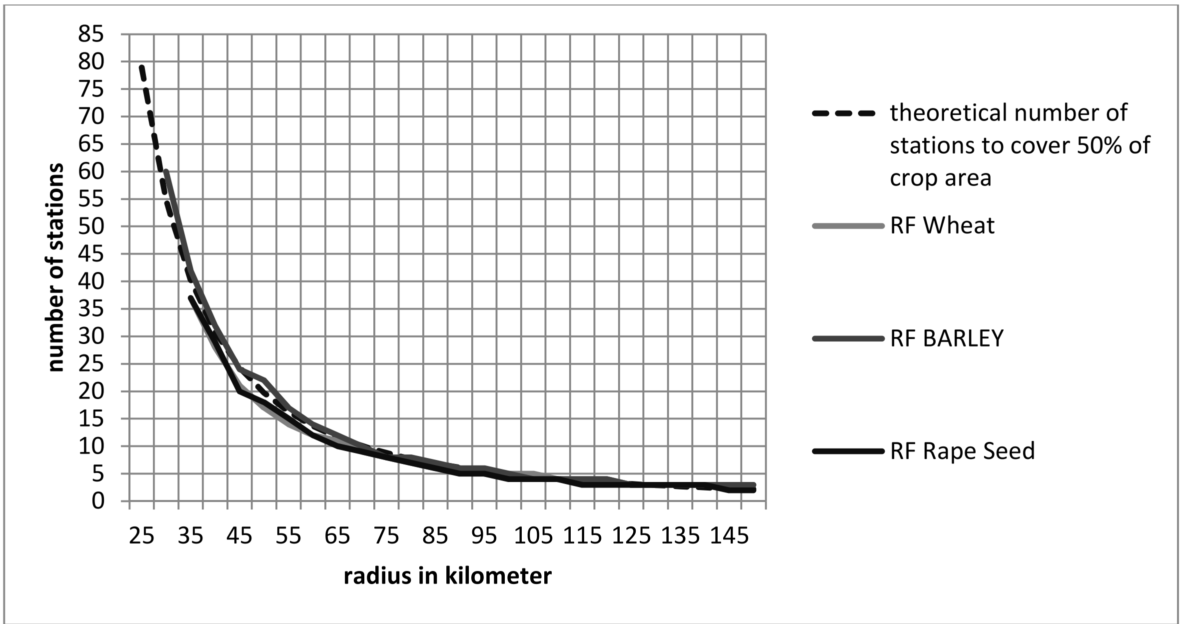


Figure 9 Sensitivity analyses of buffer zone radii and number of RWS needed for > 50% crop area coverage (Appendix IV, 1)[5]

The theoretical number of stations, presented as the dashed line, in Figure 9 is giving that 8% of each buffer zone is covered by the crop in question. The 8% coverage is derived by fitting the theoretical line to the data for barley, wheat and rape seed. The area of the buffer zone was calculated by using the equation for circle surface area $A = \pi r^2$. The total number of stations was calculated by using the equation: $n = A(total)/(0.08 * \pi r^2)$

[5] Appendix IV is containing an overview table for all Excel sheets used to process data in this report. The number behind the comma is referring to the reference number in the table in the Appendix section

3.2.1 Selection of RWS based on Portmann et al. (2010) land use data

This part is showing the results of the reference weather station selection based on the land use data by Portmann et al. (2010). For barley, rape seed and wheat the maps of the stations with their buffer zones will be shown. Detailed information for all three crops about the sum of growing area per buffer zone is presented in Appendix V.

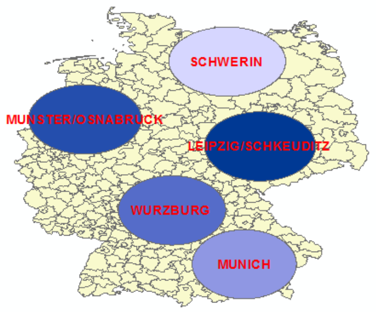


Figure 10 Selected RWS for barley based on land use data by Portmann et al. (2010), 100 km circle buffer zones. The contrast of filling correlated with the percentage of national area covered

Based on the Portmann et al. (2010) data set, a total of five RWS are necessary to cover 50% of the national harvested barley area (Figure 10). Of these five stations the buffer zones of the stations Leipzig covers 12%, Munster 11%, Wurzburg 11%, Munich 8% and Schwerin 8% of the national barley area.

In rape seed a total of five RWS are necessary to cover 54% of the national harvested rape seed area based on the Portmann et al. (2010) data set (Figure 11). The buffer zones of the stations of Leipzig and Warnemuende cover 16% and 15% of the total rape seed national growing area. The buffer zones of Wurzburg, Hannover and Munich are covering 9%, 7% and 6% of the national area respectively.

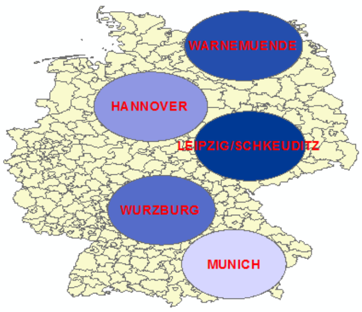


Figure 11 Selected RWS for rape seed based on land use data by Portmann et al. (2010), 100 km circle buffer zones. The contrast of filling correlated with the percentage of national area covered

Based on the Portmann et al. (2010) data set, a total of six RWS are necessary to cover 53% of the national harvested wheat area (Figure 12). The buffer zones of the stations Magdeburg and Warnemuende cover 15% and 10%, Munich and Wurzburg both cover 9%, Munster and Cuxhaven cover 7% and 4% of the national area respectively.

Figure 12 Selected RWS for wheat based on land use data by Portmann et al. (2010), 100 km circle buffer zones. The contrast of filling correlated with the percentage of national area covered

3.2.2 Selection of RWS based on national statistics land use data

The selection of reference weather stations was not only performed on basis of land use data by Portmann et al. (2010) as in Section 3.2.1 but also on basis of the German national statistics of 1999 and 2010. The selection of RWS that could fulfill the requirements of at least 50% coverage of national area is the data set for barley for the year 2010. All RWS selections based on the data sets for all crops of the land use data set of 1999 and wheat and rape seed of the land use data set of 2010 are reaching between 40% to 48 % coverage with similar weather stations but never fulfill the 50% coverage criterion (results not shown).

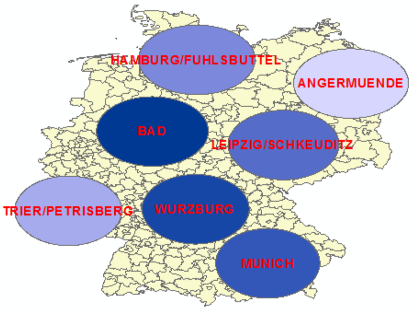


Figure 13 Selected RWS for wheat based on the national statistics of 2010, 100 km circle buffer zones. The contrast of filling correlated with the percentage of national area covered

The selection of RWS for barley based on the land use data of the national statistics of 2010 is leading to 7 stations covering a total of 51% of total national barley production (Figure 13). The buffer zones of the stations of Bad and Wuerzburg cover 12% and 11% of the total barley national growing area. The buffer zones on Munich, Leipzig, Hamburg, Trier and Angermuende are covering 8%, 8%, 5%, 4% and 3% of the national area respectively.

The crop growth areas of barley that are covered by both the buffer zones of the selected RWS base on the Portmann et al. (2010) land use data and the buffer zones of the selected RWS based on the Statistic of 2010 are shown in Figure 14. The overlapping buffer zones in Figure 14 are covering 41% of the MICRA national growing area of barley.

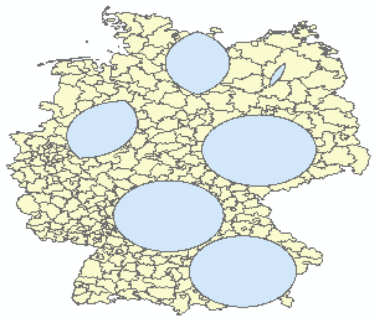


Figure 14 Overlap of buffer zones from RWS selected with land use data by (Portmann, Siebert, & Döll, 2010) and land use data of the national statistics of 2010

As discussed later the method of van Wart el al. (in press) could not be fulfilled on the basis of the national statistics. The merging of districts in the Kreisreform and the assumption that the crop growth area is evenly distributed among the district area might have led to a “thinning” of crop growth area. “Thinning” means that if two districts of the same size are merged, one having a dense crop growth area and the other having no crop growth area, the resulting merged district will have a medium dense crop growth area over a the whole area. The spatial resolution of crop growth area suffers. This might have led to a non-fulfillment of the 50% coverage criterion in the van Wart et al. (in press) methodology.

Even though the national crop growth areas of the Portmann et al. (2010) dataset differ from the national statistics, all further process steps will be based on the RWS selection based on the Portmann et al. (2010) data set.

3.3 Soil selection and sensitivity analysis

The results of the soil selection sensitivity analysis within the buffer zones are shown in Table 7. The number of selected RWS to fulfill at least 50% coverage of national production per crop based on the Portmann et al. (2010) land use data are shown in brackets behind the name of the crop. The method of selecting only the major soil type per RWS buffer zone leads to 19 % coverage of national harvest area for barley, 20% coverage of national harvested area for rape seed and 23% coverage of national harvested area in wheat.

Table 7 Sensitivity analysis of soil selection over national crop growth coverage

	Barley (6)			Rape seed (5)			Wheat (6)		
% filling in RWS	model units	avg. Soil per RWS	% nat. cov.	model units	avg. Soil per RWS	% nat. cov.	model units	avg. Soil per RWS	% nat. cov.
10%	6	1.0	19%	5	1.0	20%	6	1.0	23%
20%	6	1.0	19%	7	1.4	22%	6	1.0	23%
30%	7	1.2	21%	8	1.6	23%	6	1.0	23%
40%	10	1.7	26%	12	2.4	32%	10	1.7	30%
50%	15	2.5	32%	13	2.6	35%	14	2.3	35%
60%	20	3.3	39%	17	3.4	41%	17	2.8	38%
70%	24	4.0	42%	20	4.0	43%	24	4.0	42%
80%	34	5.7	48%	30	6.0	50%	35	5.8	48%
90%	47	7.8	53%	41	8.2	55%	52	8.7	53%

At least an average of 7.8 soil types per RWS buffer zone need to be selected in barley to cover 53% of the national barley production based on Portmann et al. (2010) land use data. In rape seed at least 6.0 soil types per RWS buffer zone need to be selected to cover 50% of the national rape seed production based on Portmann et al. (2010) land use data. In wheat at least 8.7 soil types per RWS buffer zone needs to be selected to cover 50% of the national rape seed production based on Portmann et al. (2010) land use data.

3.4 Model calibration

This section describes the trial locations per crop, additional rainfall information, changes in crop parameters of the models and the yield results of both models after the adjusted crop parameters for all crops.

Most of the suitable trials were located in the North western part of Germany and were close to the weather station Osnabrueck. The rainfall pattern of Osnabrueck for the main growth period of the crops from March till August for the years 2006 till 2010 is shown for this station in Figure 15.

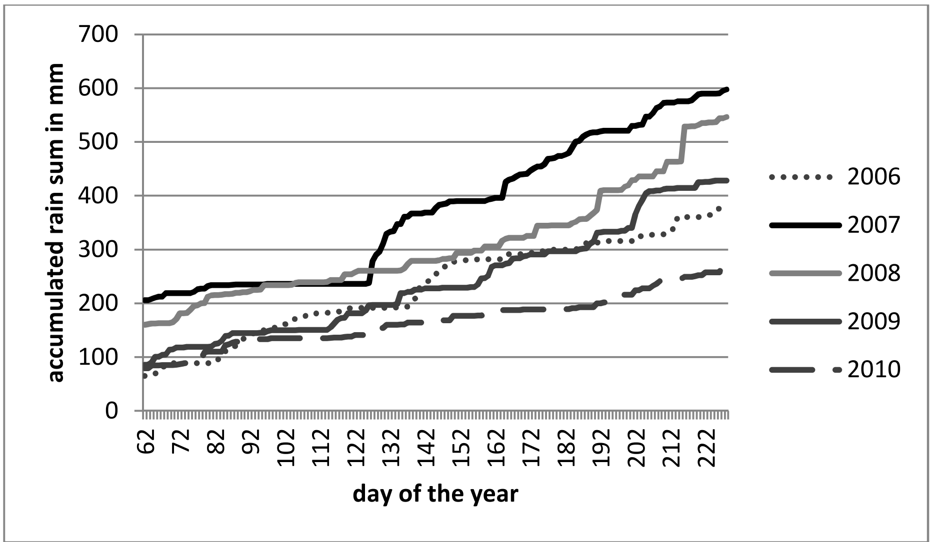


Figure 15 Rainfall patterns in the spring growing season of model station Osnabruck

The three years 2006, 2009 and 2010 start with a low rainfall sum of 90mm at the end of February, whereas 2007 and 2008 already have 200 and 160 mm of rain at this point. Field capacity will be assumed for all years since there will be soil moisture available for all years out of November and December of the previous years. The water needed for crop growth from the beginning of the growing season till maturity. Rape seed reaches its maturity around the Julian day 195 (Wolf et al., 2008b), wheat around the day 210 (Wolf et al., 2008c) and barley around the day 190 (Wolf et al., 2008a). For the year 2010 there is a total amount of rainfall available of 250 mm till wheat maturity is reached at day 210. The year 2007 offers 580 mm in the same time frame. Insufficient water supply on soils with low water holding capacity can be assumed to reduce potential crop growth conditions.

3.4.1 Overview of model parameter changes

The changes of pre- calibrated factors in the crop files of WOFOST were performed during the testing procedure and are shown in Table 8. The changes were made after reviewing the literature for observed temperature sums for the phonological parameters determining the length of vegetative and generative growth by (Wolf et al., 2008a,b,c) and consulting the model expert Joost Wolf (WUR).

Table 8 changed parameters in WOFOST

crop	Parameter	Original value	Adjusted value
barley	TDWI[6]	60	210
	SLATB (0.3)[7]	0.0035	0.0025
Oilseed rape	TSUM1	240	180
	TSUM2	600	660
Wheat	TSUM1	1100	1000
	TSUM2	1000	1100

In WOFOST no crop parameter file was available for winter barley. The initial crop weight was used from the winter wheat file. Winter wheat and winter barley are both cereals that establish their rooting system and leaf canopy in the previous fall. Therefore their initial crop weight per ha at the first of January is assumed similar. The parameter for wheat for the specific leaf area (SLATB) at the early stage (0.3) was changed since the model crop was assumed to be established at the beginning of January. The number 0.3 in parenthesis is describing the development stage DVS in WOFOST. In the spring crop file, SLATB at early stages is higher to account for thinner initial leaves that the crop produces at early development stages. These early leaf stages did occur already in the previous fall period of the winter crop. Since the crop growth modeling is starting at the first of January with an established model crop, these leaf stages don't occur anymore and the parameter needed to be changed. The temperature sums TSUM1 and TSUM2 for oilseed rape and wheat were changed based on (Wolf et al., 2008b,c).

