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Model-based Calculation of Fuel Consumption within Agricultural Process Chains

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Many factors determine the fuel consumption of agricultural process chains. The farm structure, the machinery and equipment or the type and design of process steps are some examples. A simulation model developed within the research project "Efficient fuel use in agricultural technology" (EKoTech) enables model-based calculations of fuel consumption during plant production. Model farms provide the basis for the simulation computations. They describe relevant representative agricultural regions in Germany and other European countries for various process chains as a virtual image of an average farm in the respective region. The presented simulation results quantify the development of fuel consumption in the identified process chains from 1990 through 2015 to 2030 and estimate the saving potentials of selected technologies for a fuel consumption reduction.

Keywords
Efficiency, simulation, fuel consumption

With the ratification of the Paris Agreement on climate change in December 2015, the European Union (EU) reaffirmed the goal of limiting global temperature rise compared to pre-industrial levels (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2015). The effort sharing decision (Europäisches Parlament und Rat der Europäischen Union 2018) aims to ensure that member states achieve reported reductions of greenhouse gas emissions by 2030 in specified sectors. The German Federal Government's strategy (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019) based on that decision provides for a 34% reduction in emissions in the agricultural area in comparison with 1990. The sources of greenhouse gas emissions in this sector include methane and nitrous oxide emissions from livestock farming and fertilization as well as CO_2 emissions resulting from the combustion of diesel fuel in agricultural machinery. The BMEL (Federal Ministry of Food and Agriculture) considers an increase in the energy efficiency of technology used in agriculture (BUNDESTAG 2019) as one measure for achieving the ambitious goals.

A suitable approach to evaluate the effectiveness of technical solutions in terms of energy consumption is the "Method for determining the CO_2 emissions of agricultural machinery in a process chain" presented by (Hanke et al. 2014). Within this approach, simulation calculations shall provide statements about specific results of reduction efforts regarding CO_2 emissions, under consideration of the versatility of agricultural production methods. The EKoTech collaborative project followed up this concept. Based on individual interviews with farmers in different regions in Germany and Europe, project partners developed typical production processes in form of model farms for different times of observation 1990 and 2015 as well as obvious development scenarios for 2030. In terms of the savings potentials included in this model farms, the 4-pillar model of the European Agricultural Machinery Manufacturers' Association (CEMA) and the European Construction Equipment Manufac-

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turers' Association (CECE) allows a breakdown into the areas of machine efficiency, process efficiency, operation and alternative energy sources (CECE/CEMA 2007). This paper shows the calculation of fuel demands of these multifaceted agricultural process chains using developed simulation models for individual machines and processes. The results show the impact of regional developments of machines, area structures and process characteristics on the energy demand of agricultural production at the considered times of observation and present possible future developments.

Methodical Structure of the Simulation Model

Published literature shows different approaches to calculate fuel requirements in agriculture. The Association for Technology and Structures in Agriculture (KTBL 2016) provides a comprehensive work with data on area-related fuel consumption of agricultural process steps. Further data has been published by the ASABE (2006). Measurements of fuel consumption under real field conditions and on test benches have been available to the public for various machine types since 1920 through the "Nebraska Tractor Test" (Hoy and Kocher 2020) and with the introduction of the "PowerMix" by means of the DLG test centre in Groß-Umstadt. Ortiz-Canavate et al. (2009) presented a method to evaluate the efficiency by deriving indicator-based energy efficiency classes from OECD measurements and applied it to the Spanish tractor market. An isolated view of the tractor was essential for this investigation. The potential for savings in the field of soil cultivation were demonstrated experimentally using examples of implements and cultivation methods by Moitzi et al. (2014) and Rusu (2014). When considering fuel consumption and saving potentials of entire process chains and operations, the variety of machine and operational influencing factors and the number of machine combinations as well as of processes and process steps makes a trial-based investigation difficult. Simulation models offer an alternative approach for the evaluation. A model presented by Dalgaard et al. (2001) for comparing the consumption of fossil energy sources between ecological and conventional field cultivation uses area-specific general values from databases to determine the fuel requirement. These values are limited in their reflection of the development of agricultural technology and they do not allow a sufficiently detailed representation of savings resulting from technical measures. A more detailed investigation offers the determination of part times of individual subtasks during fieldwork and their weighting with machine-specific and time-related fuel requirements, as it is presented e.g. for harvest process chains of silage maize (Sonnen 2007).

To calculate the development of fuel consumption and the corresponding savings potential, the following analysis uses typical farms and process chains in order to define the general conditions. Within the EKoTech-Project, the Thünen-Institute has established virtual model farms in different locations in Germany and Europe due to local focus group discussions. Those represent the typical form of agriculture of the particular area for the reference year 1990, the year 2015 and in 2 scenarios (conservative and optimistic) for the year 2030. Each model farm reflects the local practices and equipment for growing a distinctive crop at that given time. The information serve as input data for a simulation model to calculate fuel consumption during field cultivation.

Therefore, two separate model approaches form the overall model. Under consideration of certain input values, different machine models calculate time-related fuel requirements for quasi-static states based on degrees of efficiency, efficiency curves and regressions for power requirements of individual components. Within a process model, the respective part times for machine combinations are determined while depicting the process chains of the farms. In addition to characteristics of the machine combinations and process steps, regional information about the field structures and the road network are used. The link between those two modelling approaches is the time structure scheme of the KTBL. The total fuel requirement of a farm results from the sum of all calculated consumptions of individual process steps and fields. Figure 1 shows the general approach for the model-based calculation of fuel consumption of agricultural process chains.

