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МАТЕМАТИЧЕСКИЕ МОДЕЛИ ПРИРОДНЫХ И АНТРОПОГЕННЫХ ЭКОСИСТЕМ

сборник статей, посвященный памяти

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Книга содержит статьи, посвященные актуальным проблемам использования количественных приемов исследования и моделирования энергомассообмена и продуктивности естественных и сельскохозяйственных экосистем. Она посвящена памяти выдающегося ученого, заслуженного деятеля науки Российской Федерации, профессора Ратмира Александровича Полуэктова, основавшего и в течение почти половины столетия возглавлявшего один из самых известных научных коллективов данного направления в нашей стране - лабораторию математического моделирования агроэкосистем Агрофизического научно-исследовательского института.

Статьи сборника рассчитаны на научных работников академических и отраслевых институтов биологического, сельскохозяйственного и гидрометеорологического профилей, преподавателей и студентов экологических специальностей.

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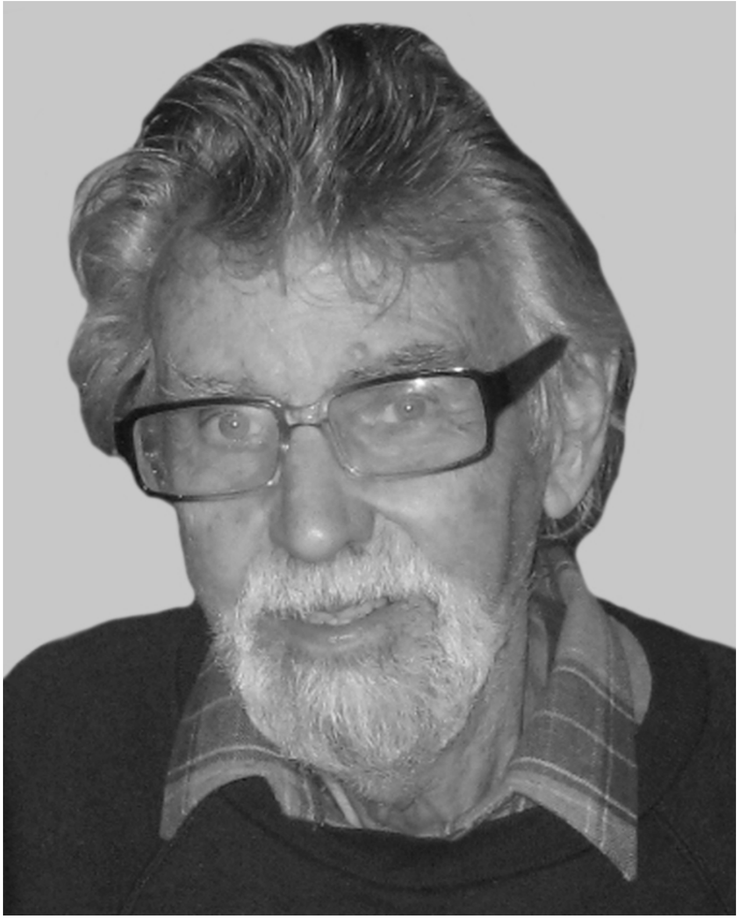

От составителей

Дорогие читатели и коллеги,

Уже больше двух лет назад, 27 марта 2012 года от нас ушел Ратмир Александрович Полуэктов. Помимо того, что он являлся выдающимся и заслуженным ученым, для многих из нас он был товарищем по работе, наставником, просто хорошим другом. Мы, его коллеги и ученики, в знак уважения приняли решение выпустить научную монографию, посвященную его памяти. Подготовка издания, приуроченного к проведению первых «Полуэктовских чтений» в Агрофизическом институте, где Ратмир Александрович работал заведующим лабораторией математического моделирования агроэкосистем в течение 45 лет, заняла у нас почти полтора года. Эту книгу вы держите в своих руках.

Как настоящий ученый-энциклопедист Ратмир Александрович Полуэктов отличался широчайшим спектром научных интересов. Однако за годы своей работы в АФИ наибольшее внимание его и возглавляемого им коллектива было последовательно сосредоточено на двух направлениях математической экологии – динамике популяций и математическом моделировании продукционного процесса сельскохозяйственных растений. При обсуждении формата настоящего издания нами было принято решение оформить его не как книгу воспоминаний, а именно как сборник проблемных авторских научных статей, посвященных последним исследованиям, а также оригинальным и прорывным результатам в этих научных дисциплинах. Нам кажется, что подобный характер книги более всего соответствует образу Ратмира Александровича, который всегда оставался человеком, открытым всем новым веяниям, не терпевшим застоя, рутины и пустой похвальбы, человеком, который превыше всего ценил научную истину, красоту и фантазию. Хочется верить, что подготовленная нами книга была бы принята им благосклонно.

Содержание

стр.

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CROP GROWTH MODELING ACROSS DIFFERENT SCALES - ADVANTAGES AND DISADVANTAGES

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Abstract

Crop growth modeling and crop yield estimation methods for arable and grassland farming across different spatial scales are very effective instruments for providing solutions to scientific, practical or impact assessment-oriented biomass and crop yield questions. The most popular utilization for both model developers and practitioners would be to have highly resilient and robust universal crop growth models applicable to different questions and spatial scales that are controlled by a

defined and widely available set of parameters, and based on available model inputs. However, experience shows that such a solution is hardly ever achieved in practice. The reality of crop growth modeling is that there is a close interaction between model type, spatial scale and input data availability.

Starting with an abstract, general definition for crop growth or agro-ecosystem models, this paper focuses on AGROSIM models and assesses physiological plant process-based crop growth approaches developed and parameterized for specific locations relating to (1) their adaptability to other European sites and (2) large regions such as counties or districts. Additionally, for larger settings, up to agro-landscape scale, a generic crop growth model approach is proposed for calculating (A) static crop values at harvest starting with crop yield estimation using the YIELDSTAT model, and (B) dynamic crop growth variables between sowing and harvest using the EVOLON approach. This generic approach contains different statistical elements. The YIELDSTAT crop yield estimation model is described in more detail.

1. Introduction

Agro-ecosystems play an essential role in matter, energy and water cycles and balances within agricultural landscapes. Analyzing and understanding interactions in the "crop□soil□atmosphere□management" system are important prerequisites for investigating the influence of weather/climate, site conditions and agronomic measures on biomass production and yield formation as well as on environmental values such as nitrogen leaching, percolation and carbon sequestration. It will become increasingly necessary to assess the impact of land use changes and changes in climate on agro-ecosystem indicators, such as crop yields and biomass accumulation.

Crop growth from the greenhouse and the natural ecosystem is influenced by numerous factor groups with varying levels of significance. The most influential factor groups are climate and weather; site conditions (including water and nutrient supply); crop properties (including cultivars, plant physiology and genetics); anthropogenic management and impacts from other system components (pests and disease). Depending on the scale, there is a wide difference in quality and/or availability of the necessary factor knowledge of each group. For agricultural plot crop growth modeling, detailed information about management, site, cultivar and weather is available. Such detailed information is not available for entire agro-landscapes, however. Here, GIS map-based information, weather information from a distributed network of meteorological stations, and management information, which is relevant to only the region concerned, serve as the only sources of information (Mirschel et al., 2004).

In order to anticipate future demands, more models applicable to large-scale agro-ecosystems need to be developed. After all, it is difficult to conduct experimental research on this large level as there is insufficient time; costs are prohibitive and the scale is too large.
Models are powerful tools for investigating the effects of different land use options and/or climate changes on crop growth and water and matter cycles as well as for bridging the gap between different temporal and spatial scales; they are urgently needed to support ecological-economic conflict solutions. Here, complex crop growth

or agro-ecosystem models play an important role in describing the influences of agro-management, soil and weather/climate on the most important ecosystem processes up to biomass accumulation and yield formation (Poluektov et al., 2006).