[6] Total initial dry weight of the crop at the beginning of modeling
[7] Specific leaf area as the function of development stage

The pre-calibrated crop file of wheat in HERMES was validated and did not require adjustments. For the barley file in HERMES the first results showed a high grain yield in the potential production situation of around 15000 kg DM/ha. The Yp of wheat on the same locations was around 3000 kg DM/ha lower. The original crop file of barley was checked and contained a mistake in the parameter of the maximum assimilation rate of the canopy (AMAX). It was changed from 55 kg CO_2 per ha leaf area per hour to the value of 37 kg CO_2 per ha leaf area per hour after consulting Dr. Kurt-Christian Kersebaum (ZALF). The yield level Yw of HERMES for barley was lower as the trial yields. Dr. Kurt-Christian Kersebaum (ZALF) suggested changing the factor that determines whether there will be drought stress (ETA/ETP). (ETA/ETP) describes the threshold at what point water stress occurs and is the ratio between actual and potential evapotranspiration. The threshold ratio is a model parameter for each development phase. HERMES modeled a hampered leaf area increase due to water stress in the first stages of crop development. This led to a low LAI and low dry matter production. The ETA/ETP parameter was changed from 0.8 to 0.4 for the phase two between emergence and double ring stage.

In rape seed the ratio (grain weight)/(total storage organ weight) was changed since the ratio is different from the usual 0.8 for cereals (Kersebaum, 2012). The factor that was used for the presented results was 0.65.

3.4.2 Model performance in the calibration process

HERMES and WOFOST simulated yields were compared to actual trial yields. The trials were performed under non-irrigated conditions. The results show the trial yields, Yw and Yp of HERMES and Yw and Yp of WOFOST for each crop on sandy and clay soil types. An overview of the trial location and the weather stations that have been used for modeling is given in Table 9. The trail results were published for seven trials; trials were associated with more than one station if the trial location was in between stations.

Table 9 Overview of trials of different crops their soil types and the associated weather stations used in the validation of crop growth models

Trial number	Crop	Soil type	Trial name as of LSV	Associated Weather station
1	Barley	Sand	Sandböden Nordwest	Emden
1	Barley	Sand	Sandböden Nordwest	Osnabrueck
1	Barley	Sand	Sandböden Nordwest	Bremen
2	Barley	Sand	Sandböden Münsterland	Osnabrueck
3	Barley	Clay	Lehmböden Südhannover	Hannover
4	Rape seed	Sand	Sandböden Nordwest	Emden
4	Rape seed	Sand	Sandböden Nordwest	Osnabrueck
4	Rape seed	Sand	Sandböden Nordwest	Bremen
5	Rape seed	Clay	Lehmböden Nordwest	Emden
6	Wheat	Sand	Sandböden Nordwest	Emden
6	Wheat	Sand	Sandböden Nordwest	Osnabrueck
6	Wheat	Sand	Sandböden Nordwest	Bremen
7	Wheat	Clay	Lehmböden Niederung	Bad Lippspringe

In case more than one weather station was associated with a trial, the crop growth model yield results for both stations were averaged and then compared to the trial yields. The average yield levels of barley for all years from 2007 till 2010 and trial location per soil type are shown Figure 16. Detailed graphs for the different years and soil types are shown in Appendix VI.

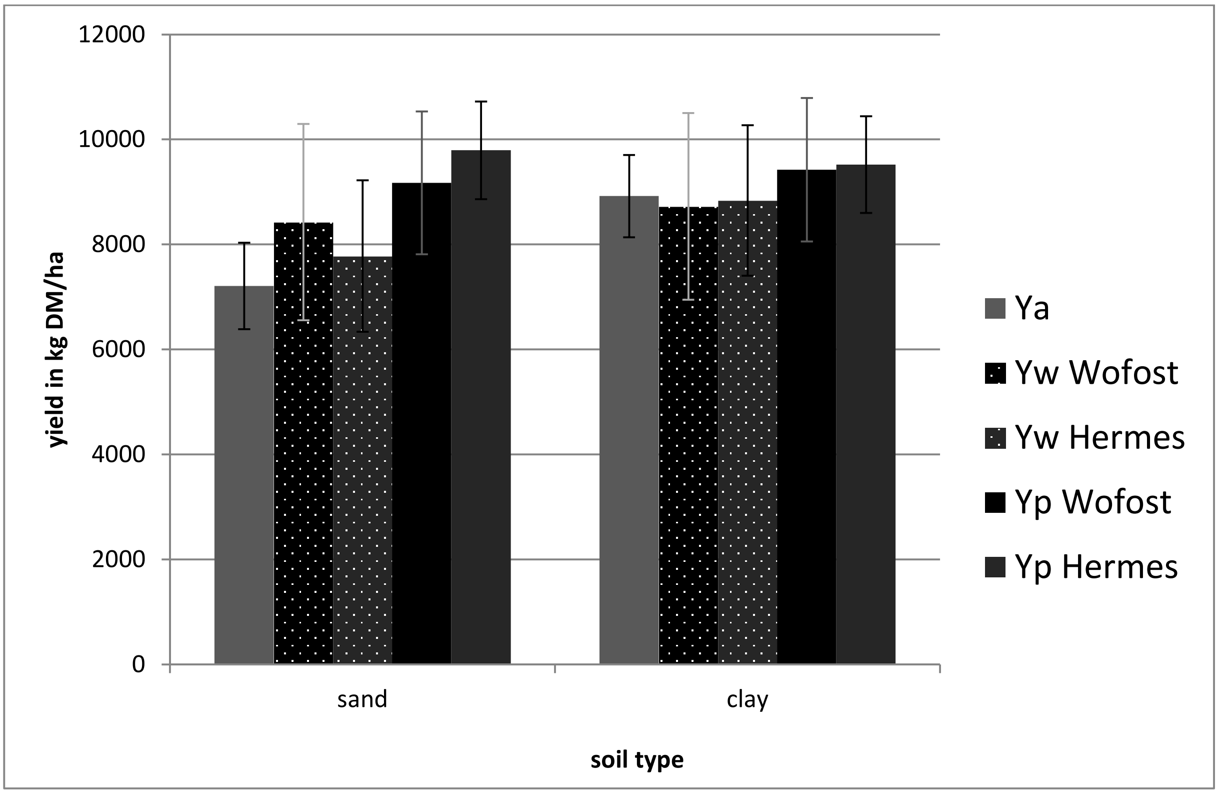


Figure 16 Model performance on sandy and clay soils for barley over 4 consecutive years from 2007 onwards. Ya is average trial yield

The average barley trial yields for sandy soils are 1700 kg DM/ha lower than the trial yields achieved on the clay soils. WOFOST estimates Yw for barley on sandy soils 1200 kg DM/ha higher than the trial yields. HERMES estimates Yw for barley on sandy soils 500 kg DM/ha higher than the trial yields. HERMES and WOFOST estimate Yp higher than Yw on sandy soils.

Yw for WOFOST and Yw for Hermes were not significant lower than the trial yields on clay soils. HERMES and WOFOST estimate Yp higher than Yw on sandy and clay soils. The difference between Yp and Yw is smaller on clay soils than on sandy soils for both models respectively.

The yields levels of Yw and Yp of both models vary more over the years than the actual yields of the trails.

The average yield levels of rape seed for all years from 2007 till 2010 and trial location per soil type are shown Figure 17. Detailed graphs for the different years and soil types are shown in Appendix VI.

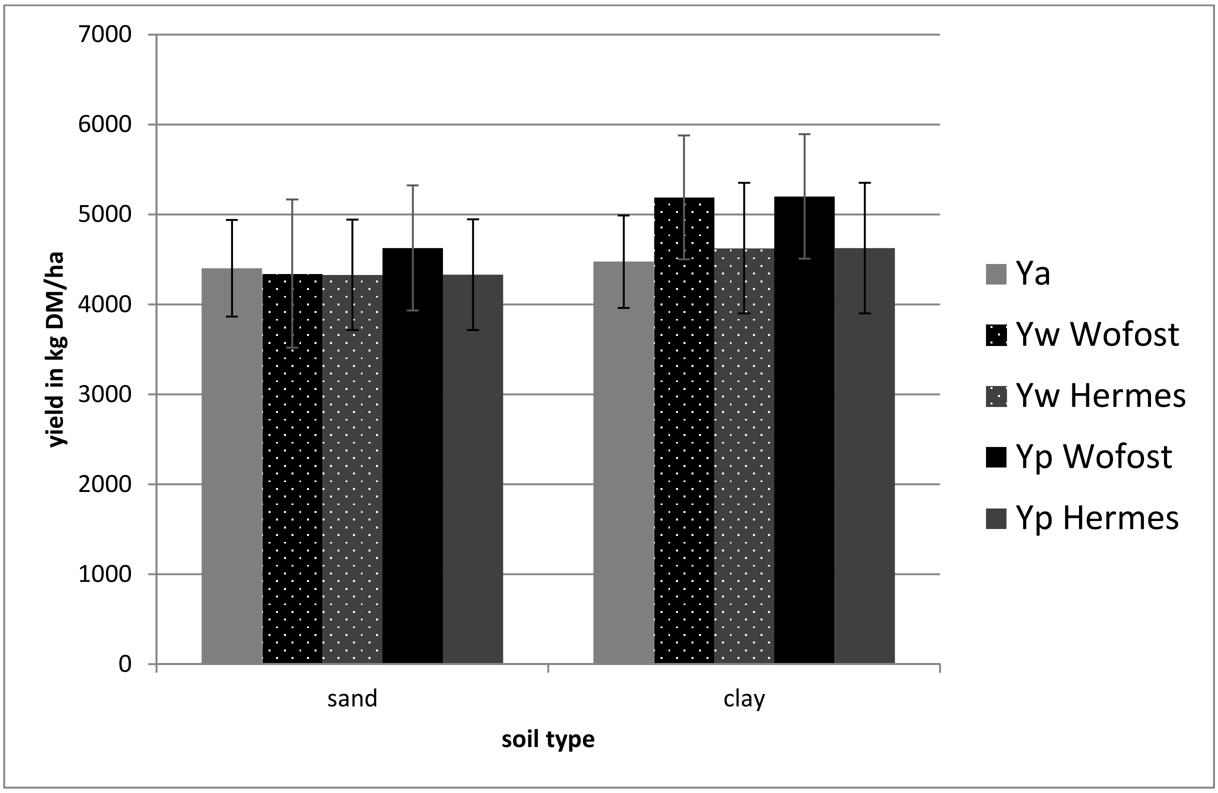


Figure 17 Model performance on sandy and clay soils for rape seed over 4 consecutive years from 2007 onwards. Ya is average trial yield

The average rape seed trial yields are similar for the sandy soils and the clay soils. Yw of WOFOST and HERMES and Ya for rape seed on sandy soils do not differ significantly. WOFOST estimate Yp significantly higher than Yw on sandy soils whereas HERMES estimates Yp and Yw at the same level.

WOFOST estimates Yw for rape seed on clay soils 700 kg DM/ha higher than the trial yields. HERMES estimates Yw for rape seed on sandy soils 150 kg DM/ha higher than the trial yields. HERMES estimates Yp at the same level as Yw on sandy and clay soils. WOFOST estimates Yp at the same level as Yw on clay soils but Yp 300 kg DM/ha higher than Yw on sandy soils.

The yields levels of Yw and Yp of both models vary more over the years than the actual yields of the trails.

The average yield levels of wheat for all years from 2007 till 2010 and trial location per soil type are shown Figure 18. Detailed graphs for the different years and soil types are shown in Appendix VI.

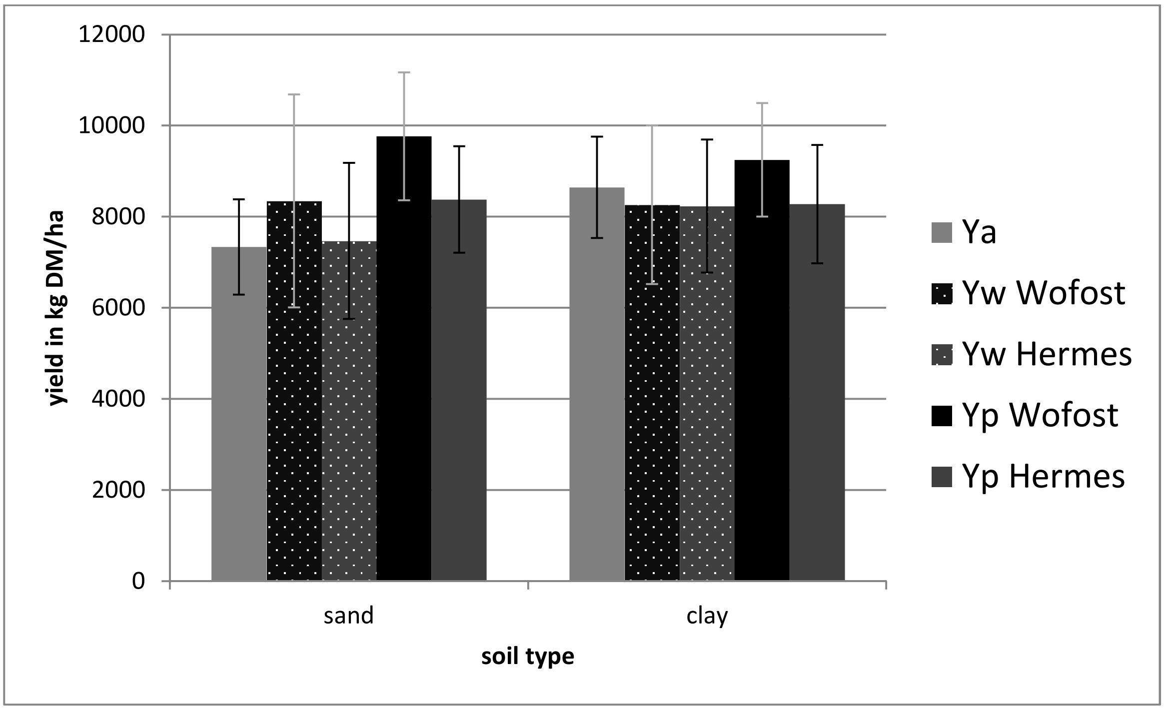


Figure 18 Model performance on sandy and clay soils for wheat over 4 consecutive years from 2007 onwards. Ya is average trial yield

The average wheat trial yields for sandy soils are 1300 kg DM/ha lower than the trial yields achieved on the clay soils. WOFOST estimates Yw for wheat on sandy soils 1000 kg DM/ha higher than the trial yields. Yw of HERMES does not differ significant than the trial yields. HERMES and WOFOST estimate Yp higher than Yw on sandy soils.

WOFOST and HERMES estimate Yw for wheat on clay soils 400 kg DM/ha lower than the trial yields. WOFOST estimates Yp higher than Yw on clay soils. HERMES estimates Yp and Yw at the same level on clay soils. The difference between Yp and Yw of WOFOST is smaller on clay soils than on sandy soils for both models respectively. The yields levels of Yw and Yp of both models vary more over the years than the actual yields of the trails.