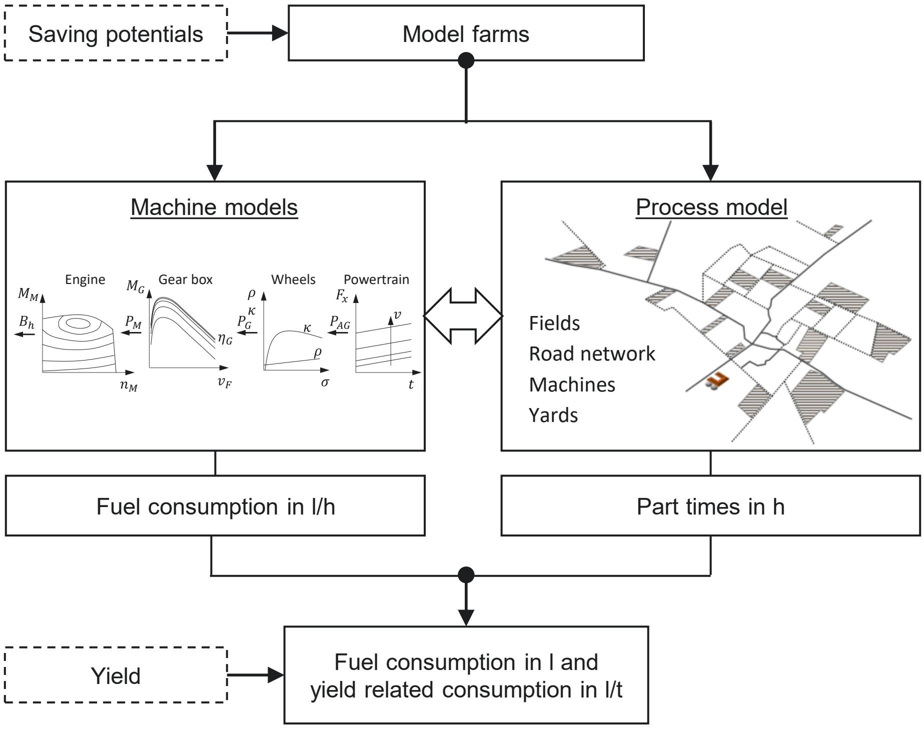


Figure 1: Structure of the master simulation model

The model farm structure defines necessary information to calculate the fuel consumption of individual process steps and entire process chains for the simulation model. The key parameters of a farm are the cultivated cropland and/or grassland, the average field size and the typical distances between the farm and the fields. Together with satellite images and a fictitious location, these data made it possible to create field structures of the farms. The analysis of the years 1990, 2015 and the future scenarios for 2030 provided a representative picture of regional developments in land use. Information from soil maps and statements from the surveyed farmers allowed a categorisation of cultivated fields into five soil classes. With the help of statistical evaluations of public yield data, it was also possible to assign forecast harvest quantities to the fields.

On each farm, appropriate machine classes define the machinery equipment of the tractors, harvesters and implements. A manufacturer-independent standardization could be achieved by using the machine classification of the KTBL (2016). This classification scheme based primarily on a differentiation of the nominal motor power, the processing width and the storage volumes. In addition to these parameters, the classes define total masses, tyre sizes, maximum speeds and geometric dimensions. Within the EKoTech project, the classes of the respective machines and implements got further detailed features to meet the technical developments between the considered years. An excerpt of these features shows Figure 2.

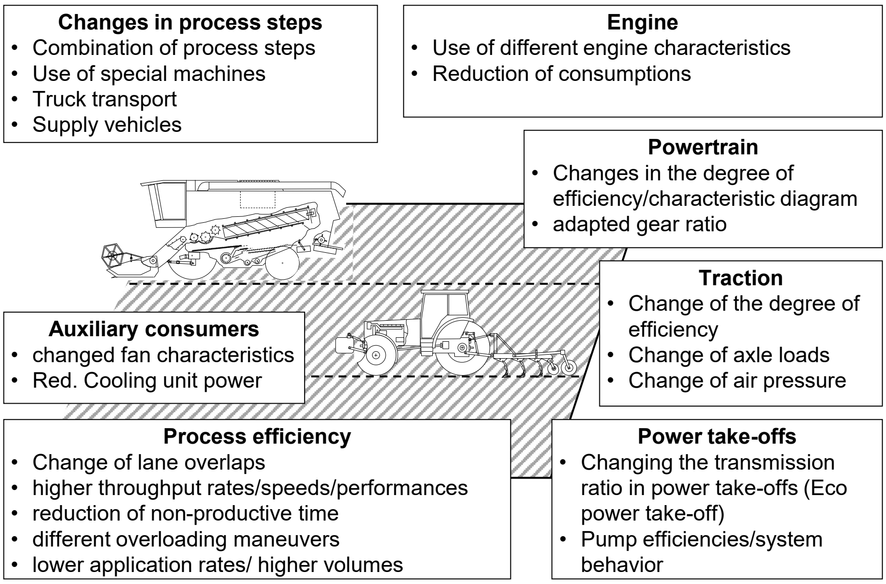


Figure 2: Options for illustrating fuel saving technologies

In the field of tractors, the extended properties include, for example, modified engine characteristics, improvements in transmission efficiency, the traction efficiency of various tyre models, changes in the drive power required by auxiliary consumers or the type of working hydraulics (constant flow or load-sensing). The equipment attributes also represent technical developments and innovations. It helped us to calculate individual fuel saving potentials for the technological developments using selected farms as examples.