The origins of crop growth and agro-ecosystem modeling can be traced back as far as the "School of de Wit" crop growth simulation models in Wageningen, the Netherlands. These models had a similar philosophy but differed in their complexity, the processes addressed and their functionality (Bouman et al., 1996). Being concerned with only process-oriented crop growth modeling, model development was stimulated by a demand for tactical and strategic decision support, yield forecasting, land zoning and explorative scenario studies. Summarized and more comprehensive examples of crop growth modeling approaches are BACROS (Penning de Vries and van Laar, 1982); SUCROS (Spitters et al., 1989); WOFOST (van Diepen et al., 1988; Supit et al., 1994); MACROS (Penning de Vries et al., 1989); LINTUL (Spitters and Schapendonk, 1990) and ORYZA (Bouman et al., 2001).

Based on traditional models from the "School of de Wit", over the last 30 years numerous crop growth and agro-ecosystem models have been developed which have some scientific merit and have also been used in practice. Among them there are plant physiological and process-based models such as CERES (Ritchie, 1993); AGROSIM (Mirschel and Wenkel, 2007); AGROTOOL (Poluektov et al., 2002; Poluektov and Terleev, 2007); HERMES (Kersebaum, 2007) and MONICA (Nendel, 2011). All these models are parameterized for different agricultural crops. The results of a comparison of 18 different crop growth and agro-ecosystem models using a consistent data set from Müncheberg (Germany) are provided by Kersebaum et al. (2007). A comprehensive, but incomplete overview of more than 250 models for agricultural systems available worldwide is supplied in the CAMASE register (Plentinger and Penning de Vries, 1995). The application of specific model types mainly depends on the available process information and, hence, the scale of usage.

Crop growth and agro-ecosystem models are more or less similar: they require meteorological values as driving forces (D_k, $k = 1, 2, \ldots n_k$); management values (M_p, $p = 1, 2, \ldots n_p$); initial values ($I_l(t_0)$, $l = 1, 2, \ldots n_l$, t_0 - starting time) and parameters (P_m, $m = 1, 2, \ldots n_m$). The states ($X_i(t)$, $i = 1,2,\ldots n_i$, t - time) of crop growth models are calculated on the basis of model algorithms between sowing (t_S) and harvest (t_H). The model states are described by

$$X_i(t) = f\,[X_i(t-1), D_k(t), M_p(t), P_m]; \qquad X_i(t_0) = g\,[I_l(t_0)]\ ;\ t_S \le t \le t_H. \qquad (1)$$

At plot level where all site conditions are well known, a detailed plant physiologic process-based crop growth or agro-ecosystem model describing all important processes can certainly be expected to produce more satisfying scientific answers than similar simple crop growth approaches. With increasing areas considered, an obvious conflict appears between spatial heterogeneity of the area, the heterogeneity in plant reaction patterns (local environmental conditions), the considered process details, and the input and parameter availability and uncertainty. The selection of an appropriate approach for the context depends on the modeling goal as well as realistic input and parameter demands so that accurate and resilient results can be achieved.

This paper focuses on the AGROSIM model and demonstrates the effectiveness of plant physiologic process-based crop growth approaches developed and parameterized for specific locations relating to their applicability to other European sites and to larger regions. Additionally, a generic crop growth model approach for use at agro-landscape level, including a yield estimation model, will be presented.

2. The AGROSIM crop growth agro-ecosystem model

At the Leibniz-Centre for Agricultural Landscape Research in Müncheberg, Germany, the AGROSIM agro-ecosystem model family (AGRO-ecosystem SIMulation) was developed and validated for the agricultural moraine landscapes of northeast Germany. The AGROSIM model family, which is mainly focused on crop growth processes, includes models for winter wheat (AGROSIM-WW), winter barley (AGROSIM-WG), winter rye (AGROSIM-WR), sugar beet (AGROSIM-ZR), and various catch crops (AGROSIM-ZF) (Mirschel and Wenkel, 2007).

2.1 Model description

The AGROSIM models belong to the process-based soil-plant-atmosphere-management models. They describe whole crop stands under field conditions for limited water and nitrogen supply between sowing and harvest. Homogeneous crop stands are assumed in the models. All models only need meteorological standard values (temperature, radiation, precipitation, CO_2 content) as driving forces and regionally available inputs and parameters. The AGROSIM models based on the same modeling philosophy have a similar modular model structure (sub-models); use rate equations for describing process dynamics; operate on a minimum time step of one day; and are sensitive to weather/climate, site and management. In all models there are realized time step-related interactions between the modules of ontogenesis, biomass growth, soil processes and the atmosphere. The general structure of the AGROSIM models for winter cereals, including the couplings of soil and plant processes within the model, are illustrated in Figure 1. One of the most important processes within the AGROSIM models is the process of ontogenesis, which acts as a time-related control variable for all other processes (Mirschel et al., 2005).

The second important sub-process within the AGROSIM models is carbon assimilation, which obtains daily increments via stand photosynthesis. The photosynthesis approach, which is used in almost all known crop growth models, is based on leaf area index (LAI) (for instance, see Poluektov et al. (1998)). This is in contrast to the AGROSIM models where the photosynthesis approach is based on a maximum photosynthetic rate per unit of green biomass, which is modified by environmental and management factors depending on photosynthetic active radiation; temperature; existing vegetative biomass; short- and long-term water stresses; nitrogen stress; atmospheric CO_2 concentration; and lengths of day-time and night-time. The descriptions of all factor dependences for the photosynthesis approach are provided by Mirschel and Wenkel (2007), as are the approach descriptions of all other crop growth and soil processes.

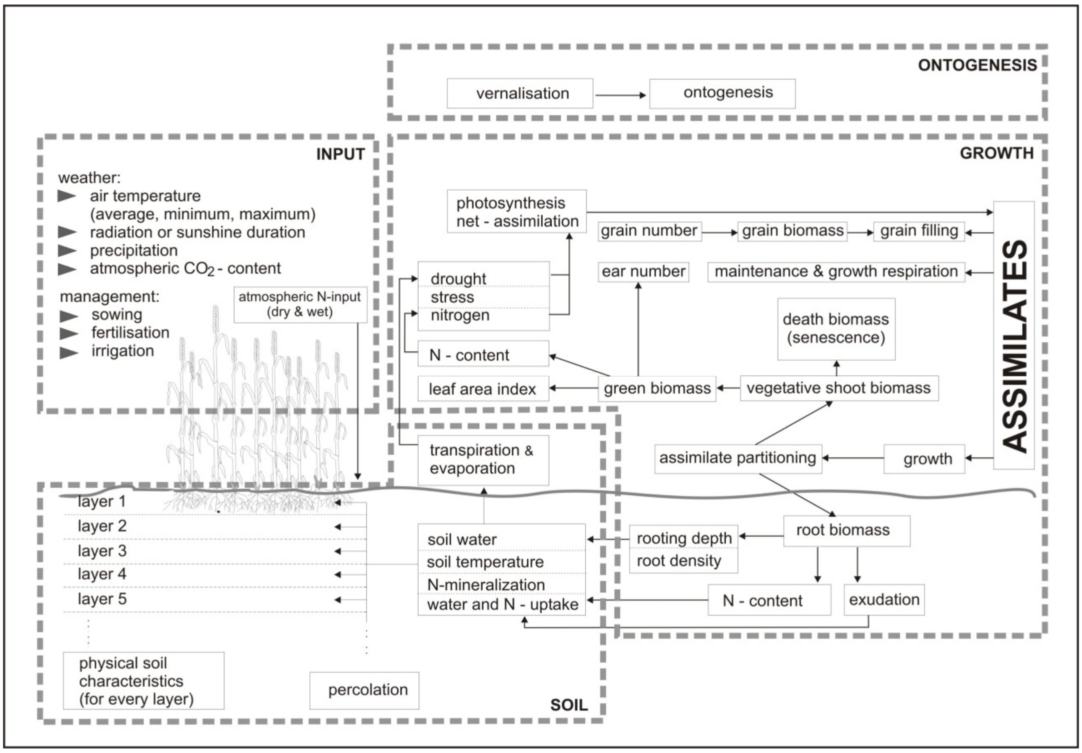

Figure 1: Model structure of AGROSIM models for winter wheat, winter barley and winter rye (Mirschel and Wenkel, 2007)

2.2 Model validation at plot level

Based on special field experiments between 1993 and 1998, the AGROSIM models were parameterized and first validated for site conditions at the Müncheberg research station. Figure 2 shows a model-experiment comparison for ontogenesis, above-ground biomass and yield for the crop rotation "sugar beet – winter wheat – winter barley – winter rye" between 1993 and 1998.