3.5 Yield results

This chapter shows the comparison of the yield data of Monfreda et al. (2008) against the average yield out of the statistics for the year 2006 to 2010. The actual yields per RWS buffer zone will be shown in the aggregation section 3.6.

For each district in the buffer zone of the selected RWS per crop the mean yield of each crop out of the Monfreda et al. (2008) 5° arc gridded data set was derived. The crop yields based on the national statistics for 2006 till 2010 are available for the same districts. Figure 19 shows the average yields per crop based on the two types of actual yield data.

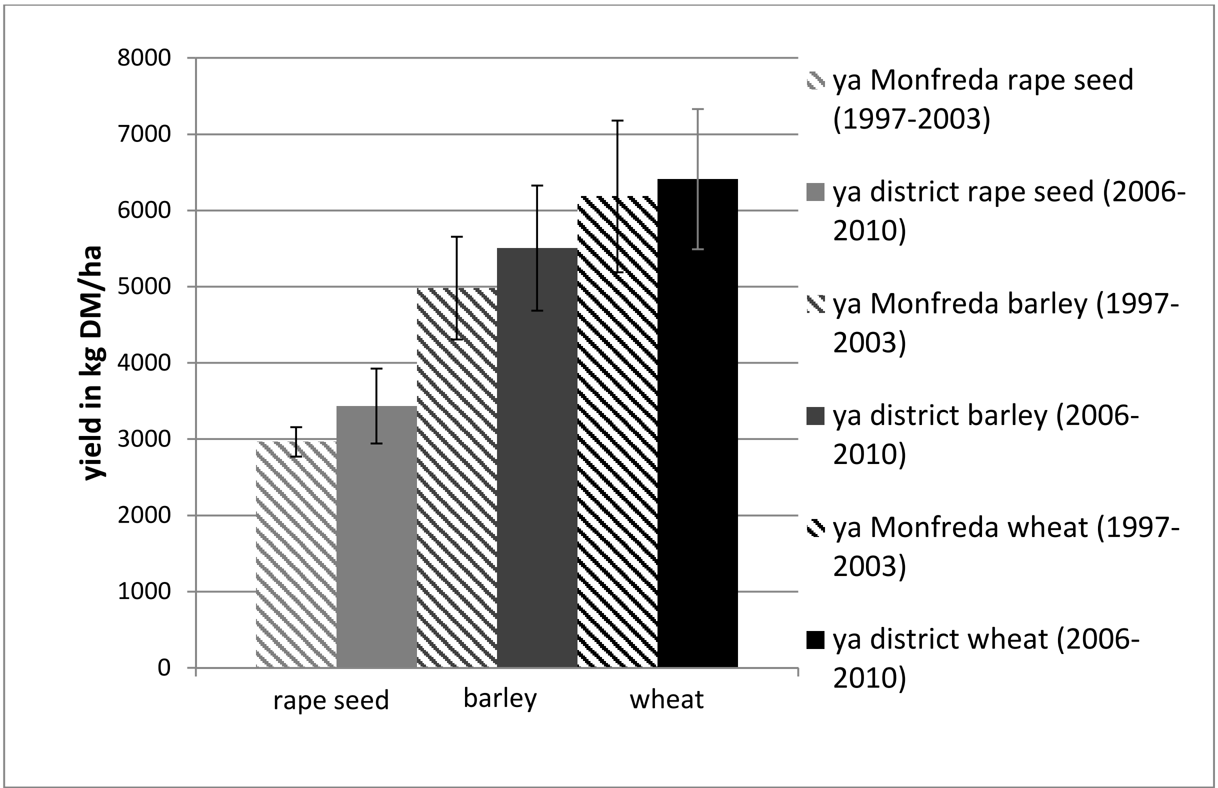


Figure 19 Monfreda et al. (2008) actual yield compared to national statistics yield

The average farm yield based on the average yield level of national statistics between 2006 and 2010 is 16% higher for rape seed, 11% higher for barley and 4 % higher for wheat than the average yield level based on the Monfreda et al. (2008) data set of 2000.

3.6 Aggregation

This section shows the results of the aggregation steps of all yield values for Ya, Yw and Yp per district within the buffer zones to one national yield value for Ya, Yw and Yp. The first step aggregates the yield levels Ya and Yw within the buffer zones to one yield value per RWS. The second step will aggregate the yield levels per RWS to one yield level at national level. Single yield values Yw and Yp that can be assumed as a false prediction (Section 2.2.4.3) values needed to be erased before the aggregation. The aggregation results based on the yield levels including the false values and without the false values are shown in comparison for one example crop for barley.

The crop growth models occasionally underestimate the yield potentials. Section 2.2.4.3 introduced a set of criteria to determine these false estimations. The underestimations were deleted to avoid false prediction of the aggregated Yw and Yp. Figure 20 shows the barley yield results (Yw) for both crop growth models including and excluding the false yield predictions. The figures for rape seed and wheat can be found in Appendix VII.

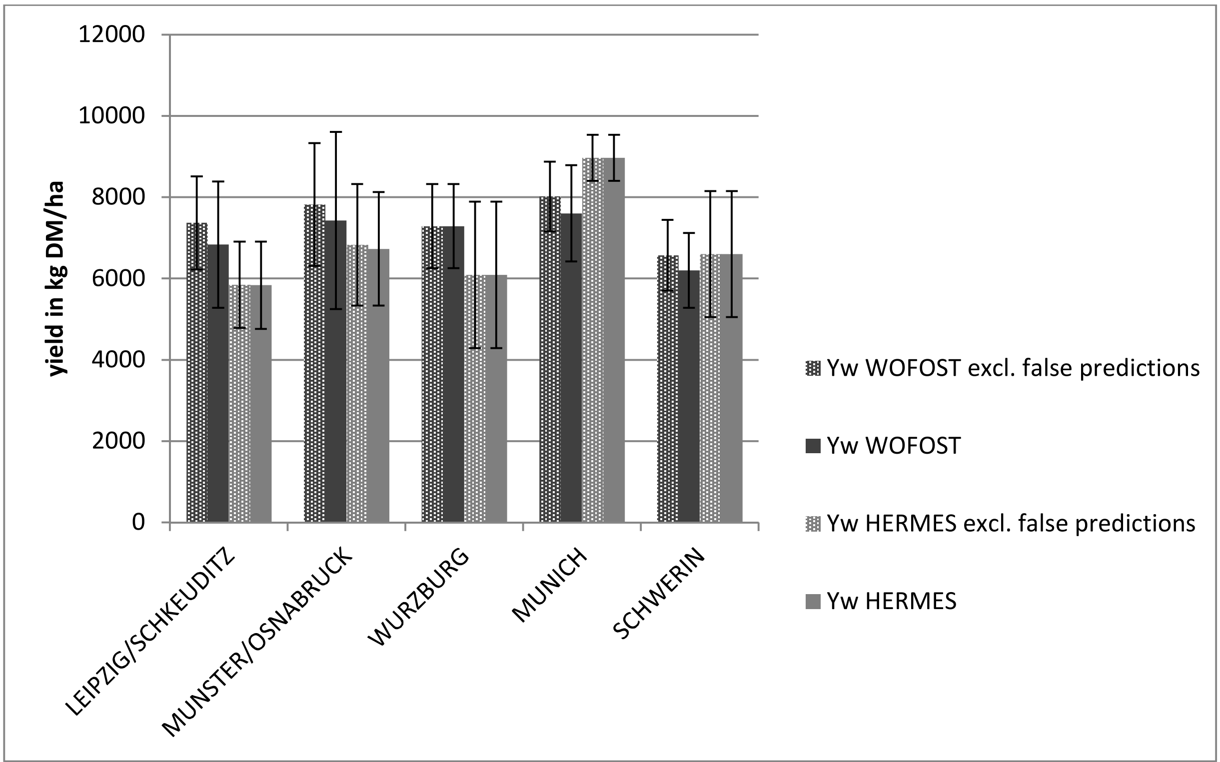


Figure 20 Yw of barley including false yield predictions and excluding false yield predictions

Excluding the false predictions leads to a lower standard deviation and in case of WOFOST to a higher average yield level for Yw compared to Yw including false predictions. The false yield values in the presented data were excluded for wheat and rape seed.

The yield level Yw per RWS was derived in two different ways. One way to asses Yw per RWS was crop growth modeling of the major soil type per RWS buffer zone suggested by van Wart et al. (in press). The second way to assess Yw per RWS was suggested in this report by crop growth modeling Yw per major soil per district within the buffer zones, aggregating the yield levels Yw per district to one value per RWS. The latter method is using a higher spatial resolution and multiple soil types. The results for wheat are presented in Figure 21.

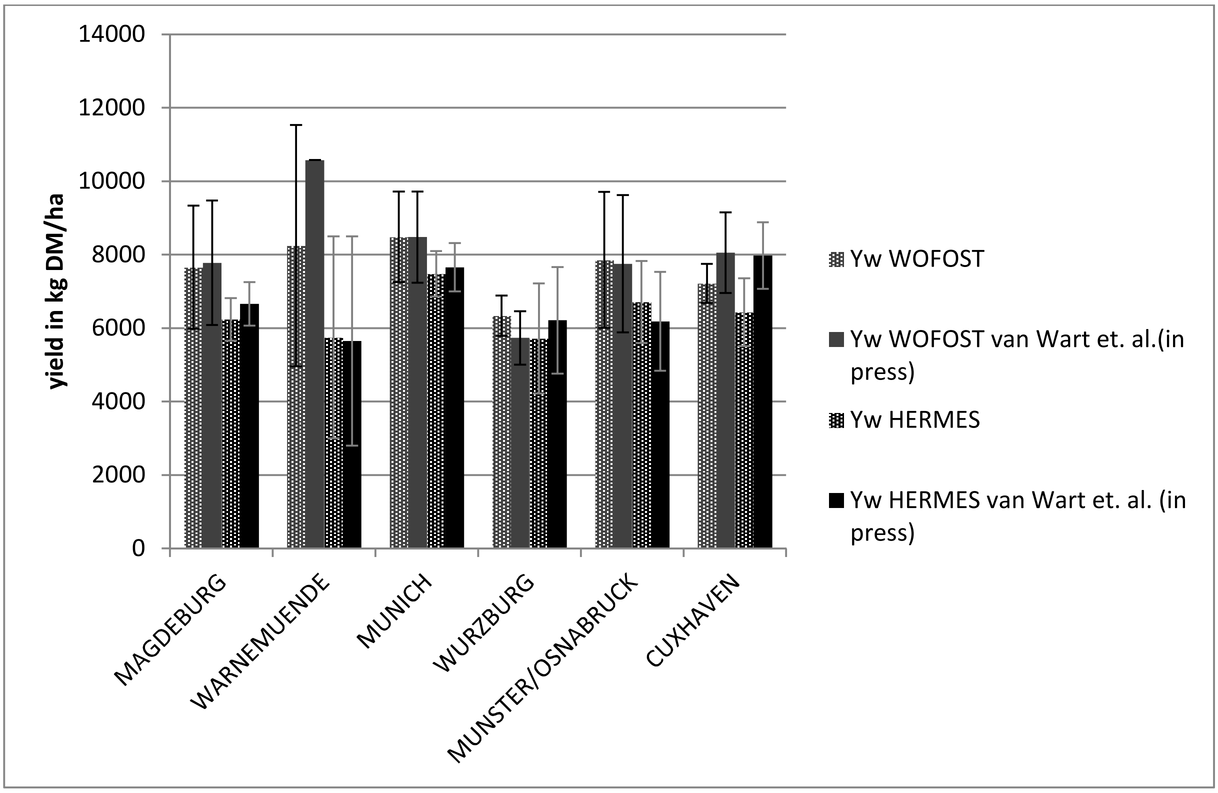


Figure 21 Comparison of in-buffer aggregation against the method of van Wart et al. (in press) in wheat

The yield level Yw of Warnemuende of the method of van Wart et al. (in press) is 2200 kg DM/ha higher than the yield level Yw of Warnemuende of the method suggested in this report. Also for Cuxhaven the van Wart et al. (in press) method resulted in somewhat higher simulations than the method of this report.

Yp, Yw and Ya of barley aggregated to national level are presented in Figure 22.

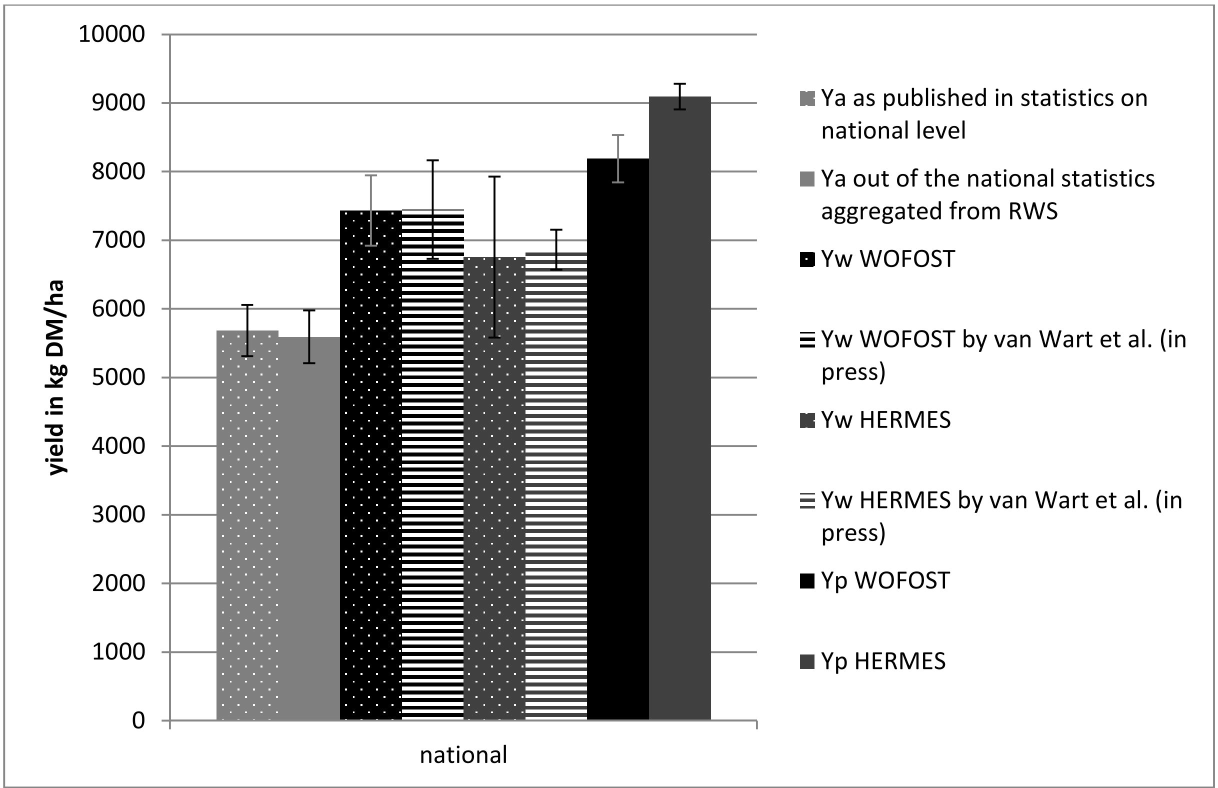


Figure 22 Aggregated national yield levels Ya, Yw and Yp of barley

The barley yield levels Ya published on national level and Ya based on the national statistics aggregated from the RWS do not differ significantly. The barley yield levels Yw of WOFOST and Yw of WOFOST by van Wart et al. (in press) do not differ significantly. The barley yield levels Yw of HERMES and Yw of HERMES by van Wart et al. (in press) do not differ significantly. Yw of WOFOST is 600 kg DM/ha larger than Yw of HERMES, whereas Yp of WOFOST is 800 kg smaller than Yp of HERMES.