The operation of a machine or machine combination has a significant influence on fuel requirement. Thus the process step and process step properties very much determines the consumption. Therefore, each model farm describes, in addition to the machinery, a typical process chain for the cultivation of the examined crop. It specifies respective process steps in the form of involved machine combination(s) and the individual characteristics (Figure 3). In terms of tillage, these properties include, for example, the velocity during working operation or the turning process, the working depth and an effective working width. Operations with inputs to be applied such as seeds or fertiliser have as additional information the area-related application rates, the material density and a definition of the type of overloading (on the farm, in the field, by a supplier) with a specific overloading capacity. Additionally, process steps can be characterised by the use of technical developments such as track guidance systems or adapted ballasting by wheel or front weights.

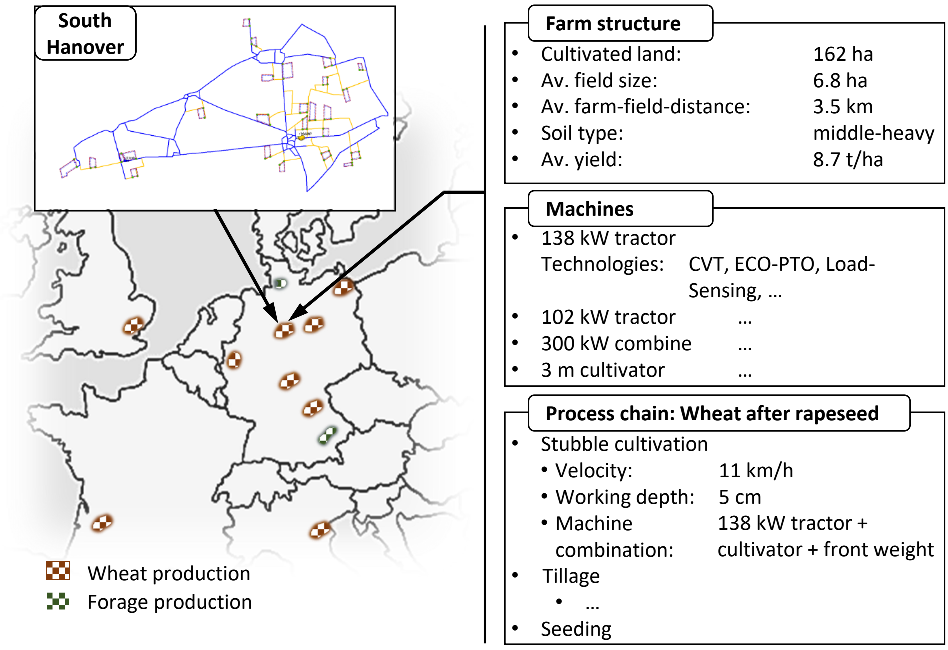


Figure 3: Characterization of the model farms exemplified by *South Hanover*

In total, the project-partners created model farms for thirteen regions in four different scenarios for the considered years of observation. With nine regions, most of these farms represent agricultural process chains in Germany. Moreover, model farms for areas in England and France and two farms for Italy were developed. The intention of the high regional coverage was a broad applicability of the results. Due to the time required, for most of the farms only one process chain was taken into account, but the preceding crop is the one from the real, multi-segmented crop rotation. We anticipated that the variance in process chains would result from the diverse composition of the different model farms and would be as meaningful as the illustration of a few model farms, each with several process chains. An example of a model farm in the region of South Hanover showed the inaccuracies associated with this simplification. In that case, the farm settings contain all process chains of a typical crop rotation for this region. The results of the evaluation support the chosen approach. In Addition, further scenarios for the farm implemented specific agricultural cultivation methods to reduce the use of herbicides. Therefore, two complete crop rotations with three and five crops represent future development scenarios for the region of South Hanover.

Generally, an iterative process within the design of the model farms defined the parameters and attributes. The participants were regional farmers and consultants as well as partners from industry and science. Statistical data predicted yield forecasts for future scenarios and verified information from surveys. Spreadsheets document the farms. The simulation model uses these farm properties to calculate the fuel requirements and part times.

The user inputs information via a graphical interface. Yards and fields are to be set on an underlying map as coordinates points. The individual fields get characteristic parameters and a process chain. The machine combinations can be determined for each process step. Additionally, the information on process specific characteristics as well as further remarks on the process sequence are necessary. During the execution of the simulation, the system creates at first job orders based for different fields on the steps within the process chain. Each job is addressed to a defined machine combination, consisting of the identification numbers of the extended machine classes for the tractor vehicle and the equipment. The jobs also describe the process step with the respective values for operating speeds, working depths, working widths and application rates. The field specifies corresponding parameters, such as the soil class, the soil condition because of the previous operation, the yield and a calculated average field incline value.