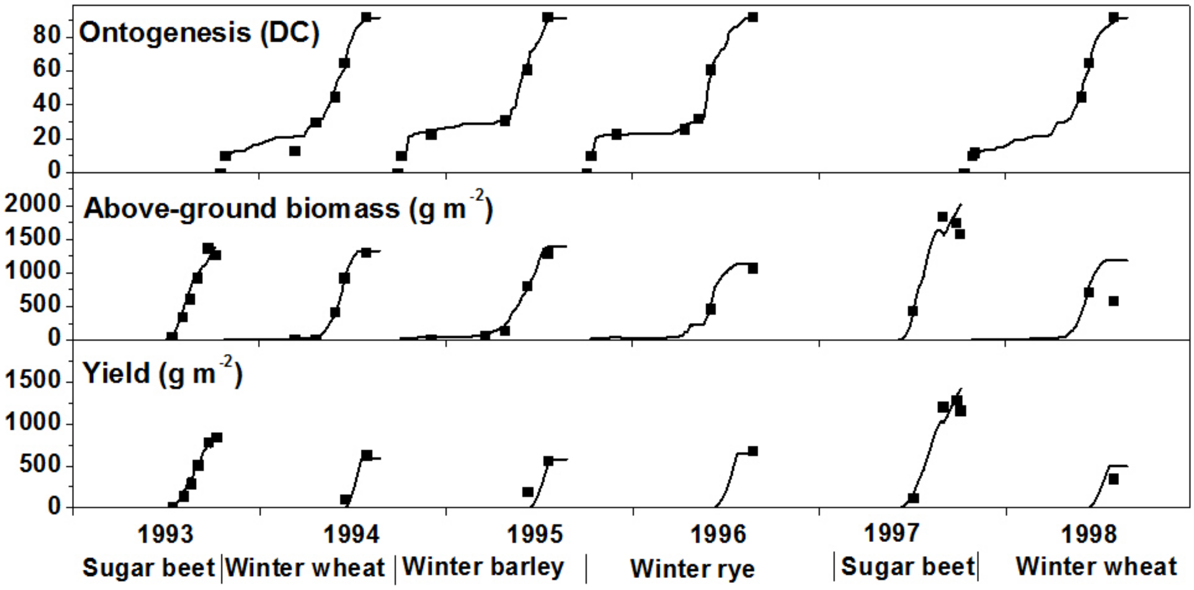

Figure 2: Model-experiment comparison for ontogenesis, above-ground biomass and yield as time courses for the whole crop rotation (1993-1998) at the Müncheberg site (lines – simulations with AGROSIM models; squares – observations) (adapted from Mirschel and Wenkel, 2007)

Considering all winter cereals the ontogenesis stages for shoot initiation, flowering and maturity were calculated with a mean absolute deviation (MABS, Rasch, 1987) of 4.5, 4.2 and 6.6 days, respectively. The MABS for yield and above-ground biomass (all three winter cereals including sugar beet) are 0.77 t ha^{-1} and 1.04 t ha^{-1}, i.e. the mean relative deviations are 14.08% and 14.84%, respectively. For both the yield and the above-ground biomass, the index of agreement according to Wilmott (1982) is 0.984 and 0.978, respectively. The model simulations were realized with a constant parameter set for each crop type.

The AGROSIM models were also validated for other research stations in eastern Germany including Hohenfinow, Ziethen, Mariensee, Bad Lauchstädt and Brunswick. For Brunswick, within the Free Air Carbon Enrichment (FACE) experiments, two different levels of atmospheric CO_2 content were taken into account, i.e. 380 ppm and 550 ppm.

As part of the scientific cooperation with the Agrophysical Research Institute St. Petersburg, Russia, the AGROSIM model for winter wheat was validated for the research stations in Sovetsk and Krasnodar. In Figure 3 the model-experiment comparisons for ontogenesis, biomass (above-ground, grain), and soil water (1 m depth) are shown as time courses for the whole vegetation period taking the examples of Krasnodar (1983/84) and Sovetsk (1987/1988).

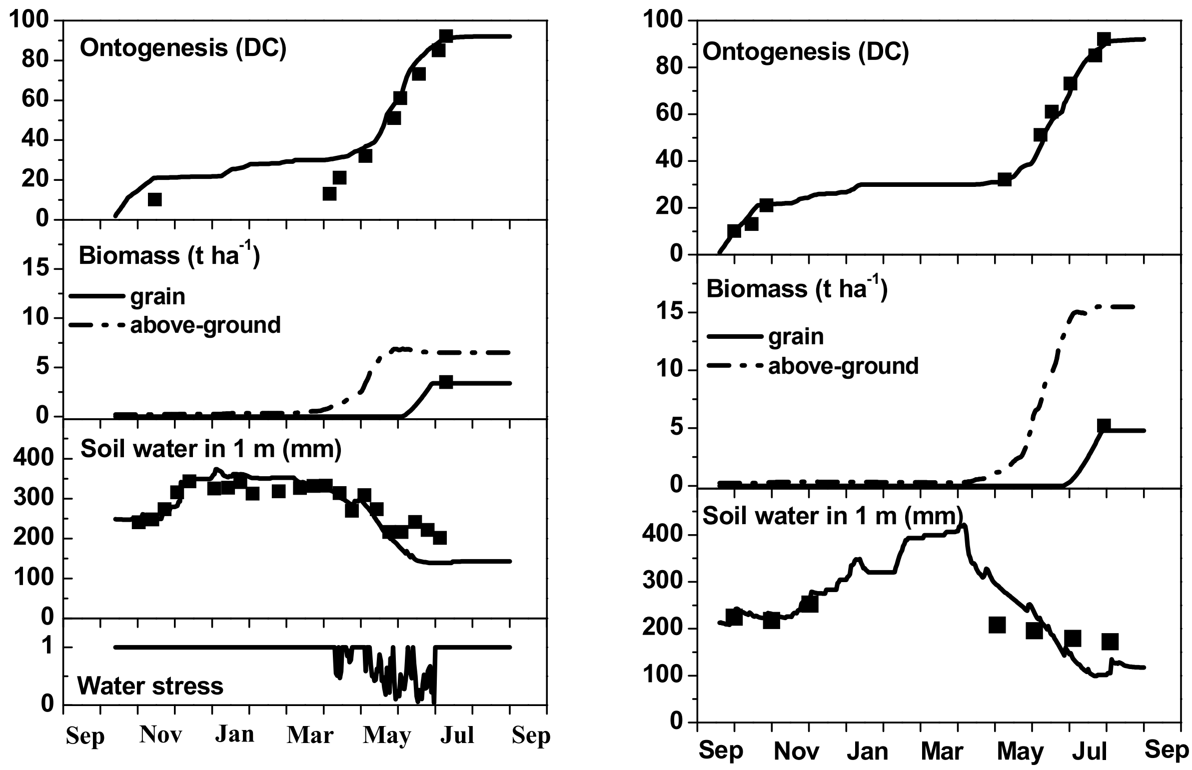

Figure 3: Winter wheat model-experiment comparison for ontogenesis, above-ground biomass, grain yield, and soil water (1 m depth) as time courses over the whole vegetation period for Krasnodar (Krasnodar region, Russia, 1983/1984, variety: Mirinovskaja-808), left) and Sovetsk (Kaliningrad region, Russia, 1987/1988, variety: Mirinovskaja-Jubilejnaja, right) [lines – simulation using AGROSIM-WW; squares – observations]

2.3 Model adaptation for winter wheat at European sites

The aim of a model development with a practical focus for crop growth should be to achieve a widely applicable model so that it can be used across a range of situations.