The crop growth model created more false yield prediction in rape seed compared to the other crops. In most cases of false prediction WOFOST predicted a total biomass above 16000 kg DM/ha and a low harvest index below 0.20. The combination of large biomass and low harvest index still led to acceptable yield prediction Yw and Yp. Figure 23 presents all yield levels of rape seed without outliers.

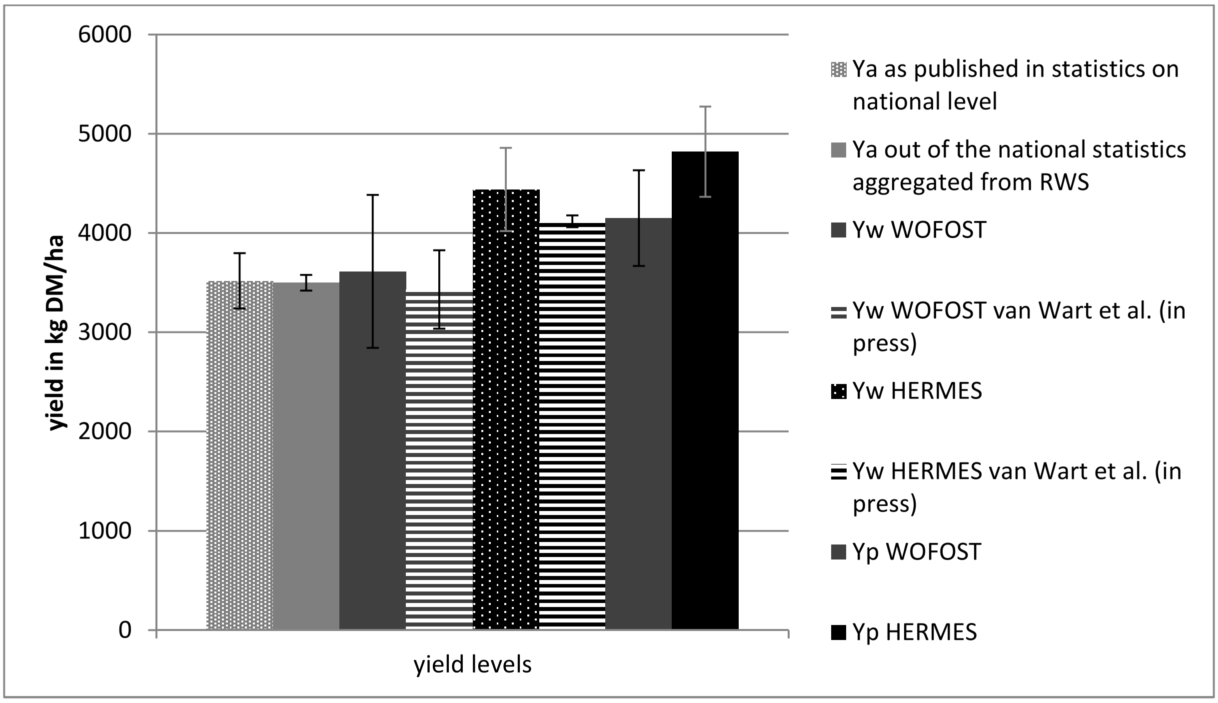


Figure 23 Aggregated national yield levels Ya, Yw and Yp of rape seed

The rape seed yield levels Ya as published on national level in the national statistics and Ya as aggregated out of the RWS buffer zones do not differ significantly. The rape seed yield levels Yw by van Wart et al. (in press) is lower than Yw by the detailed method by 200 kg DM/ha for WOFOST and 300 kg DM/ha for HERMES.

The yield results of wheat on the national scale are shown in Figure 24.

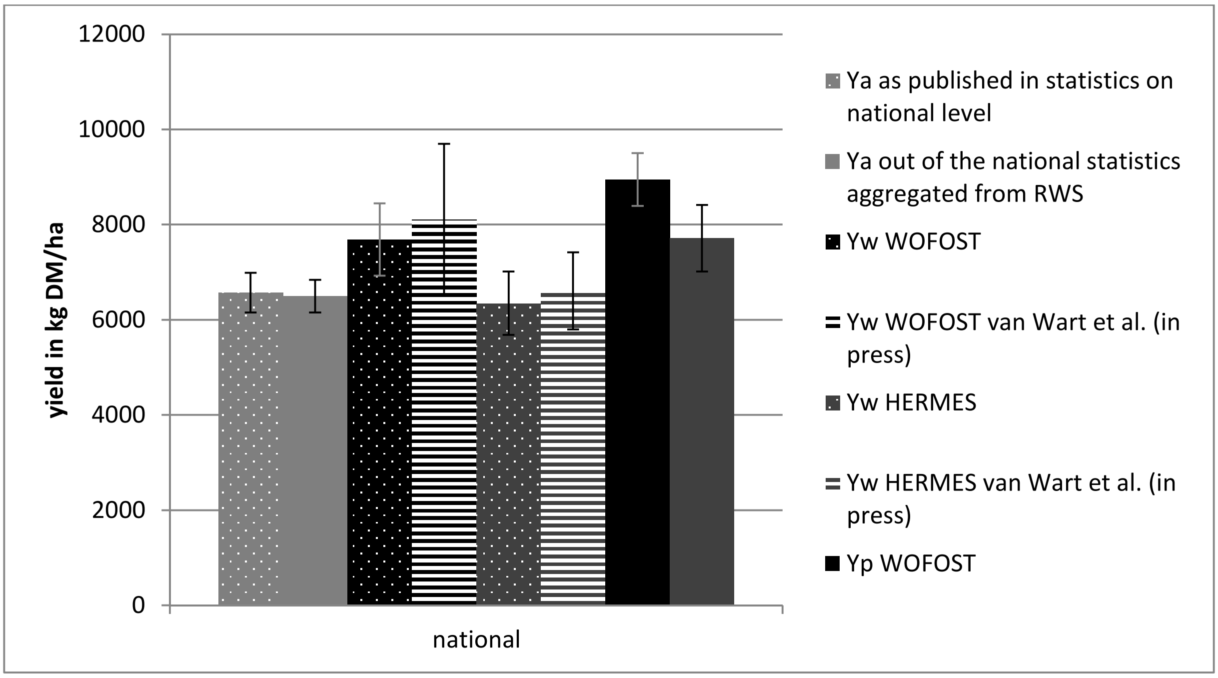


Figure 24 Aggregated national yield levels Ya, Yw and Yp of wheat

The wheat yield levels Ya as published on national level in the national statistics and Ya as aggregated out of the RWS buffer zones do not differ significantly. The wheat yield levels Yw by van Wart et al. (in press) is higher than Yw by the detailed method by 500 kg DM/ha for WOFOST and 300 kg DM/ha for HERMES.

The yield gap closure based on Ya around the year 2008 and the average Yw for both crop growth models around the year 2008 was derived per district within the RWS buffer zones. The spatial distribution of the Ygc, Ya and Yw for wheat, rape seed and barley can be found in the Figures 26 – 33.

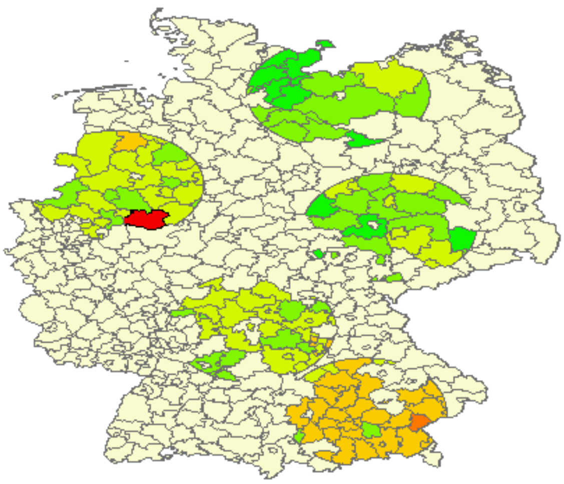


Figure 26 Spatial distribution of barley (Ya nat./Yw) of 2008. Yw as the average Yw of both models; red coloration is caused by multiple model outliers in predicting Yw

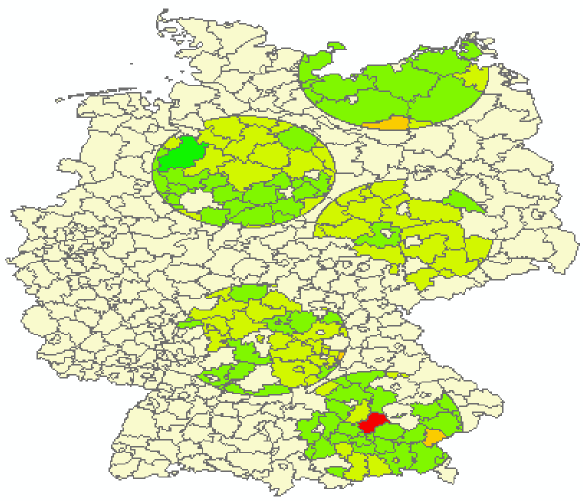


Figure 25 Spatial distribution of rape seed (Ya nat./Yw) of 2008. Yw as the average Yw of both models; red coloration is caused by multiple model outliers in predicting Yw

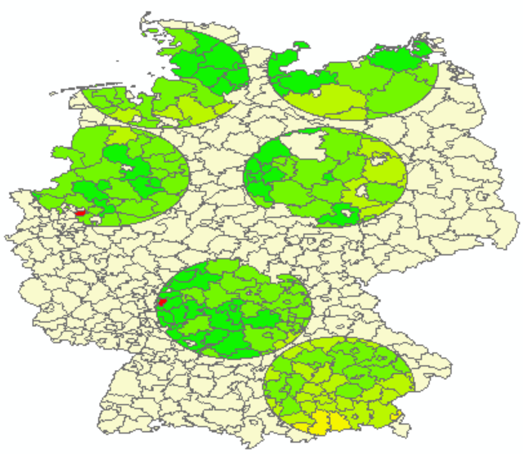
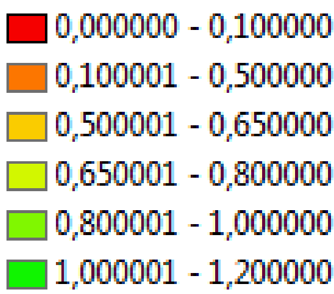


Figure 27 Spatial distribution of wheat (Ya nat./Yw) of 2008. Yw as the average Yw of both models; red coloration is caused by multiple model outliers in predicting Yw



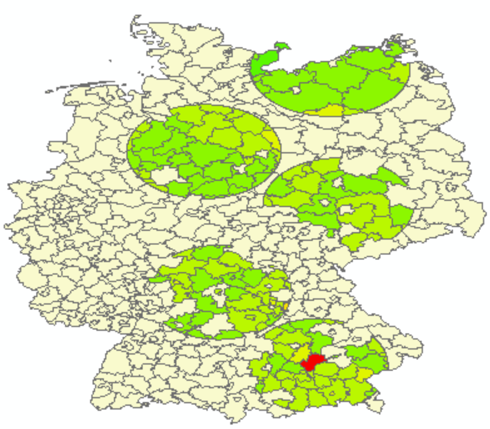


Figure 29 Distribution of avg Ya of rape seed (2006-2010)

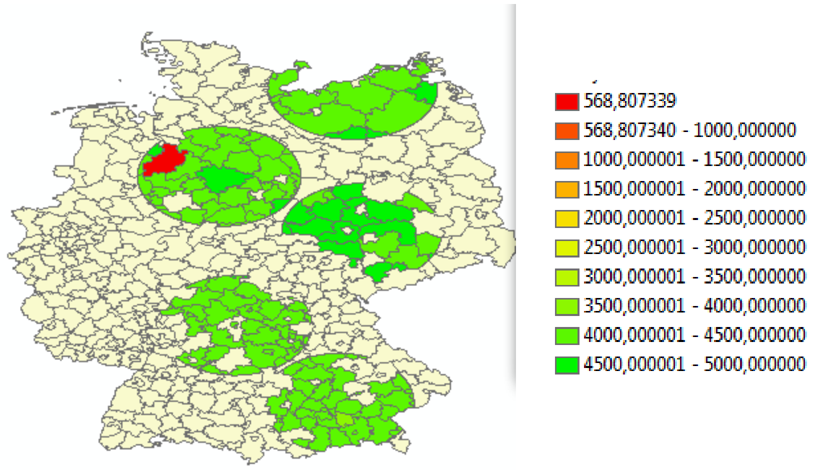


Figure 28 Distribution of avg Yw of rape seed over both crop growth models (2006-2010)

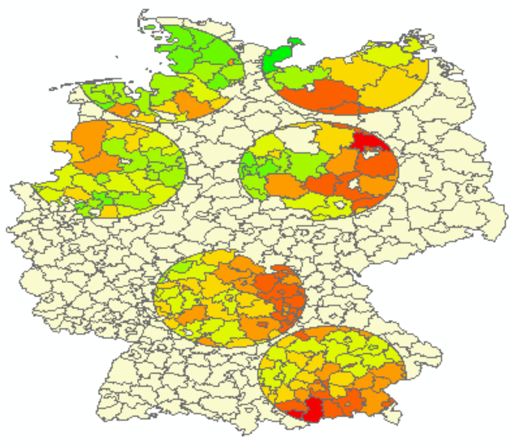


Figure 31 Distribution of avg Ya of wheat over both crop growth models (2006-2010)

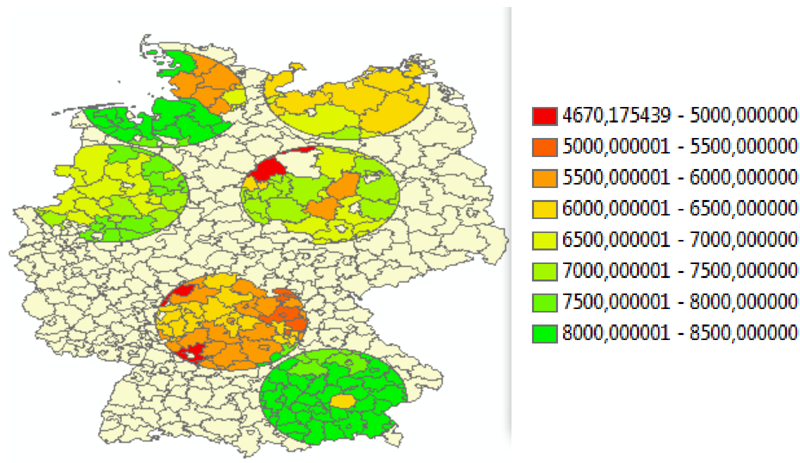


Figure 30 Distribution of avg Yw of wheat over both crop growth models (2006-2010)