Based on this information, the machine models can calculate the time-related fuel requirements and, if relevant, deviating operating speeds of the respective machine combination for statically operating points. The specification of these operating points is based on the time structuring scheme of the KTBL (Winkler and Frisch 2014). Essential for the fuel consumption calculation are the actual operation, loaded and unloaded travels both in the field and on the road, the turning process, the loading and unloading as well as the idling of the machine during a process-related waiting period or the preparation or post-processing of a job. An exchange file renders the results available for the process model. Here, an agent-based simulation map the process steps on the farmlands structure. During the simulation, the system records individual part times according to the time scheme for each machine combination. The following section provides a more detailed description of the model. The temporary fuel consumptions multiplied with each time segment result in the absolute fuel consumptions. Thus, the requirement for operating part times within a job are available. The fuel requirement of a machine combination, a process step as well as for the entire process chain of the farm are the sum of the separate job orders.

Process model

The analysis of agricultural methods with the help of model simulations allows an individual reproduction of processes during field operations. Mathematical theories, used to describe the real world situation, enable the representation of different variants and times of observation - at present, in perspective and retrospectively. Event-based simulation models are described e.g. by Kübler et al. (2006), Sonnen (2007) and Bochtis et al. (2013). Mathematical analytical approaches were presented by Fechner (2016) and Steckel (2018).

The claim of the process simulation within the EKoTech project is the determination of required times for individual subtasks in different process steps. For this purpose, the Institute of Mobile Machines and Commercial Vehicles at TU Braunschweig has developed an object-oriented simulation model, which depicts the farm structure and simulates the processes. The process model is based on the solution presented by Hanke et al. (2018). In a simulation environment, the machines or machine combinations perform in the form of agents realistic and process dependent actions. These generally consist of various supply and set-up processes and the travelling of paths both in the field and on the road. For time calculations during the process sequences, the system records the times required for individual subtasks such as turning, operation, loaded and unloaded travel. The methodology and the detailed design of the model are described by Frerichs et al. (2017), Hanke et al. (2018) and Trösken et al. (2018). Simulations of individual field operations with path and speed-based calculations of part times can also be found in the process models of Jensen et al. (2015a), Jensen et al. (2015b) and Zhou (2015).

In order to depict the entire fieldwork of a farm, the developed model allows the simulation of processes in various fields based on a considered process chain. The simulation software “Anylogic” provides a required framework for the chosen approach. With this framework, it is possible to create agents, which already have simple capabilities in their simulation environment, such as movement between two coordination points or interaction with each other. During the project, we extended the software by functions to map agricultural processes. These extensions have five modules. A presentation and description can be found in Hanke et al. (2018). The structure distinguishes between field generation, route planning, the modules of the farm facilities and machines, the organization and the simulation environment.

The process simulation generates at the beginning all agents with the help of input information of a model farm and assign the specified attributes. This includes setting the positions and storage capacities of the yards as well as the maximum speeds and storage volumes of machines. The generation of fields is based on corner point coordinates of real agricultural land. An algorithm maps the field within the cartographic framework of the simulation environment. Therefore, the coordinate points form a field polygon and with the help of machine combinations specific working widths, a headland and the main field. The following creation of subfields ensures a realistic planning of tracks and turning manoeuvres during the fieldwork.

From the height information of the GPS coordinates, a triangulation algorithm calculates an average inclination value for each field. Finally, the process chains are assigned to the individual fields. With the route-planning module, the regional road network of the free project *OpenStreetMap* extended the simulation environment. Routes between fields and operating points can be calculated and mapped because of this information. Thereby it is possible to differentiate between roads and field paths and to take inclines and speed limits into account. Paths in the field are calculated either according to (L. E. Dubins 1957), (J. A. Reeds, III and L. A. Shepp 1990) or (E. W. Dijkstra 1959) using the start and end points as well as further coordinates within the field.

Within the farms environment, the process chains are executable. The machine combinations process individual jobs by performing a sequence of defined actions. These basic actions comply with the KTBL time structuring scheme. Here, an essential part of the process model is the organization of these actions. Each agent contains a control system to select a next action for the current situation. A process step dependent state vector, consisting of the location as well as an internal and an external state, describes the situation of each agent (see Figure 4). To identify the status, the agent must perceive his environment and answer defined decision questions. During a training phase, the right options for action were given depending on these state vectors to the neuronal network of the agent control. After the training process, the agent uses its cyclically requested situation as an input vector of the agent control network to receive a vector as an output variable that reflects the next action to perform. Figure 4 shows the described procedure using the example of a transport unit during grain harvest