The model transfer possibilities were primarily investigated using the AGROSIM model for winter wheat and data sets from different European experimental sites. For these investigations, weather and experimental data from 24 sites in France (5 sites), Germany (5 sites), Hungary (1 site), Italy (8 sites), the Netherlands (3 sites), Poland (2 sites) and Russia (2 sites) was available. The data was supplied from locations between 39.4 °N ... 55 °N and 1.5 °E ... 38.5 °E; was derived from different sources and different time periods (1957 - 1997) and from 26 different cultivars. In all, 97 different combinations of weather, site and cultivars could be used.

Complex crop growth models with many site, cultivar and agronomic parameters (usually more than 100) have a great number of "degrees of freedom". Where there is a limited set of observations, similar model behavior can be achieved by using different parameter sets or parameter combinations. The greater the amount of inputs and parameters, the greater the ability to adapt a model to a new situation. However, greater effort is also required and there is also more potential for error. Where the data set is limited and there is incomplete knowledge of site conditions, the application of automatic parameter optimization procedures is not recommended. In this case, it is more effective to manually adapt the parameters. Having an awareness of the problems when applying a very comprehensive model to data sets from different decades and different regions, here, only cultivar parameters have to be adapted which reflect progress in agro-technology and plant breeding, and which describe the geographical variables (processes of ontogenesis, photosynthesis and grain filling). The relevant parameters within AGROSIM are: maximum ontogenesis and specific gross photosynthesis rates during tillering, shooting/ear formation and grain filling as well as potential grain filling rate and ear/biomass equivalent. The goal function of the parameter estimation during the course of ontogenesis was to meet the stage of flowering and, for courses of biomass and grain yield, to meet the final values at harvest. Compared to the German standard parameter set there was the aim to find a country-specified parameter set. Apart from in France and Russia, this aim was achieved. Because of a very wide range of cropping conditions for winter wheat in France and Russia, for most of the parameters mentioned above, value ranges were necessary (Mirschel et al, 2004). Table 1 gives an overview of value ranges for some of the modified parameters after they had been adapted. Figure 4 shows a comparison of measured and simulated grain yields at harvest using country-specific parameter sets.

Table 1: Country-specific parameter sets for the maximum ontogenesis rate and the gross photosynthetic rate for the AGROSIM model (Mirschel et al., 2004)

parameter	maximum ontogenesis rate			gross photosynthetic rate		
	tillering	shooting	grain filling	tillering	shooting	grain filling
country						
France	0.10...0.11	0.37	0.07	0.95...1.10	0.25...0.31	0.03
Germany	0.17	0.40	0.035	0.90	0.245	0.055
Hungary	0.10	0.45	0.07	0.90	0.245	0.055
Italy	0.10	0.34	0.12	0.90	0.26	0.03
Netherlands	0.12	0.60	0.035	0.96	0.27	0.055
Poland	0.07	0.45	0.08	1.10	0.31	0.03
Russia	0.07...0.09	0.45	0.08	1.10	0.31...0.46	0.03...0.055

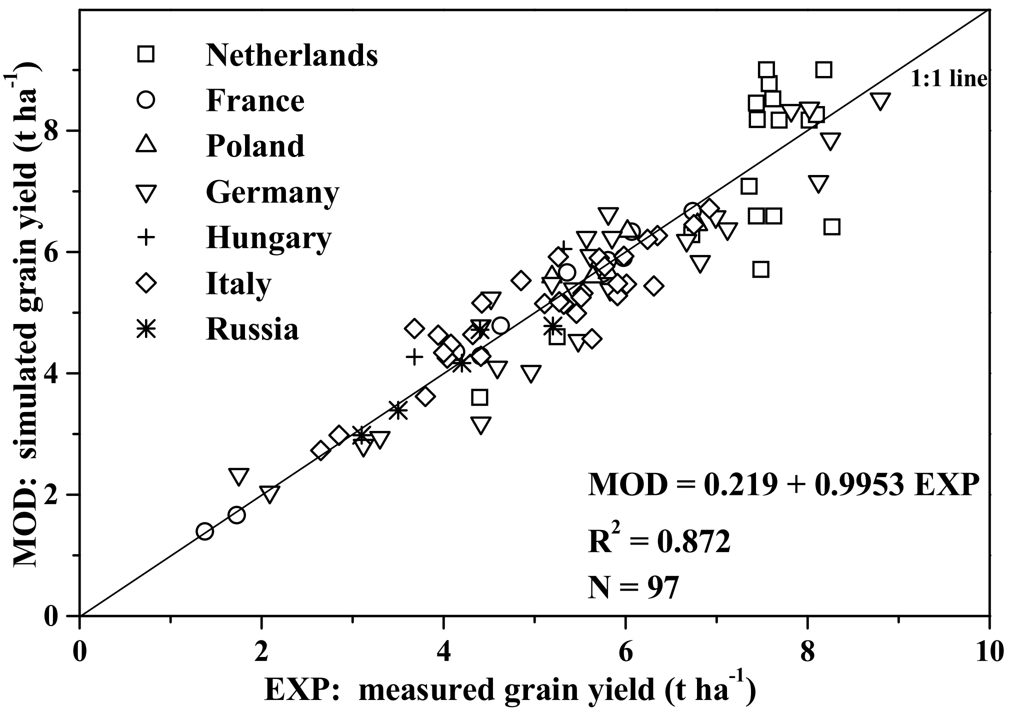

Figure 4: Comparison of measured and simulated winter wheat grain yields for different European locations (Mirschel et al., 2002b)

3. Application of process-based crop growth models at the regional level

Plant physiological process-based crop growth models are developed and parameterized to experimental conditions for a high crop yield level which differs from practical cropping conditions for large fields or at a regional level where the crop yield level is significantly lower. This means that the application of such crop growth models for the regional level must be handled very carefully. The application of such process-based crop growth models for the regional level is not possible in

every case. However, in every case it is necessary to adapt these models to the practical cropping conditions taking into account the bias between the crop yield level for research stations and the crop yield level for practical cropping conditions.
For an acceptable application of process-based models at the regional level there are two possibilities. The first is to assume that the region in question is a homogeneous area with homogenized model inputs, for example, a typical soil within the region, a weather/climate data set from a meteorological station representative of the region, and identical agro-management. In this case, the preparation of all necessary model inputs is relatively straightforward as it can be assembled from statistics.

The second option is to divide the region into relatively small grids (100m x 100m, for instance) in which the model inputs can also be defined as homogeneous. Here, the grid-specific preparation of necessary model inputs for the whole region is much more difficult. Detailed GIS map information such as spatial soil information (Badenko et al., 2013) is required. There are not resilient methods for downscaling weather/climate data based on the meteorological station network of a meteorological service which are not likely to be of sufficiently good quality. It is also very difficult to acquire grid-based agro-management information.