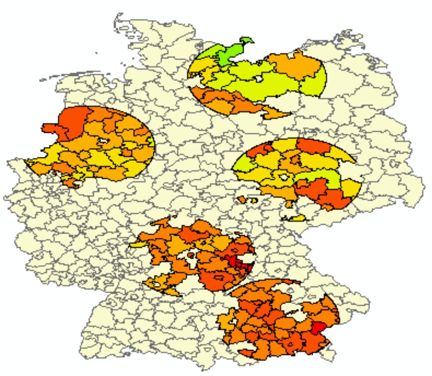


Figure 33 Distribution of avg Ya of barley over both crop growth models (2006-2010)

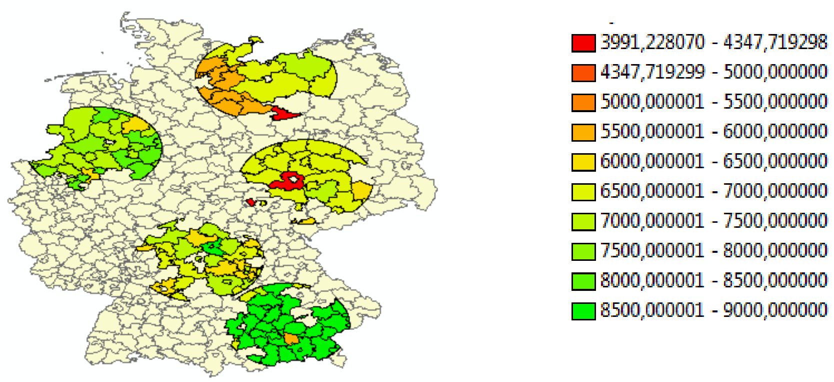


Figure 32 Distribution of avg Yw of barley over both crop growth models (2006-2010)

Figure 26 and Figure 27 show for barley and wheat, respectively. a smaller yield gap closure (around 60% for barley and 70% for wheat) for most districts in the most south buffer zone of Munich. Actual yields for both crops in the Munich region were smaller than actual yields of the crops in northern Germany on comparable soils whereas Yw did not differ as much as Ya between Munich and northern Germany.

This is most likely a result of the limited calibration of the crop growth models on all regions. An overview of all yield levels on national scale can be found in Table 10. For barley the yield gap closure rises based on the Monfreda et al. (2008) gridded data set of 2000 and the water limited yield from 70% up to 80% around the year 2008 (based on the national statistics). The yield gap closure rises from 74% up to 88 % for rape seed and from 89% up to 95% in wheat. It can be seen that Yg of wheat was already small around the year 2000 and could be almost closed completely leading to the conclusion that wheat production is performed at the crop specific maximum in the present framework conditions. Yg of rape seed was successfully closed by 14%, up to a Ygc of 88% leading to the conclusion that further significant yield increase is depending on improved varieties. Yg of barley closed by 10%, however the Ygc of 80% gives room for improving the crop performance by management up to the level of wheat and rape seed.

Table 10 Overview of yield levels Ya, Yw, Yp and yield gap closure (Ygc) based on Ya of national statistics and Monfreda et al. (2008)

			Ygc based on Ya of nat. stat. 2008		Ygc based on Ya Monfreda 2000	
crop	**yield level**	**kg DM/ha**	**Ya/Yw or Ya/Yp**	**avg Ygc**	**Ya/Yw or Ya/Yp**	**avg Ygc**
barley	Ya Monfreda	4927				
	Ya nat. stat	5684				
	Yw WOFOST	7434	76%	80%	66%	70%
	Yw HERMES	6754	84%		73%	
	Yp WOFOST	8189	69%	66%	60%	57%
	Yp HERMES	9092	63%		54%	
rape seed	Ya Monfreda	2963				
	Ya nat. stat	3517				
	Yw WOFOST	3613	97%	88%	82%	74%
	Yw HERMES	4438	79%		67%	
	Yp WOFOST	4150	85%	79%	71%	66%
	Yp HERMES	4818	73%		62%	
wheat	Ya Monfreda	6200				
	Ya nat. stat	6570				
	Yw WOFOST	7684	86%	95%	81%	89%
	Yw HERMES	6346	104%		98%	
	Yp WOFOST	8948	73%	79%	69%	75%
	Yp HERMES	7713	85%		80%	

4 Discussion

The testing and application of the method suggested by van Wart et al. (in press) led to yield gaps close to or higher than the exploitable yield gap of 80% (Lobell et al., 2009). During the process a few adjustments from the original method by van Wart et al. (in press) were tested. The results will be discussed for each step taken in the methodology and in the last paragraph the general outcome will be discussed.

4.1 Preparation work

In the preparation work, two issues were addressed. First the national irrigated crop growth area was derived to determine whether the yield gap assessment must be based on Yw or Yp. In the second step the selection of reference weather stations without prescreening for elevation was presented.

According to the Portmann et al. (2010) data set all three crops have less than 20 hectares irrigated harvested crop growth area on a national level. This is an unrealistically low area but can be explained by the description of the Portmann et al. (2010) data set. Portmann et al. (2010) assume that there is only irrigation for tuber and root crops. Other sources (Umwelt Bundesamt, 2011) however showed that 3.3 %, 560 000 ha, of the arable land is equipped with irrigation. It can be expected that wheat, barley and rape seed will be grown in a crop rotation. Therefore, none of the three crops would occupy the total area equipped with irrigation (560 000 ha) but only a fraction of the 560 000 ha. Assuming the three crops would be grown on this area, each crop would occupy approximately 185,000 ha. Comparing the 185,000 ha to the national crop growth areas in Table 6 one can see the crop growth area possibly grown under irrigated conditions is less than 20% for rape seed, less than 10% for barley and less than 7 % for wheat. The yield gap closure for the crop produced under irrigated conditions would need to be derived based on Yp instead of Yw. Using rape seed as an example (Table 10): the yield gap closure (Ygc) based on Yw is 74% and 66% based on Yp. In the example of 185,000 ha irrigated rape seed area 80% would be grown under rain fed conditions and 20% under irrigated conditions. The joined yield gap closure for the crop grown under rain fed and irrigated conditions can be derived as: Ygc = 74% Ygc_{Yw}[8]*80% + 66% Ygc_{Yp}[9] * 20% = 72.4 %. The result for the joined Ygc is 68.7 % for barley and 88% for wheat. Considering the potential irrigated crop growth areas, instead of assuming all crop

[8] Yield gap closure for rain fed crops based on Yw
[9] Yield gap closure for irrigated crops based on Yp

growth is not irrigated, does not significantly change the yield gap closure. One can conclude that performing the method of yield gap assessment based on van Wart et al. (in press) for barley, wheat and rape seed in Germany based on Yw is valid, even though the irrigated crop growth area of Portmann et al. (2010) is not correct.

In the second step of the preparation work the prescreening of the weather station for elevation differences was performed. The results (Figure 8) show that weather stations are selected as RWS with an elevation larger or smaller than the mean elevation of the area around it. The difference in altitude will most probably lead to a change in weather patterns (Kotlarski et al., 2012) (Minder et al., 2010) (Varney, 1920). The larger the altitude difference the larger the temperature differences (Kotlarski et al., 2012); the RWS is then not representing the weather patterns for the complete buffer zone around it. This will lead to different estimations of Yp and Yw at the point of the RWS and hence the Yp and Yw estimated for the buffer zone. Van Wart et al. (in press) proposed that Yp and Yw at the RWS should be representative for the whole buffer zone. The pre-screening for elevation in Germany in this report was performed after the weather data quality check. The pre-screening reduces the number of stations from 70 weather stations down to 42 weather stations that fulfilled data quality and elevation requirements. Elevation pre-screening significantly reduced the number of available weather stations but reduces the potential shortcoming of the effect of different weather patterns at the RWS and the buffer zone. One can conclude that the pre-screening for elevation is a necessary tool within the yield gap assessment in Germany.

4.2 Reference weather data and land use selection

The RWS buffer zone area for which Yp, Yw and Yg was estimated was selected based on the Portmann et al. (2010) land use data set and the national statistics. These give different values for the total harvested area per crop (Table 6). Comparing the Portmann et al. (2010) data set and the statistical data of 1999 for barley, the Portmann et al. (2010) data set shows a total growing area that is 0.50 million or 36 % hectares larger. The assumption that in the German climate region all cereal crops are sown in the previous fall of the harvesting year is made in the Portmann et al. (2010) data set. The statistics for 1999 is using the value for winter barley only. However the sum of spring and winter barley in the statistics of 1999 is leading to a 0.3 million hectare higher crop growth area than the result of Portmann et al.

(2010) (results not shown). The total crop growing area of the Portmann et al. (2010) land use data are 15 % lower for rape seed and 5 % lower for wheat than in the statistics of 1999.

One can conclude that the crop growing areas for wheat and rape seed around the year 2000 for the statistics and the Portmann et al. (2010) data set are similar (Table 6). In barley Portmann et al. (2010) use the average between winter crop growth area and the sum of spring and winter crop growth area. The crop growth area for all three crops is larger in the statistics of 2010 than in the statistics in 1999. The total national available arable land however did not change significantly between 1999 and 2010. Apparently, the three crops are grown more frequently on the existing arable land. The distribution of crop growth area was tested by selecting RWS based on the data set.

The selection of RWS according to the method of van Wart et al. (in press) based on the Portmann et al. (2010) land use data set for all three crops and the statistics of 2010 for barley could fulfill the methodology requirements of at least 50% coverage of national production. For all crops the statistics of 1999 and for wheat and rape seed the statistics of 2010 this requirement could not be fulfilled, although the coverage of national production reached values between 40% and 48%. The spatial references of the statistics were the borders of the districts. Since no data for the distribution of arable land was available, the assumption was made that the crop growth area is evenly distributed over the district. During the "Kreisreform" districts were merged to larger units. The spatial distribution of the crop growth area got less accurate. For example (Figure 34): three districts were merged into one district. One of the three districts before the "Kreisreform" contained 100 ha of growing area, the two other did not contain any growing area. After merging, one larger district is left that contains 100 ha of growing area. If the RWS buffer zone would intersect only with the top left district in Figure 34, the growing area would be accounted for with 100 ha before the "Kreisreform". After the "Kreisreform" the crop growth area in the original district (containing 100 ha before the "Kreisreform") only contains 33 ha. The Portmann et al. (2010) data set was created based

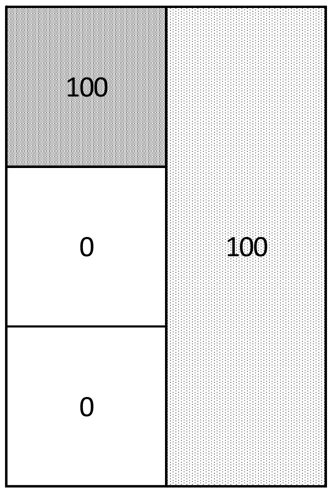


Figure 34 Example of the "Kreisreform", the numbers represent crop growth areas in ha, left before the "Kreisreform", right after the "Kreisreform", one cell equals one district

on the district information before the “Kreisreform”. This effect of less spatial accuracy in the national statistics due to the “Kreisreform” might have led to not fulfilling the 50% coverage requirement of van Wart et al. (in press).

Even though the Portmann et al. (2010) land use data set showed significant differences in total crop growth area compared to the national statistics, it was used for the selection of RWS and throughout the method to be consistent. However the Portmann et al. (2010) data set should be validated with national statistics for the total growing area of irrigated and rain-fed production. The effect of the share of irrigated growing area on yield gap assessment was not significant for Germany but it most likely will be in dryer climate conditions.

In the second step of Section 3.2 the results of the sensitivity analysis of the radius of the buffer zones were shown. According to Figure 9 it is possible to cover 50% of the national crop growth areas in the buffer zones with a smaller radius of the RWS buffer zones than 100 km. The analysis was performed for 240 weather stations that were screened for elevation differences as described in Section 2.1.1. The statistical prescreening for data quality was not performed since this criterion depends on the study time frame. For this study from 2006 to 2010, 42 weather stations passed the prescreening of data quality and elevation criterion. The results of Figure 9 are the absolute minimum radii for the buffer zones since the number of weather stations is likely to decrease after the data quality check. The minimum zone radii for the time frame of 2006 till 2010 were around 70 km (results not shown). A smaller circle radius is preferable to increase the accuracy of yield prediction. The effect of different radii on yield gap assessment was not part of this study. However, the question could be raised whether the minimum possible RWS buffer zone radius fulfilling the 50% coverage requirement instead of a constant 100 km buffer zone radius should be used. In order to be consistent with other studies the radius of 100 km was selected.

4.3 Soil type selection

The assessment of the water-limited yield within the study area is not only depending on the weather data but also the soil type. Van Wart et al. (in press) suggested to use one soil type per RWS buffer zone. This does not result in 50% coverage of the growing area as shown in Table 7. Almost all soil types per buffer zone were selected to cover the complete crop growth area by Portmann et al. (2010) per buffer zone. This means that the crop in question is not only grown on the major soil type but on all soils. However the assessment of water-limited yields per RWS buffer zone based on one major soil type compared to multiple soil types per buffer zone differs significantly only in a few cases for all three crops (Figure 21,Figure 43,Figure 44). The maximum yield level difference of Yw on national scale between the methods of selecting one soil type per RWS buffer zone to multiple soil types per RWS buffer zone are 500 kg DM/ha in wheat for Yw estimated with WOFOST (Figure 24).

One can conclude that strictly speaking the proposed requirements of van Wart et al. (in press) to cover at least 50% of the national production within the buffer zone is not fulfilled by selecting only the major soil type. However the effect of selecting one or multiple soil types per RWS buffer zone on the assessment of Yw on national scale in Germany is rather small.

4.4 Assessment of yield levels and yield gap

The assessment of potential and water limited yield with crop growth models with limited calibration leads to quite a large deviation between model results and reality (Palosuo et al., 2011). This could also be observed in this study while comparing the modeling results to trials. The usage of pre-calibrated files without adjustments in WOFOST showed for winter rape seed a strong underestimation for Yw and Yp. The crop files for all crops in WOFOST were composed and calibrated in the year 1995. During the last 15 years, breeders observed a yield increase for rape seed of 1.3% per year. This increase was mainly based on an increased number of kernels per pod and increased number of pods per plant. Breeding experts could not observe a significant correlation between the higher yield and only total biomass or only harvest index (Örtel, 2012) but rather a combination of the two factors.

In WOFOST TSUM1 and TSUM2 were adjusted to fit Yw to the trial results. The modeled flowering and harvest dates were checked with the results of Boons-Prins et al. (1993) and Wolf et al, (2008a,b,c). Trial data of current varieties under potential crop growth conditions was not available. Therefore the usage of pre-calibrated crop files for Germany with minor adjustments in TSUM was performed. The change of TSUMs was a compromise to bring the Yw of the model closer to the trial results. The range of deviation between trial yields and results of crop growth models was similar with other studies (Palosuo et al., 2011).