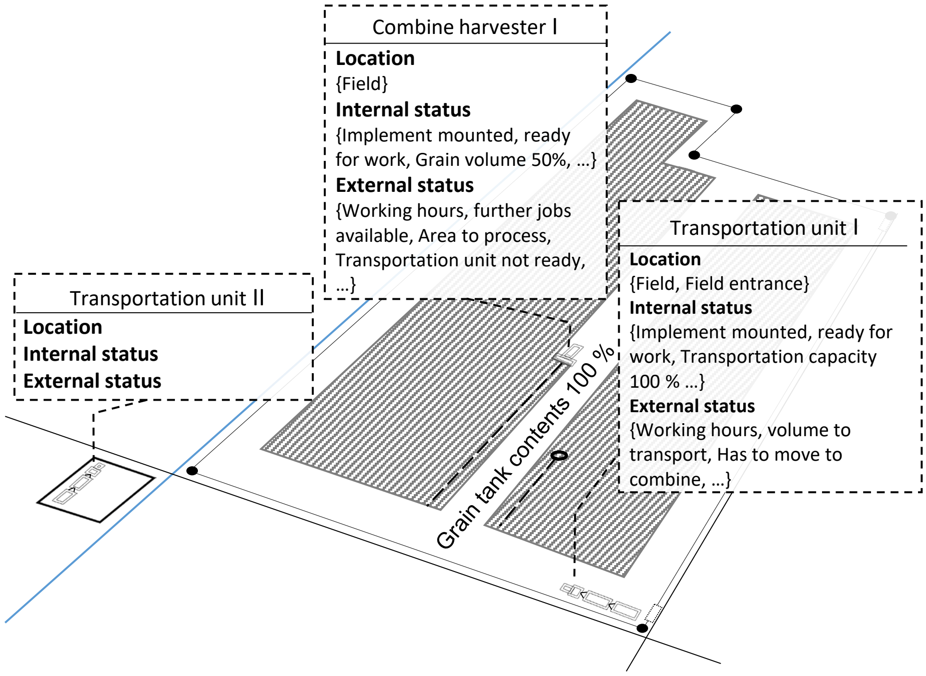


Figure 4: Process simulation on the example of transport during combine harvesting

The transportation unit I is located on the field next to the field entrance and has an assigned transport capacity. During the current action (process-related idle time) of the machine, the agent controller regularly checks the situation and can perceive the other agents. The combine harvester I is in operating mode and is working on one lane of the field. During this time, the level of the grain tank increases depending on the amount of yield, the working width and the working speed. As soon as grain level meets a threshold level, the situation of transportation unit I changes. The next action is to initiate the overloading manoeuvre by calculating an overloading section and driving the agent to the nearest overloading point using route planning and a set speed.

Meanwhile, the simulation environment record the required time and add it either to the operating time, loaded or unloaded travel in the job document, depending on the load status of the transport unit. Using the results of the machine model for this machine combination and part time, the system can calculate and record the fuel consumption in the job as well. Thus, the structure of the model makes time and fuel savings because of process and procedure changes representable. In addition, the differences in fuel consumption between model farms due to regional characteristics are evident.

Machine simulation

Time-related fuel consumption together with the part times from the process model form the overall fuel consumption on a model farm for each subtask according to the KTBL-time-scheme (Winkler and Frisch 2014). The Hohenheim Machine Model (HMM) has been developed for the calculation. Its structure is presented in Meiners et al. (2017) by taking the tractor as an example and will not be the focus here. The machine combination is the central element for which a fuel consumption in l/h can be simulated for any part time based on the load of the implement. Figure 5 shows the modular approach adopted in this context.

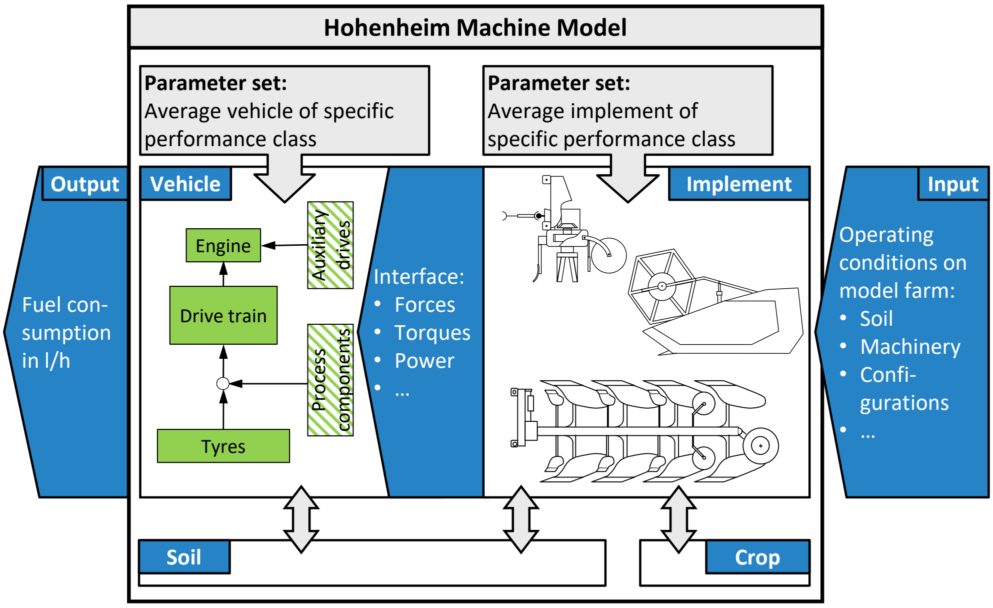


Figure 5: Modular set-up of the Hohenheim Machine Model for the simulation of time-related fuel consumption

One or more rear and front implements together with the vehicle form the machine combination. In the sub-models of the implements, the application-specific loads are calculated according to established literature approaches such as the ASABE standard (Harrigan and Rotz 1995) or using model equations derived from own measurements. This results in forces, torques and power requirements which are transferred to the vehicle model. Instead of a plough or a short disc harrow, the implement can also be a grain header, which in this case can only be used in combination with a combine harvester as vehicle.