An example of the first option demonstrates how detailed, plant-physiologic process-based models can be used to estimate grain yields in practice under cropping conditions at district level with the help of AGROSIM models, here taking the example of winter rye and winter barley. The investigations were carried out across a ten-year time period (1980-1989) in the districts of Prenzlau (795 km^{-2}) and Strausberg (689 km^{-2}) in northeast Germany. As the weather during the 1980s was extremely variable, there is a wide spectrum of different behavior patterns (annual precipitation: 420 ... 700 mm, annual average temperature: 8.2 °C ... 9.9 °C). If models like AGROSIM are to be applied to agricultural practice, model and parameter adaptations are urgently required to cope with the problem of yield differences between experimental plots and fields at farms. The general idea behind the application of AGROSIM models for biomass and yield estimations at district level is to consider the area of the district as one homogeneous field with a dominating soil, grown with the same average cultivar, and that agricultural management practices are consistent.

Acknowledging the differences in yield between trials and practice, a productivity factor was introduced which was normalized to the interval [0, 1], thus offsetting disadvantageous effects, and was linked to the processes of biomass and grain yield formation. In addition, the ontogenesis reaction to water shortage was modified. It should be mentioned that the productivity factor increased within the previous decades due to improved management and is greater for winter barley than for winter rye. The model starting values and daily inputs were derived as average values from generally available district information. The dominating soil layer information was derived from soil maps using a transformation algorithm by Weise (1978). The weather data for the districts Prenzlau and Strausberg was taken from the representative meteorological stations Prenzlau and Müncheberg, respectively.

The comparison of winter rye and winter barley yields simulated using the modified AGROSIM models with the statistical district average yields is shown in Figure 5.

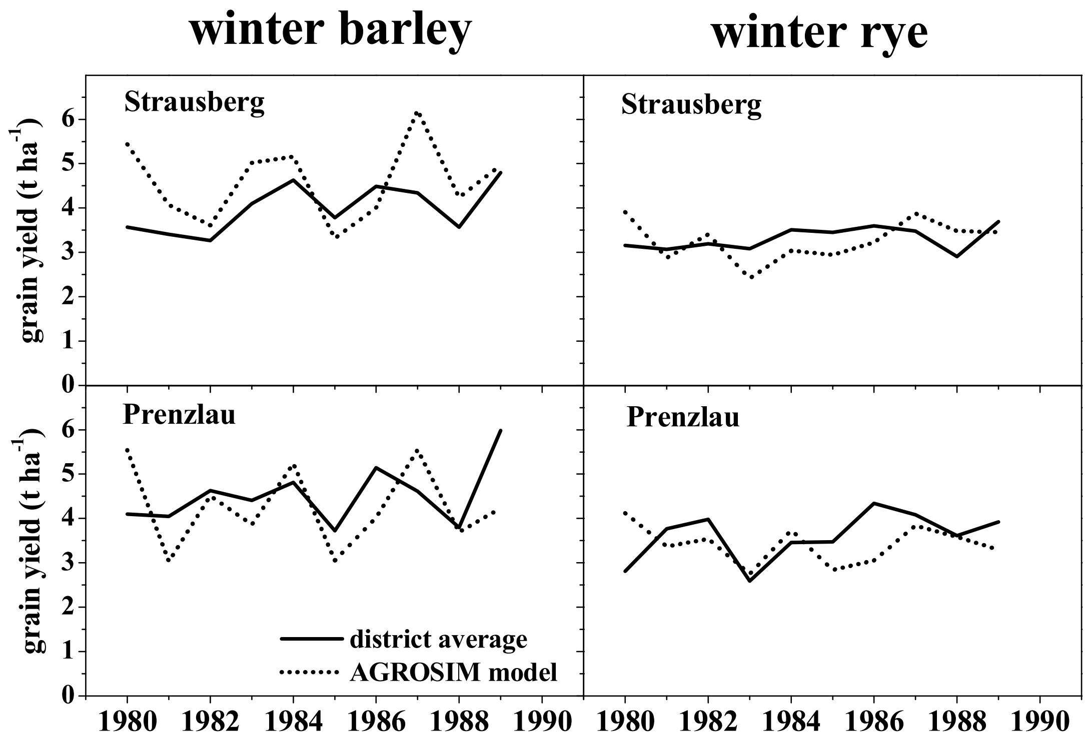

Figure 5: Comparison of simulated and statistical average grain yields at district level (Mirschel et al., 2004)

For both crops and districts, the mean absolute deviation is 0.65 t ha^{-1} and accordingly 16 %. On average, district yields are slightly overestimated by the AGROSIM models. Sensitivity analyses concerning model starting values and inputs showed that considerable yield variations are possible when changing the average sowing date, the latitude of the growing site or the nitrogen management.

As an example of the second case, it is demonstrated how the MONICA model (Nendel et al., 2011) was used to investigate the application possibilities of such crop growth model types for larger areas. MONICA is a plant-physiologic process-based agro-ecosystem model which was developed based on the HERMES model (Kersebaum, 2007) using model algorithms from the AGROSIM (Mirschel and Wenkel, 2007) and DAISY (Hansen et al., 1991) models. The second question was to test the effect of different spatially resolved soil and weather data used as input for the MONICA model. The investigation was conducted across the whole Federal State of Thuringia, Germany, which has an area of 16,172 km^{-2} (Nendel et al., 2013). Thuringia was covered by a 1 ha grid (100m x 100m) meaning that the MONICA model calculated more than 1.6×10^6 times per simulation day. For all these grids the necessary model input data was either directly or indirectly derived from map information. For the model applicability in the first step, MONICA was tested against actual field experiment data from representative stations across Thuringia and with the knowledge that the yield level of the experimental stations is higher compared to the yield level of large-scale commercial agriculture (Nendel et al., 2013).

The results of the investigation with winter wheat can be condensed as follows: “The combination of one representative soil and one weather station for the whole Federal State of Thuringia was insufficient to reproduce the observed mean yield of 6.66 ± 0.87 t ha^{-1}. The use of a 100 m × 100 m grid for soil and relief information combined with only one representative weather station yielded a good estimator (7.01 ± 1.47 t ha^{-1}). The soil and relief data grid used in combination with weather information from 14 nearby weather stations produced even better results (6.60 ± 1.37 t ha^{-1}); the same grid used with 39 additional rain gauges and an interpolation algorithm that included an altitude correction of temperature data slightly overpredicted the observed mean (7.36 ± 1.17 t ha^{-1}). It was concluded that the apparent success of the first two high-resolution approaches over the latter was based on two effects that cancelled each other out: the calibration of MONICA to match high-yield experimental data and the growth-defining and -limiting effect of weather data that is not representative for large parts of the region. At county and farm level, the MONICA model failed to reproduce the 1992–2010 time series of yields, which is partly explained by the fact that many growth-reducing factors were not considered in the model.” (Nendel et al., 2013). Based on these results, when the MONICA model was subsequently used for agricultural areas at a regional level, a practice factor for adapting the yield level to large-scale commercial agriculture was introduced.

4. Dynamic crop growth modeling and spatial scaling

Plant physiological process-based crop growth models are developed and parameterized for experimental conditions for small plots with homogeneous and optimal growing conditions, also taking into account special climate chamber experiments. Crop, soil and management conditions are well known, and there are excellent measurements for model calibration and parameter optimization. Such models describe the growing situation under experimental conditions at a high crop yield level which differ from practical growing conditions at large fields or at regional level where the crop yield level is significantly lower (by 10 … 20 % in Germany). The reasons are heterogeneities in soil properties; diverse nutrients and soil water distributions; pest infestations; management quality differences; harvest losses and others. Therefore, if models such as AGROSIM or MONICA are to function for large-scale commercial agriculture, model and parameter adaptations are urgently required to cope with the problem of yield differences. In addition, the existing complex dynamic crop growth models do not take into account all relevant processes and interactions influencing the biomass accumulation and yield formation. Usually here the interactions between the plant at one location and pests, deceases or weed pressure at another have not yet been taken into account. Therefore, more research is required here. This procedure is very time-consuming and costly. The first efforts in this direction were in the mid-1980s by Bellmann et al. (1986). Fostering this approach in model development means that considered processes and parameters are multiplied as are the problems connected with model parameterization.