HERMES needed to be adjusted for winter barley and winter rape seed. Since no trial data for crop growth under potential conditions was available a limited number of factors were changed (Section 3.4.1); for rape seed the factor accounting for the grain fraction in the storage organ was changed and for barley the maximal canopy assimilation rate and the water stress sensitivity in the post emergence stage of the crop was changed.

The performance of both HERMES and WOFOST in predicting Yw was poor with dry spring conditions (year 2010, Figure 35). In reality the dry spring could most likely be compensated by the plants with reallocating more resources to root growth and the exploration of more available soil water. It could be observed in the models that for the years with dry springs the growth was hampered during the establishment of the leaf area. The leaf area was not sufficient at grain filling which resulted in a low yield.

The assessment of the different yield levels was made for the years 2006 to 2010. This short timeframe of 5 years will lead to a CV between 0.15 and 0.20 for Yw of WOFOST and HERMES over all crops and RWS stations. Van Wart et al. (in press) showed for maize a minimum of 8 years in a climate with 650 mm rainfall per year to achieve a CV <= 0.05. They showed that for higher yearly precipitation fewer years are needed to reach a CV <= 0.05. For Germany rainfall is more than 600 mm per year for the selected stations. The dry spring periods lead to strong variations in Yw. The assumption of no ground water influence in both models on all soil types might be wrong. The actual water availability might have been higher on clay soils in some regions through capillary rise. This will result in a higher yield level Yw, especially in the year 2010 with wheat and barley (Figure 35).

The definition of potential and water-limited yields of WOFOST and HERMES is slightly different. WOFOST starts a model run at the first day of the year with optimal initial conditions for the crop dry matter and the soil water content whereas HERMES continuously models the water balance for all years and uses emergence dates for the crops. HERMES uses one year of weather data without crop growth to initiate soil water balance. Since all years showed sufficient rainfall over winter the soil water content in HERMES was, like WOFOST, at field capacity before the growing season in the spring. However the timing of seeding and the establishment of the crop in the fall season in HERMES led to different initial growing conditions in the spring compared to WOFOST. A dry fall period could create a model crop with small initial weight and leaf area within HERMES. The emergence dates for

HERMES were used from actual data from the DWD, provided by Dr. Kurt-Christian Kersebaum (ZALF). The Yw and Yp of HERMES may therefore not be the potential yield since earlier or later sowing might have led to a higher yield in theory.

One can conclude that the model results should be interpreted carefully due to the limited number of model years and the limited calibration of WOFOST and HERMES. However using two models might give a better result than just using one model (Palosuo et al., 2011). The results showed that the prediction of Yw per RWS buffer zone deviates slightly less by using many soil types instead of only the major soil type (Figure 21,Figure 43,Figure 44). This cannot compensate for the shortcoming of using fewer years in the assessment of Yw. However the results for the national level of this study show the same levels of yield gap closures as other studies on larger scale (Licker et al., 2010).

4.5 Actual yields

The comparison of the Monfreda et al. (2008) yield data to the actual farm yield out of the statistics showed a strong yield increase of rape seed of around 2% per year over the 8 year time period between 2000 and 2008. This is higher than the breeding success of the breeders (Örtel, 2012). The explanation as suggested by Örtel (2012) is that the nitrogen use efficiency of the crop increased. Around 210 kg nitrogen per hectare was necessary in the year 2000 to achieve optimal yields with old varieties. With current varieties only 170 kg nitrogen per hectare is needed to produce high yield levels. This makes the crop more efficient in economic terms and farmers can produce closer to the optimal yields under the same input costs and product price conditions. This fact in addition to the high prices of agricultural products over the last years (von Ledebur & Schmitz, 2011) led probably to the higher yields in canola.

The average national yields as published in the statistics are similar to the actual farm yield aggregated out of the RWS buffer zones for all crops (Figure 22). The latter are the yield on 50% of the crop growth area. This leads to the conclusion that the average farm yield on 100% of the crop growth area (average national yields) is the same as in the study area (RWS buffer zones). The study is therefore covering a representative share of the crop production area.

4.6 Aggregation

As mentioned before the aggregation of Yw for different soil types within the buffer zones shows a different result than Yw derived out of the major soil type per buffer zone (Figure

21). The difference is caused by model errors and the usage of different soil types. Model errors occur on soils with low water holding capacity and crop growth conditions with a large water deficit (year 2010). The errors in Yw prediction for single years and soil types can compensate by multiple model runs per RWS over many soil types in the buffer zone. However the yield results Yw still have a CV between 0.15 and 0.20. The aggregated yield levels Yw should therefore be carefully interpreted as yield estimations or yield levels rather than an absolute numbers.

The national yield levels of Yw for each crop derived by the method of van Wart et al. (in press) and the method of selecting multiple soil types per buffer zone showed not a large difference. Van Wart et al. (in press) showed for Yp in rice in China that the variation in estimated national Yp across all RWS is becoming smaller with increased number of selected stations; meaning that the estimation of national Yp does not significantly improve once a certain amount of RWS is selected and averaged. The correlation between variation in estimated national Yp and number of selected RWS however was not linear but almost logarithmic. This relation might also be the case for the Yw yield levels in this report. The higher spatial details at the beginning of aggregation step one (in buffer aggregation) does not lead to a large difference in the results on national level after the second aggregation step.

4.7 Yield gaps

The yield gap closure derived out of Yw (2006 – 2010) and Ya (Monfreda et al., 2008) compared to the yield gap closure derived out of Yw (2006 – 2010) and Ya (2006 – 2010) increases by 10%, 14% and 6% for barley, rape seed and wheat, respectively. This was caused by the increase in Ya since Yw around the year 2000 was not estimated. Örtel (2012) showed for rape seed an increase in water-limited yield Yw of 1.3% per year. This would mean that Yw of rape seed in 2000 must have been roughly 10% lower than Yw in this study (2008). As shown above an increase in yield gap closure of 14 % for rape seed was reached, leading to the conclusion that the closure of the yield gap for rape seed was larger than the breeding success.

The absolute yield gap for wheat is smaller than for rape seed and barley. A significant yield increase can be achieved by increasing the yield potential by breeding.

5 Conclusion and Recommendations

The yield gap closures of wheat, rape seed and barley in Germany around the year 2008 were 95%, 88% and 80%, respectively. The yield gap closures of this study are similar to yield gap closure results of other studies (Fischer et al., 2002). Economically exploitable yield gap closures for farmers are usually around 80% (Ya/Yw) (Fischer et al., 2009). The yield gap for all three crops became smaller in 2008 compared to the year 2000. The levels of yield gap closures of all crops in this study in Germany are within the economically exploitable yield gaps. A further yield gap closure is possible by changes in the economic framework conditions. As shown in the yield gaps based on Yp in Table 10, the yield can still be increased by irrigation. Without irrigation however a yield increase is possible by breeding success on resources use efficiency and therefore an increased crop yield potential.

The method of van Wart et al. (in press) was suitable to assess yield gaps on the national scale for Germany. However the selection of RWS stations and buffer zone radius requires a careful pre-selection of weather stations to assure the weather patterns at the RWS to be representable for the whole buffer zone. Different methods of acquiring the representative study area, like e.g. the usage of climate zones created by Fischer et al. (2002) should be tested.

The global data set by Portmann et al. (2010) on crop areas used for the method of van Wart et al. (in press) gave wrong values for the irrigated crop growth area for all three crops. This did not have a significant effect on the assessment of the yield gap closure in Germany. However the effect in other regions might be significant.

Selection of one major soil type per RWS buffer zone did not lead to a fulfillment of the 50% coverage requirement; however the effect of selecting the dominant rather than several soil types on nationally assessed Yw was not significant. The calibration of crop growth models and the modeling over a longer time frame is of higher importance than the detailed soil selection for German conditions.

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7 Appendices

7.1 Appendix I

Table 11 is containing an overview of all web links that were used to acquire the data for this research. In the document the links will be referred to with the Appendix number and the reference number behind the Appendix name.

Table 11 Overview of weblinks for the data download

Reference number	Name
1	http://gis.ncdc.noaa.gov/map/cdo/
2	http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov
3	http://dds.cr.usgs.gov/srtm/
4	http://www.isric.org/data/data-download
5	http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/data_download/index.html
6	https://www.regionalstatistik.de/genesis/online;jsessionid=89B015F6E89453D543EBECD417013A32
7	http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=5&gdz_user_id=0
8	http://www.geog.mcgill.ca/landuse/pub/Data/175crops2000/

7.2 Appendix II

All raw data that has been used in this report are provided in the data folder on the attached CD. The overview is provided in Table 12. In the document the data will be referred to with the Appendix number and the reference number behind the Appendix name.

Table 12 Overview of the data provided on the attached CD

Reference number	Name
1	1_download weather stations.xls
2	2_check for missing NOAA and NASA data.R
3	3_anbaufrüchte_bundesebene_aus_regionaldatenbank_import.xls
4	4_116-42-4.xls[10]
5	5_115-02-4.xls[11]
6	6_yields_folder
7	7_Regiostatistic explanation 1999 code 41120.pdf
8	8_Regiostatistic explanation 2010 code 41141.pdf
9	9_verwaltungsgrenzeng2500_geo84.zip
10	10_ANNUAL_AREA_HARVESTED_IRC_CROP1_HA.ASC.gz
11	11_ANNUAL_AREA_HARVESTED_RFC_CROP1_HA.ASC.gz
12	12_ANNUAL_AREA_HARVESTED_IRC_CROP4_HA.ASC.gz
13	13_ANNUAL_AREA_HARVESTED_RFC_CROP4_HA.ASC.gz
14	14_ANNUAL_AREA_HARVESTED_IRC_CROP15_HA.ASC.gz
15	15_ANNUAL_AREA_HARVESTED_RFC_CROP15_HA.ASC.gz
16	16_barley_yield.zip
17	17_rapeseed_yield.zip
18	18_wheat_yield.zip
19	19_wheather stations for Yw
20	20_DEM_MIL-PDF-89020B.pdf
21	21_DEM_DATA
22	22_soil_data_lenny.zip
23	23_Yields_no_dry_matter_in_national_stat.pdf
24	24_Emergency date Kersebaum.zip
25	25_BAR302.CAB
26	26_RAP1005.CAB
27	27_WWH103-GAP_adjustedTSUM.CAB
28	28_LSV_winter_rape_seed.zip
29	29_LSV_winterbarley.zip
30	30_LSV_winterwheat.zip

[10] table 116-42-4 in the online portal of the national statistics office (Appendix I, 6); sampling method in (Appendix II, 7)

[11] table 115-02-4 in the online portal of the national statistics office (Appendix I, 6); sampling method in (Appendix II, 8)

7.3 Appendix III

The ArcMap© software allows to create process models for all calculations of data. These models include automated calculation steps. The process steps in the methodology were transferred into process models. They can be found on the CD attached to this thesis.

Reference number	**Name**
1	1_import_weather_stations
2	2_make_layer
3	3_import_DEM
4	4_clip_DEM
5	5_part1_calculating_elevation
6	6_part2_calculating_elevation
7	7_selection_of_DEM_cleared_stations
8	8_make_layer_of_stations
9	9_sum_harvested_area_MICRA
10	10_merge_sum
11	11_part1_sorting_and_deleting
12	12_part2_sorting_and_deleting
13	13_half_of_country_area_selected
14	14_choose_major_soil_type
15	15_clip_harvest_area
16	16_clip_soil_to_Germany
17	17_import_Monfreda
18	18_link_landuse_kreise
19	19_import_table_landuse
20	20_link_landuse_kreise_2010
21	21_calculate_area_kreise_barley
22	22_merge_tables_barley
23	23_calculate_area_kreise_wheat
24	24_merge_tables_wheat
25	25_calculate_area_kreise_rape_seed
26	26_merge_tables_rape_seed
27	27_import_added_table
28	28_prep_deleting_stations
29	29_deleting_stations
30	30_MICRA_RWS_soil_Monfreda
31	31_prepare_Kersebaum_list
32	32_Kersebaum_list.py
33	33_calculate_total_for_Germany
34	34_import_yield
35	35_link_yield_to_shape

7.4 Appendix IV

Table 13 is containing an overview of all processed data including the presented graphs. In the document the links will be referred to with the Appendix number and the reference number behind the Appendix name.

Table 13 Overview of the processed data

Reference number	Name
1	1_MICRA_RF_ALL_OLD_plus_growing areas
2	2_RWS_100km_lenny_data_weather_stations_soil_MICRA
3	3_Kreise_RWS
4	4_detailed_result_MICRA_SOIL_MONFREDA
5	5_DEM_heights_rf_wheat_kreise
6	6_MICRA_area_per_soil
7	7_rainfall_pattern_example_OSN

7.5 Appendix V

All additional information for Section 3.2 Reference weather station and land use selection is provided in this Appendix. Each table is explained by the title.

Table 14 Selected RWS for barley based on Portmann et al. (2010) land use data

		50%
Station name	**MICRA area in 10^3 ha**	**% of national area**
LEIPZIG/SCHKEUDITZ	216	12%
MUNSTER/OSNABRUCK	213	11%
WURZBURG	212	11%
MUNICH	156	8%
SCHWERIN	148	8%

Table 15 Selected RWS for rape seed based on Portmann et al. (2010) land use data

		54%
Station name	**MICRA area in 10^3 ha**	**% of national area**
LEIPZIG/SCHKEUDITZ	163	16%
WARNEMUENDE	148	15%
WURZBURG	85	9%
HANNOVER	71	7%
MUNICH	64	6%

Table 16 Selected RWS for wheat based on Portmann et al. (2010) land use data

		53%
Station name	**MICRA area in 10^3 ha**	**% of national area**
MAGDEBURG	374	15%
WARNEMUENDE	247	10%
MUNICH	225	9%
WURZBURG	215	9%
MUNSTER/OSNABRUCK	163	7%
CUXHAVEN	100	4%

Table 17 Selected RWS for barley based on the land use data of the national statistics

		51%
Station Name	**Area_2010 in 10^3 ha**	**% of coverage**
BAD	193	11.7%
WURZBURG	186	11.3%
MUNICH	137	8.4%
LEIPZIG/SCHKEUDITZ	130	7.9%
HAMBURG/FUHLSBUTTEL	89	5.4%
TRIER/PETRISBERG	62	3.8%
ANGERMUENDE	48	3%

Table 18 Total barley crop growth area covered by the selected RWS of Portmann et al. (2010) and the national statistics

Overlap Method	
MICRA area in 10^3 ha	**% of national area**
774	41%

7.6 Appendix VI

All additional information for Section 3.4.2 Model performance in the calibration process is provided in this Appendix. Each figure is explained by the title. First the results for barley are presented, followed by rape seed and wheat.