From the loads applied to the vehicle, the modules for chassis, powertrain and engine with stored efficiency maps simulate fuel consumption in l/h for a stationary operating point. The approach is based on the simulation model developed by Schreiber (2006), which with slight modifications is also used by Weisbrodt (2016) for the analysis of fuel consumptions during the operation of tractors. Further development to include auxiliary drives (e.g. hydraulics or a power take-off) for use in the EKoTech project completes the range of applications. With dedicated modules for process components, the vehicle model was enhanced to a self-propelled harvester.

In the case of the combine harvester, for example, the threshing unit, residual grain separation, cleaning system including grain recovery, straw chopper, straw distribution, grain tank auger and working hydraulics are integrated here. The process power results from the sum of the component power requirements. This is derived both component-specific and operating point-specific as a constant characteristic value, from a characteristic curve over one influencing parameter or from a characteristic map over several influencing parameters. The resulting power is applied to the combustion engine parallel to the power requirement of the drive train. By replacing individual components, such as the threshing unit, different combine harvester designs can be realized simply by changing the parameter set of the process components. The operating conditions are defined by the model farm. This includes, for example, the soil conditions and yields, the concrete individual machine combinations with their settings, as well as the available technologies or savings potentials and the subtasks to be simulated.

As the parameterization of the models is done for average machines of a performance class according to the KTBL scheme (KTBL 2016) , a certain level of general relevance and manufacturer independency of the simulation results is guaranteed within the selected performance class. Self-propelled machines require more extensive parameterization due to the process components. Using the example of a hybrid combine harvester with 300 kW nominal power, the set-up, parameterization and validation of the model are presented by Meiners and Böttinger (2018) and will not be further discussed here.

The modular and component-centred model structure opens up far-reaching possibilities for the implementation of innovations. Figure 2 shows an excerpt of possible links to specifically influence the model. For example, a modern tyre technology can be modelled by adjusting the net traction ratio/slip curve of the tyre-soil-model (Schreiber and Kutzbach 2008, Meiners et al. 2020). A load-sensing working hydraulics, on the other hand, is modelled via a changed system behaviour of the hydraulic system and changed efficiency maps of the hydraulic pump. For each technology defined within the project, an individual solution was found.

Results

Within one task of a machine combination, the individual results from the process model and the single machine model are added together for each part time, which gives the absolute fuel consumption in l of one subtask. If all part times are cumulated, the absolute consumption for a task is obtained, e.g. that of the combine harvester for harvesting a complete field. If this is also done for the tractors with grain carts and all fields are summed up, the consumption of diesel for the entire harvest can be calculated for the model farm. This is equivalent to the procedure for the other process steps in the entire process chain, so that finally the overall fuel consumption of the farm is determined. In order to make this value more accessible and to allow a certain comparability between individual farms, the two evaluation quantities area-related fuel consumption b_A (l/ha) and yield-related fuel consumption b_m (l/t) are useful. The overall consumption is related either to the cultivated area or to the total amount of yield harvested in one year. However, the latter can only be the basis of comparison if the crops are identical.

Calculation of fuel consumption in process chains

A breakdown of the area-related consumption for the individual process steps in the wheat process chain on the model farm *Magdeburger Börde* is shown in Figure 6. The process chains usually start after harvesting the previous crop, in this case rapeseed, so that tillage here includes stubble cultivation and primary soil tillage. The seedbed preparation is part of the sowing process. Transport processes of seeds, fertilizer, crop, etc., on the road and in the field, are assigned to the process step in which they occur. The individual measures for fertilisation and plant protection are listed cumulatively. The scenarios simulated on each model farm at the time steps 1990 and 2015, as the current status, and the two future scenarios for forecasting the development until 2030 are shown. The conservative future scenario continues the previous development of, for example, land growth, yield, machinery equipment and the market penetration of fuel-saving technologies. The optimistic estimation assumes favourable boundary conditions, especially in terms of the last point. Each scenario of a model farm reflects the cultivation of the typical process chain in the region with the typical machinery and the available setting of innovations under the typical structural conditions of the farm in the respective scenario.

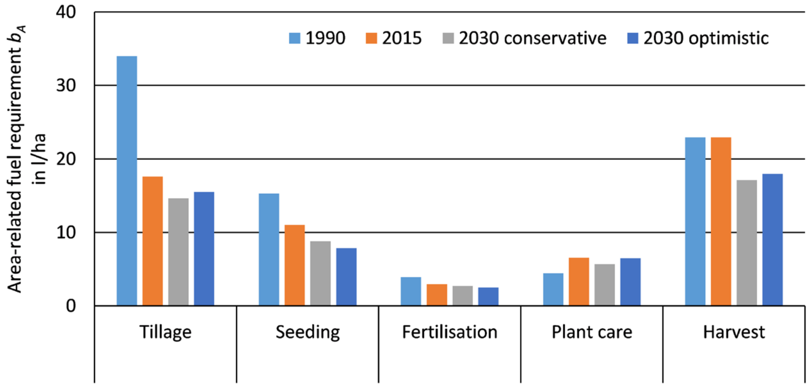


Figure 6: Area-related fuel consumption on the model farm Magdeburger Börde in the process chain “wheat after rapeseed”