Another difficulty in the application of complex dynamic crop growth models across large spatial and temporal scales, for example, regional crop yield simulations during climate change, is that they do not take into account the yield trends resulting from progresses in plant breeding and agro-technology. In complex dynamic crop growth models, usually genetic parameters are considered such as assimilation and respiration rates, ontogenesis rate, senescence rate or shoot/root and grain/straw ratios. Genetic parameters are used, for example, in the well-known CERES models (Ritchie et al., 1988), in which there exist continent-based genetic parameter sets. In general, these genetic model parameters are verified for fixed levels of progress in plant breeding and growing. To solve this problem, it would be necessary to replace these genetic fixed parameters with parameter functions dependent on progress in plant breeding and agro-technology.

The use of complex dynamic crop growth models on a large scale, i.e. for unknown environments that have not had parameters set for the model, produce potential errors caused by the model itself and the large number of assumptions that do not apply to the scale of model validation. These assumptions are mainly connected with the restrictions on the input data required to drive the model (Nendel et al., 2013). On a large scale, the data situation is limited compared to the data requirements for running complex dynamic crop growth models. In order to apply these models on a large scale, the first necessary step is to prepare the data required for the model to run directly from map information or, as is more usual, indirectly by deduction from other information available for a large scale. Consequently, there is a considerable likelihood of error.

In the past, the limited availability of computer processing power for running complex dynamic crop growth models on large scale was often a reason for the unfeasibility of such models. Nowadays this is no longer the case as parallel processing enables high-resolution simulations of large areas using sophisticated process-based crop growth models to be performed.

The problems connected with the use of complex dynamic crop growth models at regional level as described above show that this model type is not effective at all levels, i.e. from field via farm and region up to national level. The determination requirements for values and parameters influencing the biomass accumulation, the possible error sources for its determination, and the error propagation within models may also negatively influence the practical use of such model approaches. In order to achieve a practical application of model approaches to describe biomass accumulation and yield formation with resilient model outputs, it may ultimately prove necessary to replace the theoretical process-based approaches with simpler model approaches. According to Ewert et al. (2011), modifying model parameters and simplifying model structures are the first steps for model simplification. Similar conclusions are given by Schultz (2002).

Because of required model simplifications on the one hand and increasing difficulties in the process of input data availability (homogenization, aggregation, interpolation, direct or indirect deduction) connected with increasing scales on the other, it follows that there is a mutual dependency between scale and applied model type for crop growth. This position is supported for agricultural arable and grassland areas (Ewert et al., 2001; Nendel et al., 2013; Gimona et al., 2006; Folbert et al., 2012) as well as for forest areas (Xi et al., 2009; Pinjuv et al., 2006). Consequently, the model type for crop growth should be changed according to the scale. In order to obtain resilient and robust results in crop growth modeling on a large scale across a wide range of agricultural crops grown on arable land, it is recommended that generic hybrid crop growth models are used. These combine different statistical, matrix, fuzzy and expert knowledge based approaches with empirical algorithms. Knowledge-based approaches can take into account circumstances influencing crop growth and yield formation which are difficult to quantify using other approaches due to a lack of data. Here only practical experience and expert knowledge accumulated over a long period of time can be used.

5. Generic hybrid crop growth model for landscape scale

Landscapes can be described quantitatively and qualitatively by using landscape indicators. Biomass accumulation as the basis for matter balances and yield as the basis for economic calculations belong to such landscape indicators. For agricultural land (here, arable and grasslands) within agro-landscapes, crop growth models are necessary for different agricultural crops and grassland types as well as for different management intensities (e.g. organic and conventional farming). On arable and grassland sites in northeast Germany, for instance, about 20 different arable crops and 14 grassland vegetation types (grass communities, Mirschel et al., 2010) are grown. At landscape level, only a limited amount of data is available. Here, only GIS-based data with different spatial resolutions can be used with no specific management and cultivar information and only weather/climate information from the official weather service's station network. Acknowledging all these restrictions, it becomes apparent that for the agro-landscape level classic plant physiological-based agro-ecosystem, it is not an option for models to use a lot of detailed processes involving a large number of parameters (among them also genetic parameters) which often need very specific input information for each crop or grassland type. For this scale, a generic crop growth model is required which has manageable crop specific parameter sets and general input data which is only available at agro-landscape level. According to Mirschel et al. (2004), a generic crop growth model as a part of a complex landscape model should be:

(1) sensitive in its responses to climate, site characteristics, and management practices;
(2) robust in its functions and not inordinately sensitive to coarse parameters imposed by regional databases;
(3) both simple and complex enough to include all relevant dependencies using different model algorithms and approaches;
(4) compatible with landscape models and general software formats using object-oriented modeling methods;
(5) able to output crop-relevant crop growth and yield values for interaction with other landscape model parts and simple balance models based on a well-defined data exchange;

(6) be parameterized and validated for all necessary arable crops and grassland types and

(7) capable of making model extrapolations for simulation runs that can project future trends.

5.1 Generic crop growth model

Such a generic crop growth model was developed at the Institute of Landscape Systems Analysis of the Leibniz-Centre for Agricultural Landscape Research (ZALF) Müncheberg by using object-oriented modeling methods. This generic crop growth model, which is subdivided into two parts, interacts with different soil models. The model structure is shown in Figure 6. In the first part of the model, different static crop variables such as crop yield, above-ground biomass, root biomass and total biomass at harvest time are estimated using fairly simple model approaches. A more detailed description of the YIELDSTAT spatial crop yield estimation model, which plays an essential role within this generic crop growth model, is given in Section 5.2. Starting with the biomass and yield situation at harvest in the second model part, dynamic crop variables between sowing and harvest are calculated using the EVOLON differential equation approach (Peschel, 1988). Applying the EVOLON parameters, which are influenced by temperature, water and nutrient stress factors, destruction and cooperative growth processes can be considered as well as the process velocities (acceleration, deceleration, interruption). The biological time is controlled using the crop ontogenesis. Here the ONTO model based on temperature sums (Mirschel, 2010b) is used for the most important agricultural crops. For all other crops, the simplified model approaches used for the BEREST90 irrigation scheduling system (Wenkel and Mirschel, 1991) are used. For calculating the crop's specific potential evapotranspiration (PET), Wendling et al.'s (1991) simple approach is used.

This generic hybrid model for crop growth has been parameterized so far for winter wheat, winter rye, winter barley, rape, field grass, sugar beet, potatoes, peas for fodder, silo maize, grain maize and spring barley, and has been used taking the example of the whole Uecker catchment (5,300 km^2) in the northeast German region (Mirschel et al., 2002a).