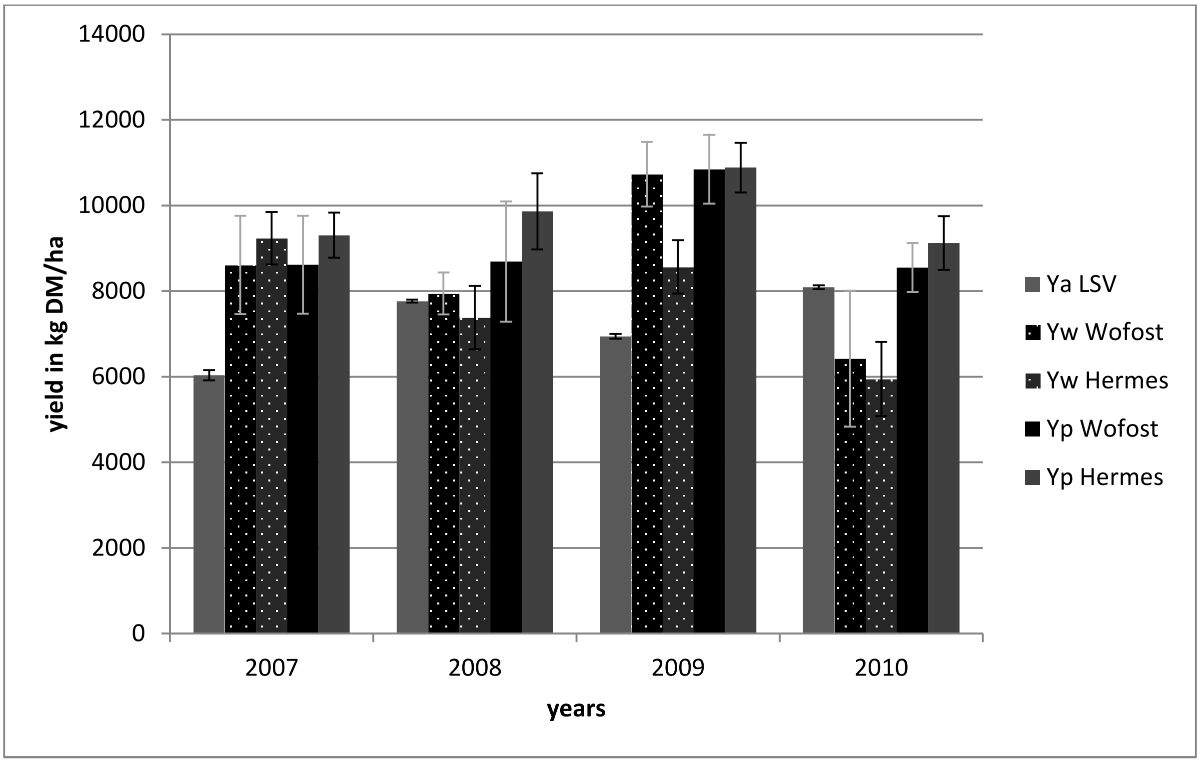

Figure 35 Model yield comparisons on sandy soils for barley

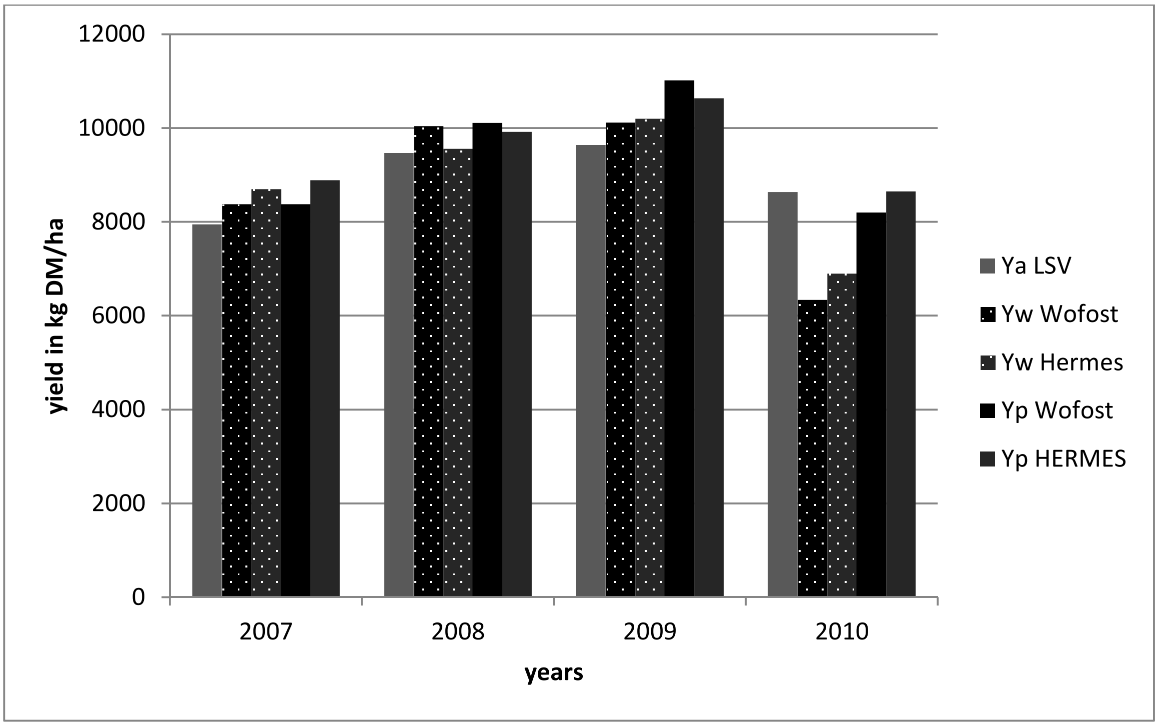

Figure 36 Model yield comparisons on clay soil for barley

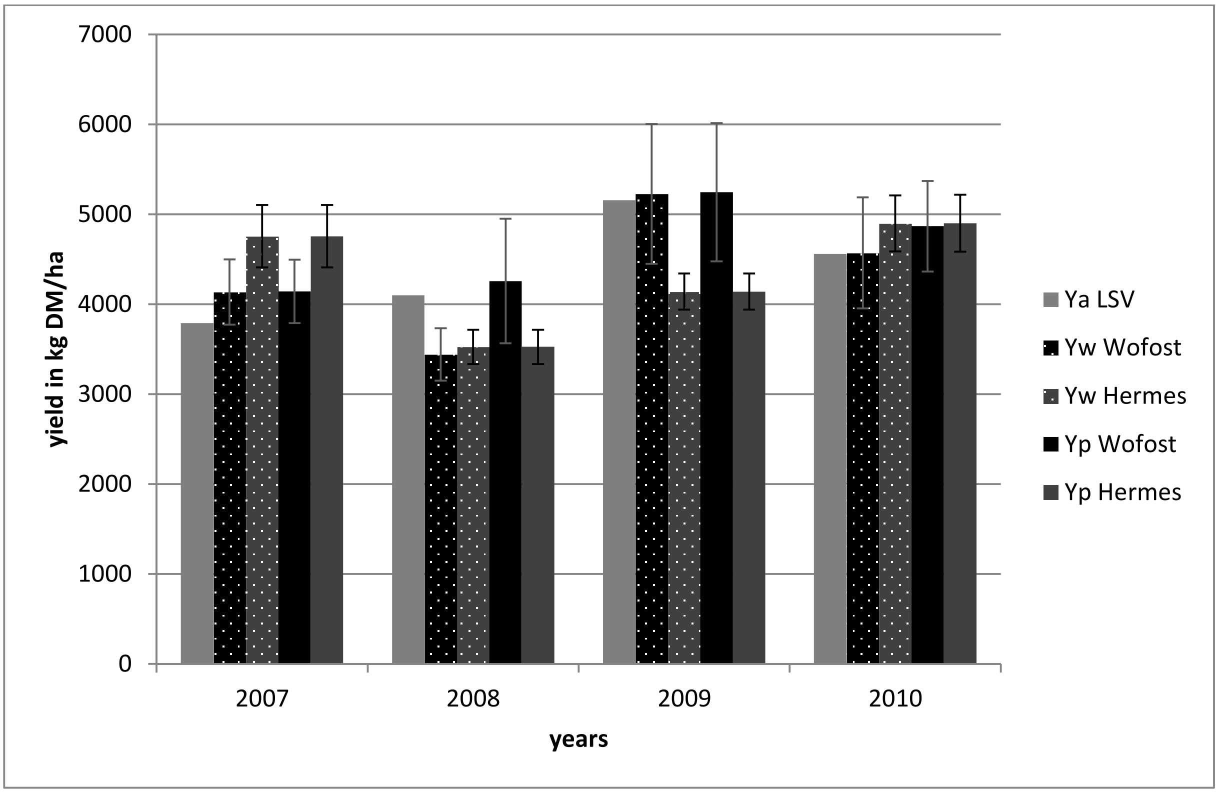

Figure 37 Model yield comparisons on sandy soils for rape seed

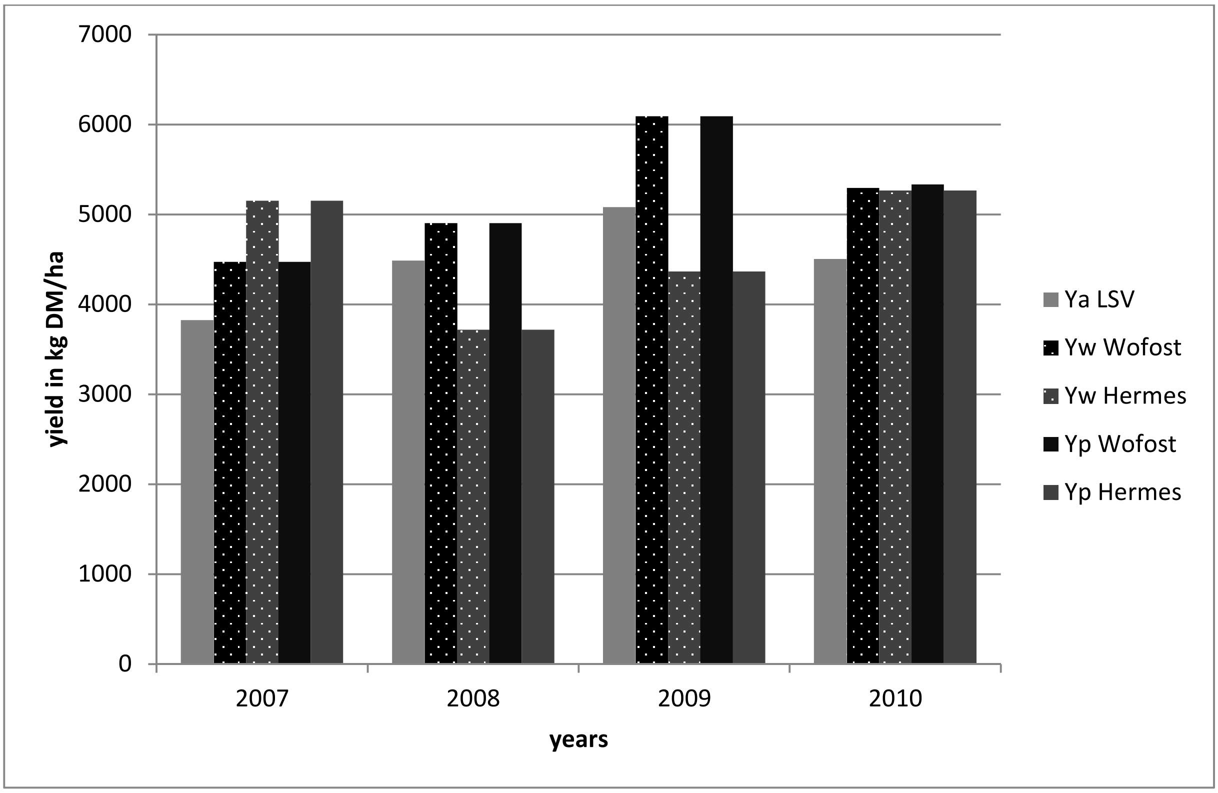

Figure 38 Model yield comparisons on clay soil for rape seed

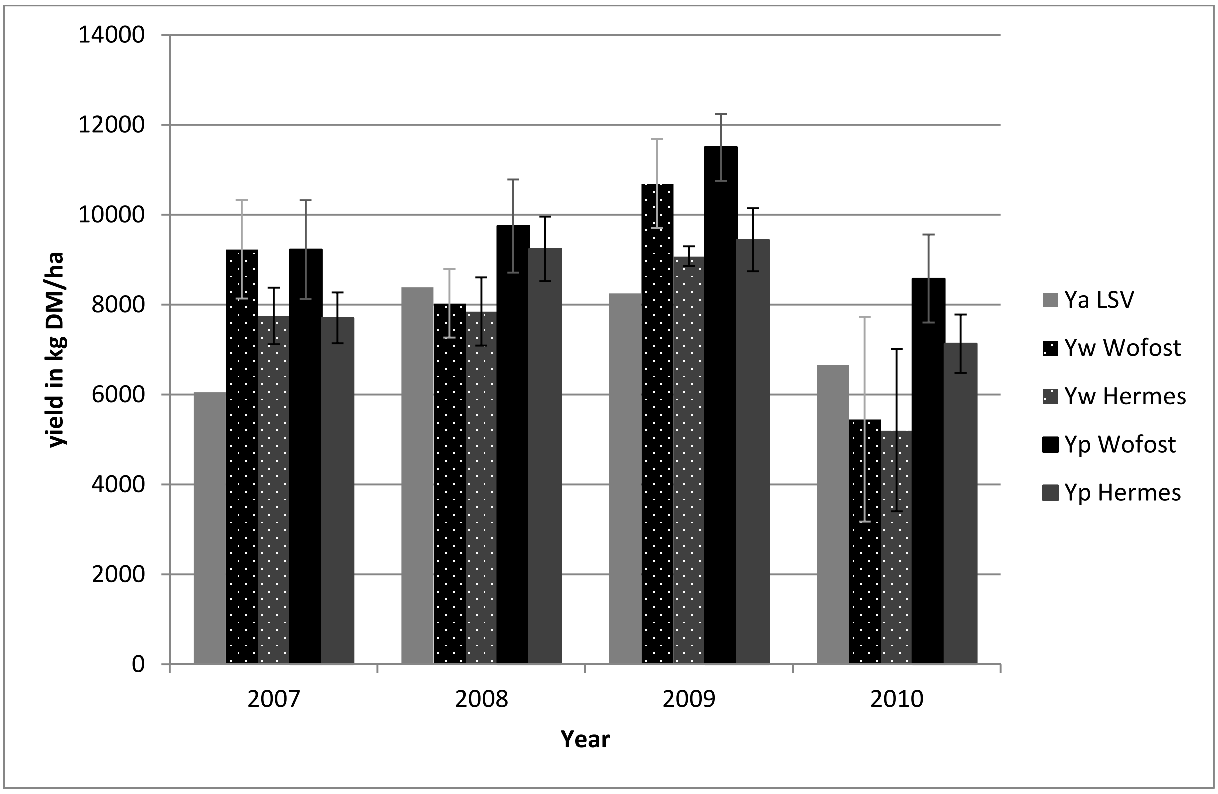

Figure 39 Model yield comparisons on sandy soils for wheat

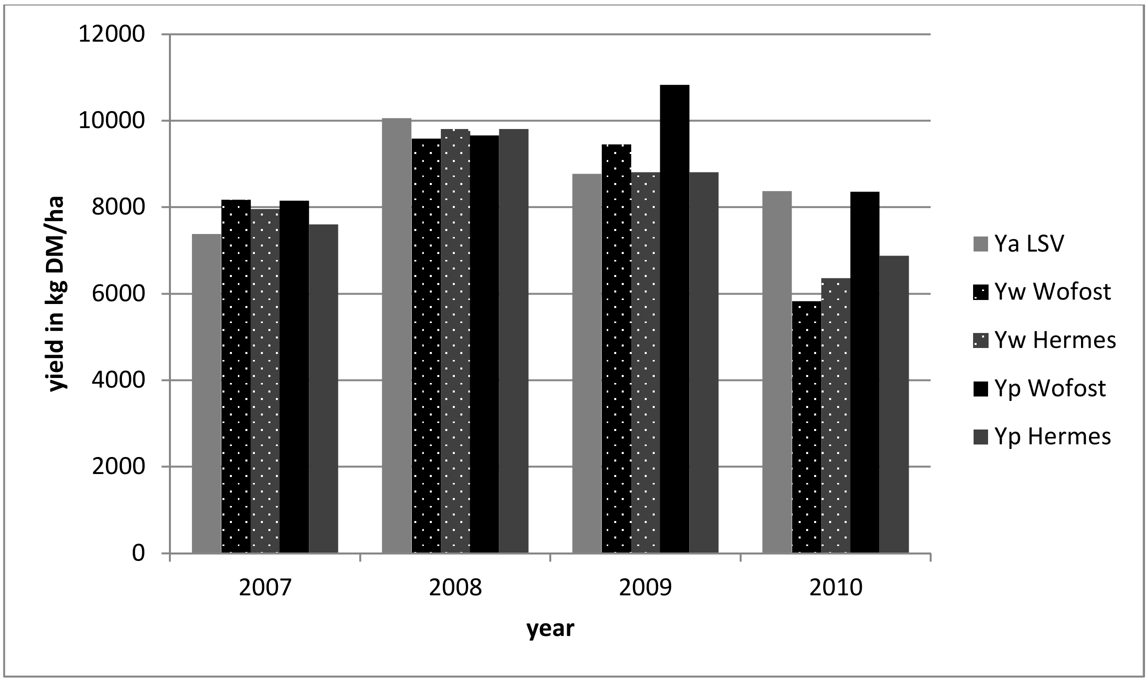

Figure 40 Model yield comparisons on clay soil for wheat

7.7 Appendix VII

The additional figures of the clearance of false predictions in Section 3.6 are provided in this Appendix. Each figure is explained by the title.