In all scenarios, tillage and harvesting in the *Magdeburger Börde* region make up the largest share of fuel consumption, with the exception of 1990, when the harvest requires the most. The least is spent on fertilization. The remarkable reduction in consumption in tillage goes hand in hand with the conversion from ploughing to conservational soil tillage, which became feasible with the cultivator and seeding technology that was available for the new federal states from 1990 onwards. The same is true for seeding, as in the course of mulch seeding it was possible to omit extensive seedbed preparation. The reduction in consumption during harvesting cannot be seen in this diagram for this period, as the yield and thus the harvesting and transport effort has increased considerably in the same period. By 2030, the use of fuel-saving technologies and ongoing developments in all process steps will have a significant impact. However, the example of grain harvesting and crop protection also clearly shows that a further expansion of farm land will have a negative impact on fuel consumption in this case. The transport effort due to the assumed increase in distances from an average of 9 km (2030 conservative) to 11 km (2030 optimistic) cannot be compensated by further innovations.

On the model farm *Fränkische Platte*, primary soil tillage is carried out with the plough at a relatively shallow level in 1990 (Figure 7). In 2015 it switches to tillage without a plough, which is initially carried out more intensively in two separate steps, but is extensified by 2030. In the optimistic scenario, the seeding technique is changed to a mulch seeder in 2030 and is replaced otherwise by a combination of a conventional seed drill with a rotary harrow. Due to the smaller structure of the farm, the overall consumption is higher than in the *Magdeburger Börde*, which is particularly evident in the harvest and the associated transport processes due to the long farm-field distance. Here, too, the increase in yield has an effect on the area-related consumption.

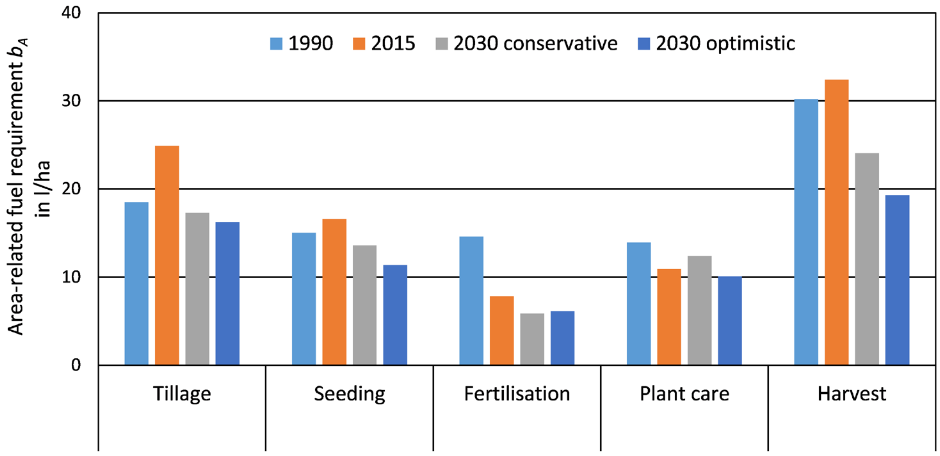


Figure 7: Area-related fuel consumption on the model farm *Fränkische Platte* in the process chain “wheat after rapeseed”

The simulation results for a process chain with silage maize cultivation are shown in Figure 8 for the model farm *Southern Bavaria*. Prior to the primary soil tillage, with exception of scenario 2030 optimistic ploughing is carried out here, an incorporation of the liquid manure with the cultivator (only 1990) or the compact disc harrow is done after each of the two cycles of organic fertilisation using a drip hose boom in both 2015 and 2030. From 2015 onwards, after the preceding crop and the first organic fertilisation, a catch crop is integrated into the process chain and in consequence a stubble cultivation of the preceding crop is required. The overall consumption for soil cultivation and seeding is relatively high due to the complex process chain, but despite the significant intensification from 1990 to 2015, it increases only slightly due to technological improvements and can be significantly reduced in the future. In 2030, for example, manure injection and seeding of the catch crop are combined.

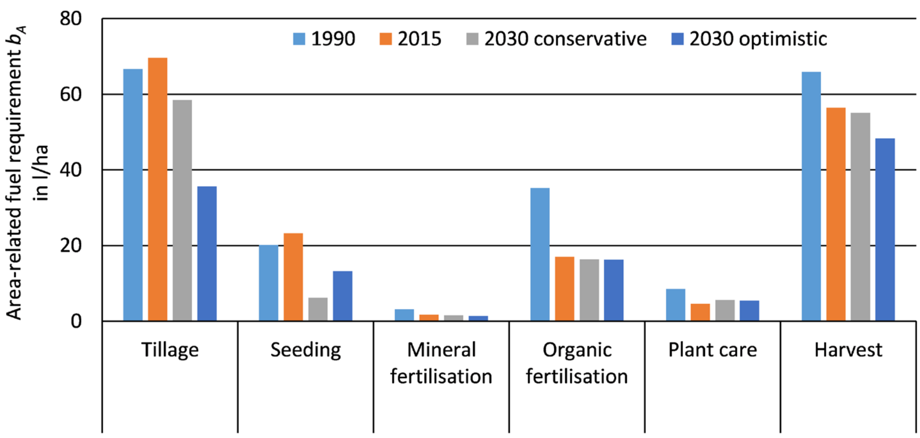


Figure 8: Area-related fuel consumption on the model farm *Southern Bavaria* in the process chain “silage maize after winter wheat”

Particularly in the case of organic fertilisation, it is becoming evident that area-related consumption can be reduced by 2030 because of increased transport volumes and more efficient tractors with a simultaneous increase in farm-field distance to over 200%. In addition, however, the application rate is also reduced by about 30% until 2015. Truck transport or the combined application and incorporation of organic fertilisers are not expected to become typical processes in this region until 2030 either.