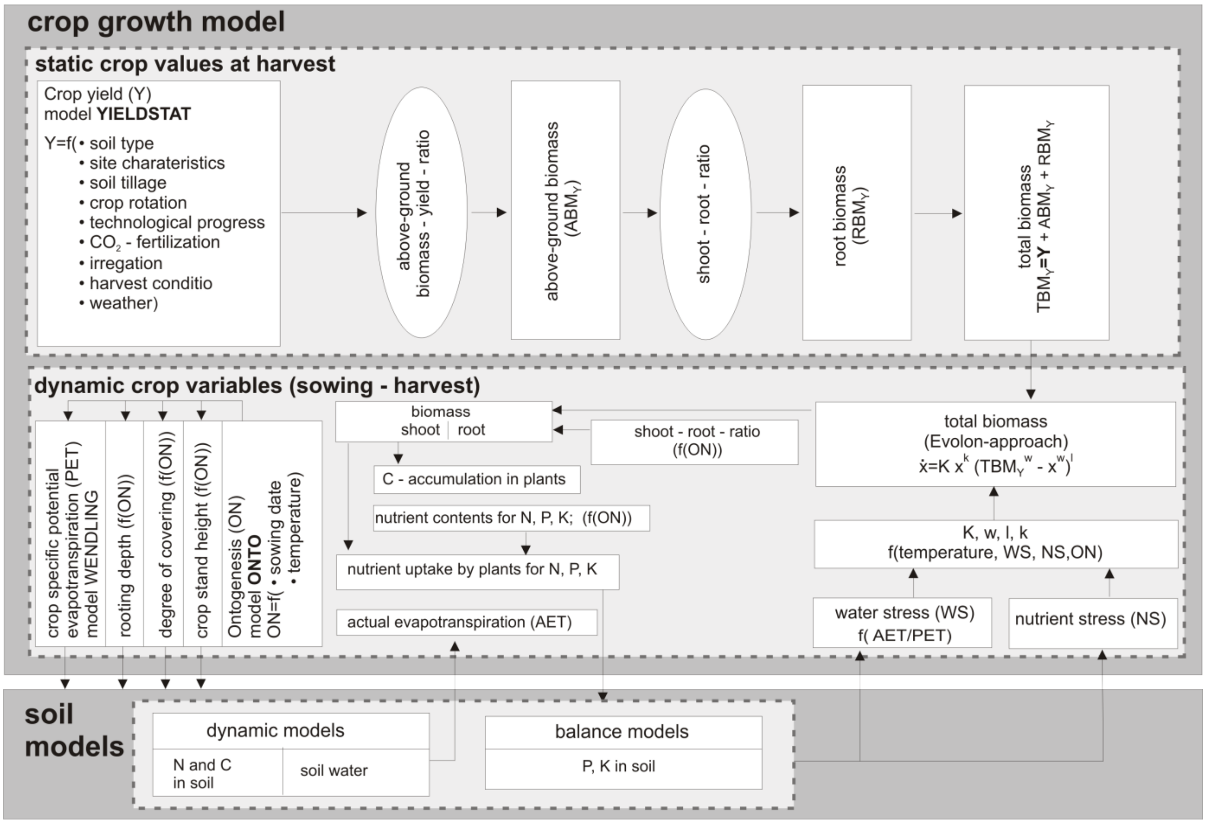

Fig. 6: Structure of the generic hybrid model for crop growth (taken from Mirschel et al. (2004), modified)

5.2 YIELDSTAT spatial crop yield estimation model

YIELDSTAT (YIELD estimation based on STATistics) is a spatial statistic-based crop yield model based on field crop yield observations distributed on the arable land of more than 300 large agricultural enterprises within different climatic regions of eastern Germany up to the early 1990s. YIELDSTAT is a hybrid model which combines eight different yield-influencing modules which are combined as follows:

$$Y = ((Y_s + Y_{Site}) \cdot f_{PrCr} \cdot f_{Till} + Y_{Tech}) \cdot f_{CO2} + Y_{Irri} - Y_{LoHa} \qquad (2)$$

where Y is the crop yield (t ha^{-1}); Y_s is standardized yield (t ha^{-1}); Y_{Site} is the site-specific yield modifier (t ha^{-1}); f_{PrCr} is the pre-crop modifier; f_{Till} is the tillage modifier; Y_{Tech} is the regional crop yield trend (t ha^{-1}) driven by progress in plant breeding and agro-technology; f_{CO2} is a factor accounting for the effect of increasing atmospheric CO_2 on crop photosynthesis and water use efficiency; Y_{Irri} is the yield increase by irrigation (t ha^{-1}); and Y_{LoHa} denotes yield loss caused by adverse weather conditions during harvest (t ha^{-1}).

Y_s based on a natural yield matrix developed by Kindler (1992) and Mirschel (2009) combines different arable crops (winter wheat, winter barley, winter rye, winter triticale, spring barley, oats, potatoes, sugar beet, winter rape, maize for silage, clover, clover-grass mix, alfalfa, alfalfa-grass mix, field grass) and two grassland types (intensive grassland, extensive grassland) with 56 different types of agricultural sites grouped into diluvial, alluvial, loess and disintegrated soils. The agricultural site types are based on the Medium Scale Site Map (MMK) for arable land (Schmidt and Diemann, 1991) which covers the whole of the eastern part of Germany in a high resolution. As an example for winter wheat and triticale, the normalized natural yield matrix is provided by Mirschel et al. (2011).

Y_{Site}, the site-specific yield modifier, calculates a positive or negative yield extra charges to the basic natural yield depending on site-specific characteristics such as stoniness, slope gradient, altitude, hydromorphy, the soil quality index for agricultural land in Germany, growth temperature according to Adler (1987), mesoscalic climatic zones according to Adler (1987), winter temperature and climatic water balances (KWB) for the vegetation year. As an example, the vegetation year for winter wheat is from September to August; for winter rape from August to July; and for silage maize from November to October. This algorithm qualifies the functions according to Kindler (1992). The potential evapotranspiration for calculating the KWB is based on the Wendling approach (Wendling et al., 1991) which needs daily values for global radiation and temperature only. Depending on site-specific characteristics, the calculation algorithm for yield extra charges for winter wheat and winter rape can be provided by Mirschel et al. (2011) and Mirschel et al. (2006), respectively. For taking into account the water supply during the crop-specific main growing period for winter cereals, winter rape and silage maize were introduced as an added yield correction value which calculates multiplying the KWB for the crop-specific growing period by a crop-specific correction factor. This factor is 0.004 [t ha^{-1} (mm $KWB_{April - June})^{-1}$] for winter cereals, 0.002 [t ha^{-1} (mm $KWB_{April - May})^{-1}$] for winter rape and 0.02 [t ha^{-1} (mm $KWB_{June- August})^{-1}$] for silage maize.

The influence of a previous crop (f_{PrCr}) on crop yield of the actual grown crop is estimated using a matrix ($\|M\|$ (actual crop, previous crop)) which for each combination contains statistical average reactions based on thousands of crop rotation experiments. The influence is taken into account multiplicatively. For winter barley with winter wheat as the previous crop, this influence is 1.0, with winter rye, triticale and winter barley as the previous crop, the influence is 0.9, with peas, beans and lupine as the previous crop, it is 1.04, and with oilseed rape and sun flowers as the previous crop, it is 1.05.

The main influence of different soil tillage methods (f_{Till}) on crop yields is via the soil water supply. In comparison to the conventional soil tillage (with plough), in this context the preserved soil tillage and non-tillage are taken into account. Comprehensive expert knowledge and extensive soil tillage experiments are the basis for the statistical estimate of the soil tillage effect on crop yields. Consequently, it is necessary to distinguish between the two groups of previous crops, first: winter and spring cereals and maize, and second: bean, pea, lupines, rape, sunflower, potato, sugar beet, clover, clover-grass mix, alfalfa, alfalfa-grass mix, rye grass. In comparison to conventional soil tillage primarily used for winter wheat, the preserved soil tillage gives a crop yield increase of 5% for the second group of previous crops and of 0% for the first group. For non-tillage, the influence is 3% for the second group and -5% for the first group of previous crops. For winter rape, this influence is 4%, 0%, -5% and -10%, respectively. For the diluvial soil types (poor sandy soils) with a total precipitation of less than 530 mm in the vegetation year for all crops, the yield loss is 5% for the preserved soil tillage and 10% for non-tillage.