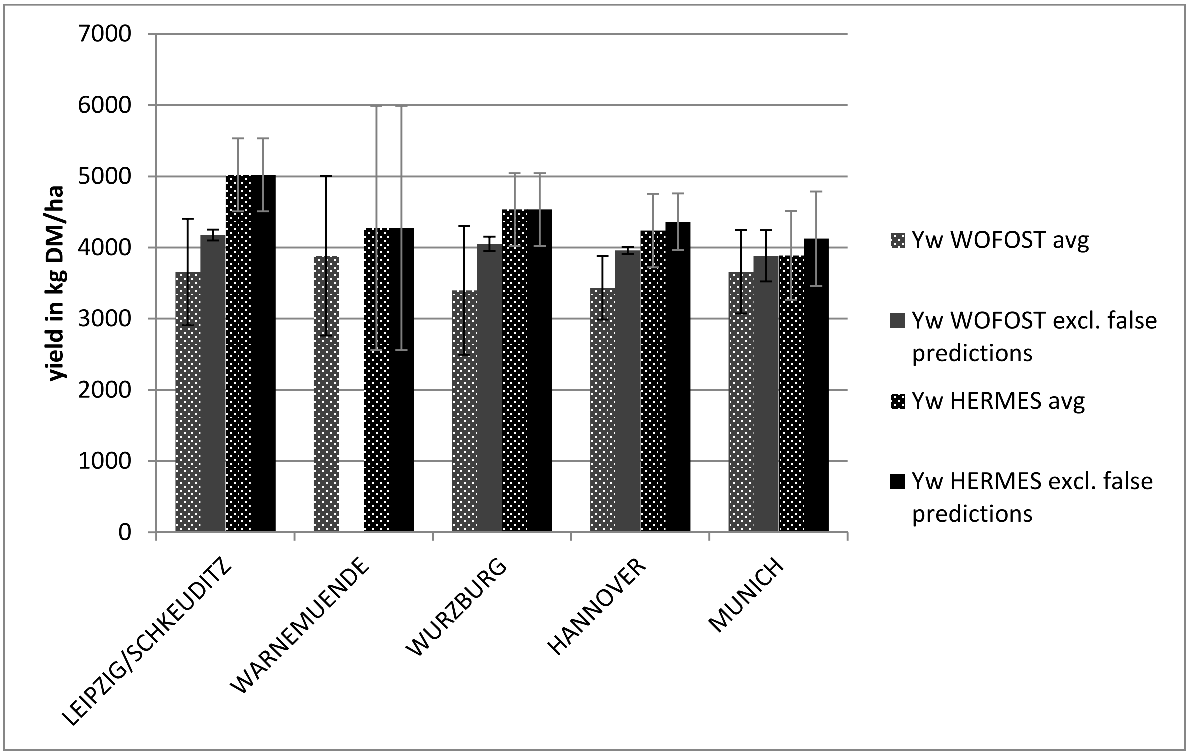

Figure 41 Yw of rape seed including and excluding false yield predictions

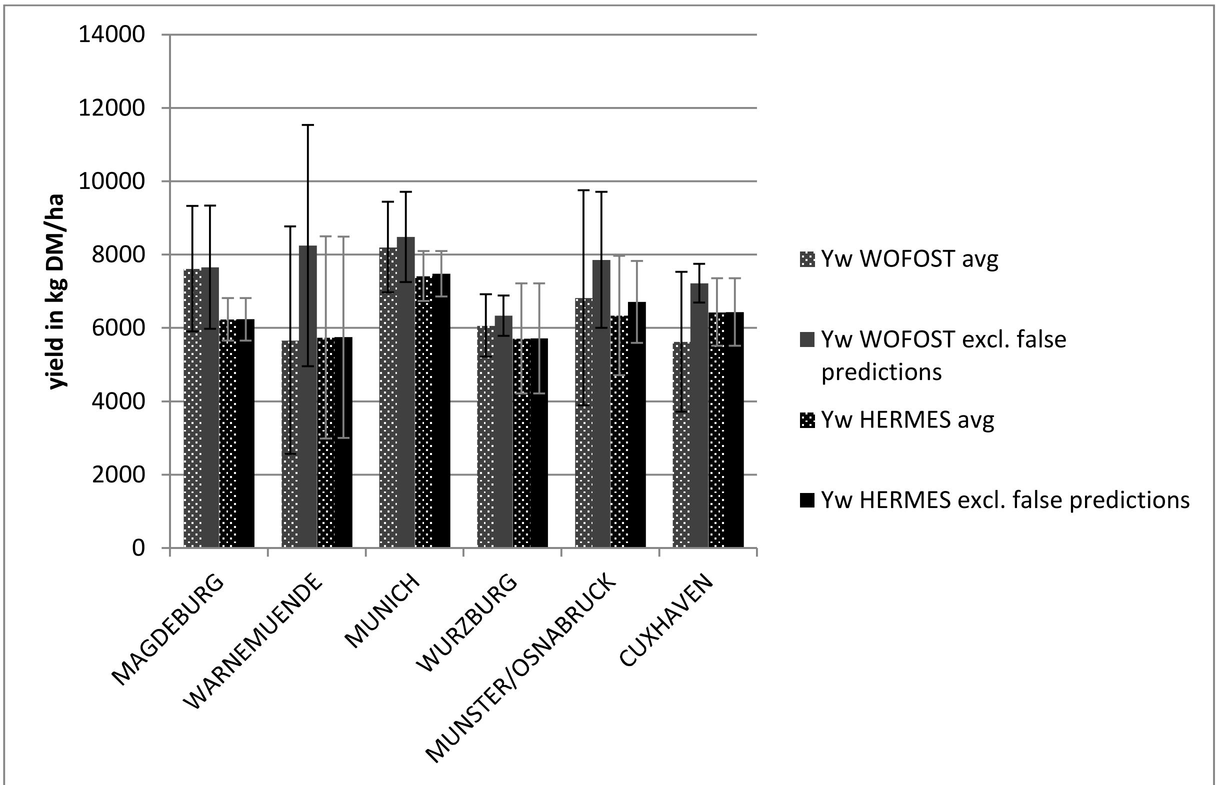

Figure 42 Yw of wheat including and excluding false yield predictions

7.8 Appendix VIII

The additional figures of the different aggregation methods per buffer zone in Section 3.6 are provided in this Appendix. Each figure is explained by the title.

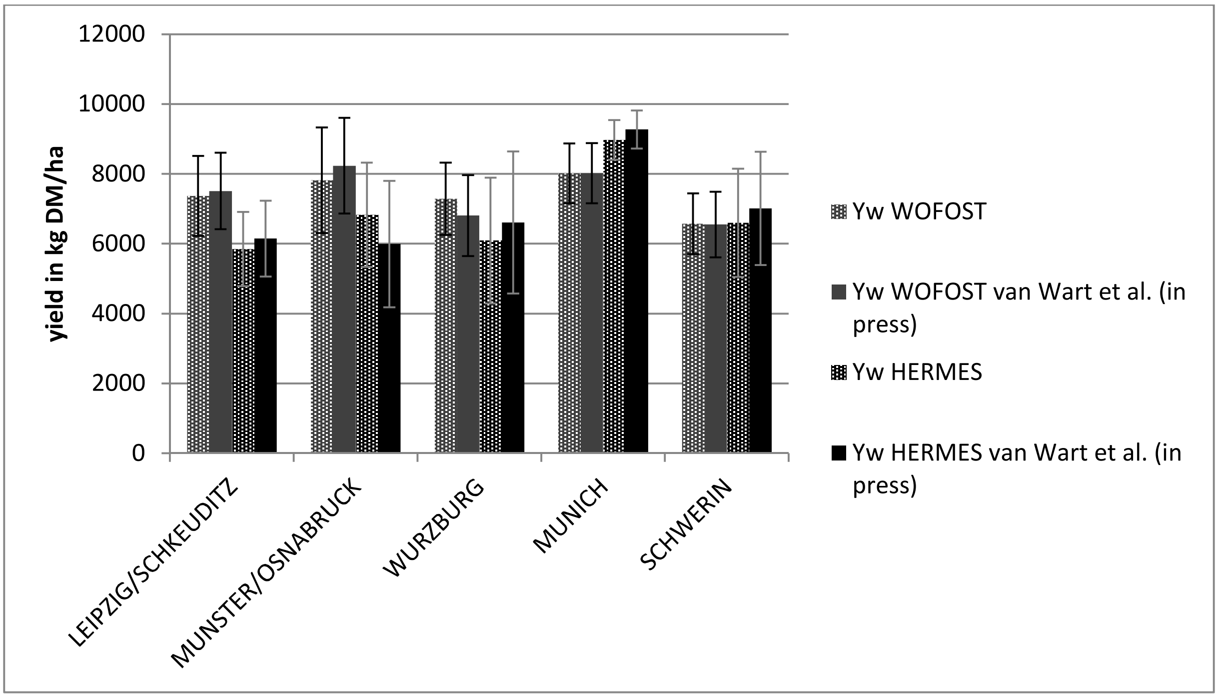

Figure 43 Comparison of in buffer aggregation against the method of van Wart et al. (in press) on Yw in barley

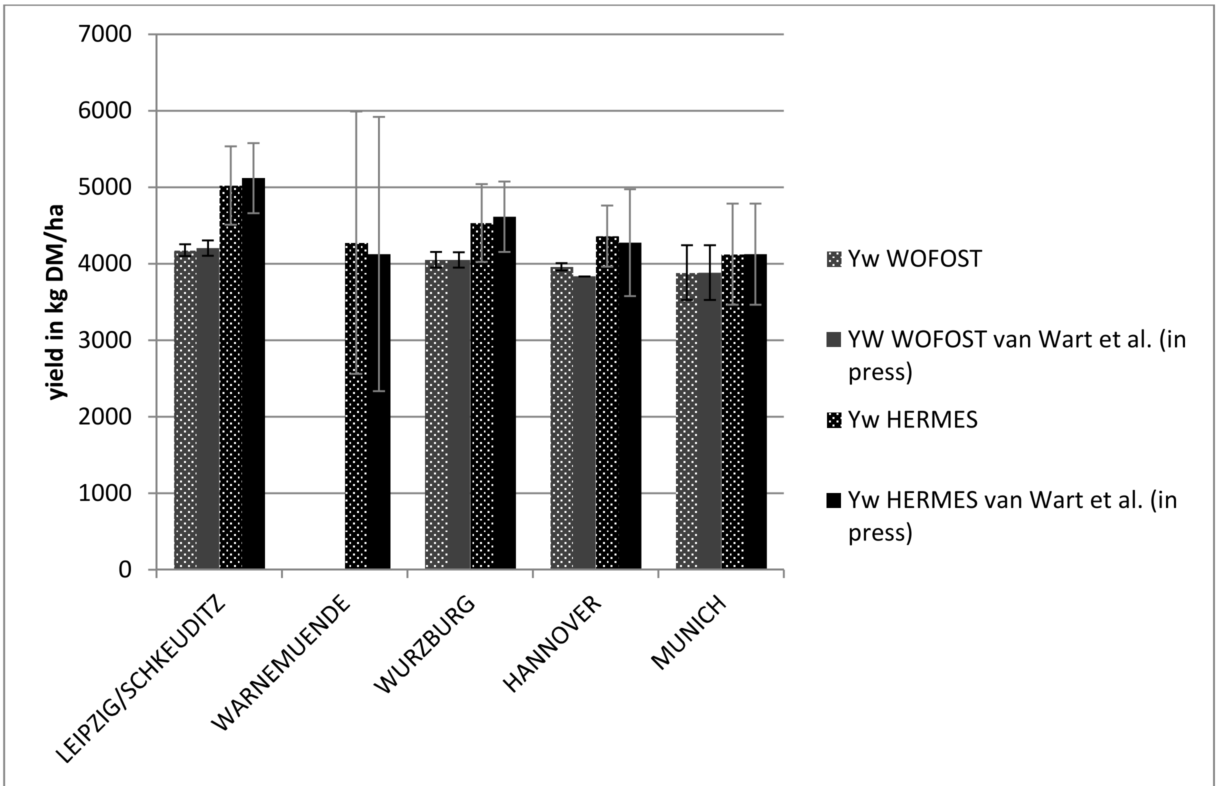

Figure 44 Comparison of in buffer aggregation against the method of van Wart et al. (in press) on Yw in rape seed