Using YIELDSTAT for forecasting, it is necessary to take into account the possible crop yield trend (Y_{Tech}) caused by developments in plant breeding and agro-technology. Hence, in the YIELDSTAT model a crop- and region-specific trend algorithm is implemented based on plant breeding and management techniques from the 1990s as follows:

$$Y_{Tech}(Year) = T_{crop}(Year - 1990) \quad (3)$$

Here the Year is the year of simulation and T_{crop} is the crop- and region-dependent trend factor.

For simulations with climate scenarios, it is necessary to take the fertilization effect (f_{CO2}) of rising CO_2 into account. For the YIELDSTAT model based on the results of 141 climate chamber experiments, 98 open-top experiments and 55 free air carbon enrichment (FACE) experiments assembled in a database by the Centre for the Study of Carbon Dioxide and Global Change (CO2SCIENCE, 2010), the following statistical approach was applied:

$$f_{CO2} = [CO2(KlSz,J) - 385] \begin{cases} CO2_{Eff}; & KWB \geq -50 \\ CO2_{Eff}\left(1 + 0.186\dfrac{|KWB + 50|}{80}\right); & -130 \leq KWB < -50 \\ 1.186 * CO2_{Eff}; & -130 > KWB \end{cases}, \quad (4)$$

where f_{CO2} denotes a factor of complex impact of CO_2 on yield; CO2(KlSz, J) represents CO_2 content in the year (J) of a specific climate scenario (KlSz); $CO2_{Eff}$ denotes an efficiency factor (% per 1 ppm CO_2 increase) (Table 2), and KWB is the climatic water balance (mm) for the vegetation year (Mirschel et al., 2011).

Table 2: Effectiveness of a CO_2 increase in the atmosphere on biomass accumulation of agricultural crops [% (1ppm CO_2 increase)$^{-1}$]

Crop	$\mathbf{CO2_{Eff}}$	**Crop**	$\mathbf{CO2_{Eff}}$
Winter wheat	$6.218\ 10^{-2}$	Silage maize	$1.589\ 10^{-2}$
Winter barley	$7.547\ 10^{-2}$	Clover	$9.046\ 10^{-2}$
Winter rye	$6.883\ 10^{-2}$	Alfalfa	$7.853\ 10^{-2}$
Sugar beet	$3.744\ 10^{-2}$	Grass	$4.308\ 10^{-2}$
Winter rape	$9.434\ 10^{-2}$	Clover-grass mix (70:30)	$7.748\ 10^{-2}$
Potato	$6.162\ 10^{-2}$	Alfalfa-grass mix (70:30)	$6.727\ 10^{-2}$

Agricultural yields depend heavily on the amount and within-year distribution of precipitation. Irrigation is the most effective agro-management measure for stabilizing yields. The algorithm for the irrigation modifier Y_{Irri} is based on crop- and site-specific irrigation water demand (IWD_{CrSi}, mm) and crop-specific irrigation water use efficiency ($IWUE_{Crop}$, kg ha^{-1}mm^{-1}). The irrigation-induced yield increase is given as:

$$Y_{Irri} = IWD_{CrSi} \times 10^{-3} \cdot IWUE_{Crop} \quad (5)$$

IWD_{CrSi} is calculated using the approach proposed by Roth (1991, 1993), expanded by two terms for (i) the degree of change in climatic water balance and (ii) the increase in water use efficiency due to the rising atmospheric CO_2. This new approach for calculating IWD_{CrSi} – the ZUWABE model – is described in detail in Mirschel et al. (2012). When averaged over all available experiment results, $IWUE_{Crop}$ amounts to15 kg $ha^{-1}mm^{-1}$ for winter wheat; 17 kg $ha^{-1}mm^{-1}$ for oats; 12 kg $ha^{-1}mm^{-1}$ for winter barley; 95 kg $ha^{-1}mm^{-1}$ for sugar beet; and 120 kg $ha^{-1}mm^{-1}$ for potato.

Because of adverse weather conditions during the harvest period such as long-term rain storms and hail, it can be impossible to harvest the full grown crop yield, i.e. weather-induced crop yield losses (Y_{LoHa}, t ha^{-1}) and yield quality losses are the consequence. The outcome may be different, ranging from waterlogged harvested material; loss caused by hail; loss caused by lodging of crops; harvesters being unable to access fields; flooding of fields; very late harvest, and others. Taking into account weather and yield statistics, an algorithm for climate-induced harvest loss was developed:

$$Y_{LoHa} = -\,0.1 \begin{cases} 0\,;\, NiTage \le miNiTage \\ A + B * NiTage + \begin{cases} 0\,;\, Ni\Sigma \le miNi\Sigma \\ C + D * \begin{cases} Ni\Sigma\,;\, miNi\Sigma < Ni\Sigma \le maNi\Sigma \\ maNi\Sigma\,;\quad Ni\Sigma > maNi\Sigma \end{cases} \end{cases} \end{cases} \tag{6}$$

where NiTage – number of days with precipitation (> 0 mm) within the mean harvest period (MHP); miNiTage – long-term average of number of days with precipitation within MHP; Ni∑ - precipitation sum within the MHP (mm); miNi∑ - long-term average of precipitation sum within the MHP (mm); maNi∑ - maximum of precipitation sum within the MHT (mm); A, B, C, D – statistic parameters.

A detailed description of the YIELDSTAT model together with a model validation at three different spatial scales (experimental station, county, state) for the Federal State of Thuringia, Germany, are given in Mirschel et al. (2014).

6. Conclusions

As with ecological and environmental modeling, in crop growth modeling, there is not one single approach that can be applied to all spatial scales to address model crop biomass or crop yield. Due to spatial heterogeneity, natural variability and the limited availability of input data, it is evident that not only do the chosen model approaches produce certain errors which are revealed when comparisons are made with the data for developing and testing the models, but the data itself also cannot be regarded as reliable. Therefore it is unwise to search for an optimum modeling approach that can be used across all scales. Instead, it is advisable to find the best suitable modeling approach according to the scale of the project.

Determining the influence of spatial scale data on the selection of the modeling methods, however, is more difficult and warrants additional research in the future. The choice of modeling approach should be based on the problem being tackled and should be dependent on the spatial scale for which crop growth modeling is realized. It is better not to recycle an existing model, but to clearly express the model demands around the task in hand and to develop a modeling approach that is appropriate for the spatial scale of the project.

If the accuracy of the description of the final biomass accumulation or yield at harvest is the only criterion for choosing a certain approach, simple tried and tested models can be used.

In cases where diversity in the data for model development is significant and the relationships between variables are only vaguely understood, artificial neural network models are a suitable approach for finding appropriate nonlinear model structures for crop growth processes.

The advantages of complex plant physiological-based algorithmic models do not lie in more accurate forecasts, but in their ability to evaluate processes and interactions between different system parts more effectively and to express side effects.

If it is possible to regionalize model driving forces, inputs and parameters with a reasonable effort and to restrict model modifications to a minimum, for the most important agricultural crops it is possible to use originally field-related, physiologically based models as AGROSIM, MONICA or AGROTOOL also for practically oriented applications on higher spatial scales, but these are not appropriate for the landscape scale.

Because of the wide range of different arable crops and grassland types, limited data sources and the absence of specific management and cultivar information from agro-landscapes, on this scale, generic crop growth models are more successful options for biomass and yield modeling.

Nevertheless, in the science of crop growth modeling, various problems remain unsolved and others have only been partially resolved. Three examples of these problems are (1) the degree of generalization depending on spatial scale; (2) the long-term reliability of certain model approaches; and (3) the robustness of using models for large-scale projects, i.e. whole landscapes.

The special challenge in crop growth modeling, i.e. modeling biomass growth and yield formation, is to find a balance between the modeling goal, input data availability (quantity and quality), spatial scale, and the model's approach for obtaining resilient and robust results.

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