In addition to silage maize, a second process chain for grassland is established on the model farm *Southern Bavaria*, Figure 9. In 1990, a total of four cuts are carried out here, which are increased to five in 2015. Each cut is preceded by an organic and a mineral fertilization. Consumption in organic and mineral fertilisation therefore shows no clear downward trend. Two developments introduced from 1990 onwards show effects on consumption on this model farm. On the one hand, the working widths of the mower, tedder and swather have increased considerably, which has led to a significant increase in the area efficiency and the load of the tractors. On the other hand, the increasing use of the ECO PTO, especially in the process steps of tedding and swathing, has led to a shift of the operating point in the engine characteristic map and thus to reduced consumption in low-load operation.

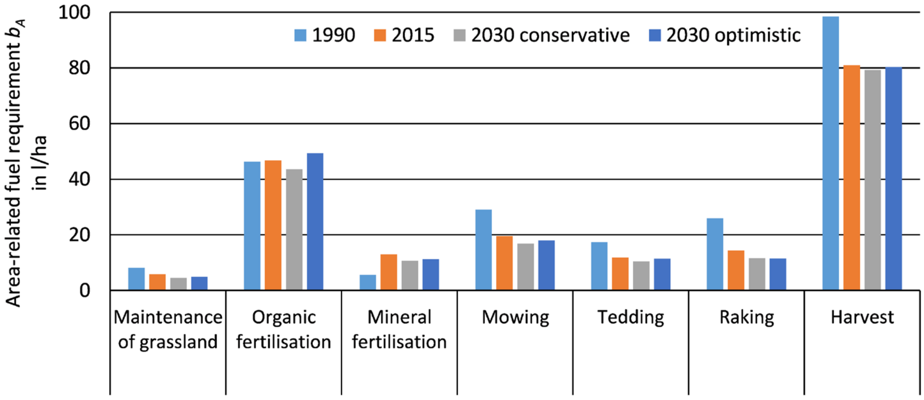


Figure 9: Area-related fuel consumption on the model farm *Southern Bavaria* in the process chain "grassland"

A comparison with data in literature verified the plausibility of the presented results on fuel requirements of individual elements of the process chains. The diesel consumption is mainly determined by the boundary conditions, such as the machine combination used, the process and field parameters as well as the application quantities and harvest yields. For this reason, there are sometimes very large variations in results (Moitzi and Boxberger 2009, KTBL 2016). Accompanying to the creation of the virtual farms by the focus groups, conducted by the Thünen-Institute, the attending farmers in each farm region provide information on area-related fuel consumption in the different process steps for 1990 and 2015. KTBL then subjected the results to a plausibility check. The consumption of individual process steps was determined based on farm information using the calculation tools of the KTBL. Figure 10 summarises the information provided by the regional focus groups and the values of the KTBL using the example of the model farm South Hanover and compares them with the results simulated for this farm.

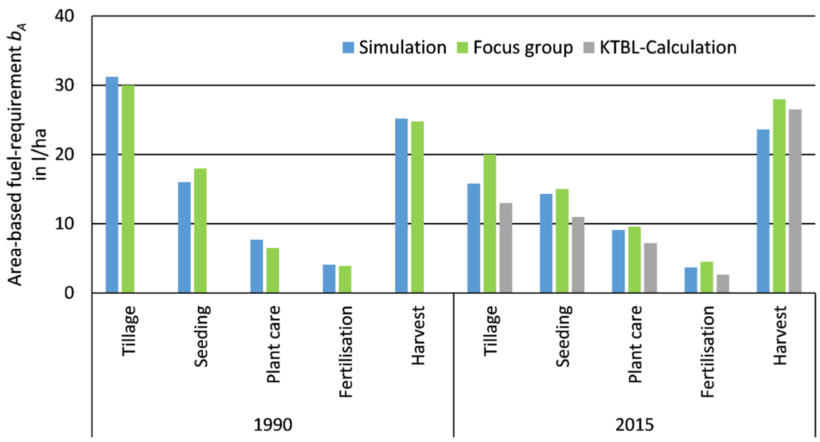


Figure 10: Plausibility check of the area-related fuel consumption on the model farm *South Han over* or the process chain "wheat after sugar beet"

With the exception of the 2015 harvest, the simulation is confirmed by the data from practice. The maximum deviation is 20%. The type and performance class of the combine harvester were subsequently changed to simulate the farm in 2015, so that the specified consumption is not comparable. The comparison between practice and simulation results turn out quite similar for the other model farms. By means of project-internal experts, such as the KTBL, and comparisons with literature, the results were fully verified for plausibility.

Figure 11 summarises the development on the model farms with grain cultivation from 1990 to 2030. For the nine farms included in the study, the area-related consumption is classified according to the process steps. In 1990 in particular, tillage accounts for a large share of overall consumption. The reduction potential here is the largest in both relative and absolute terms. Up to 53% are possible until 2030, whereas 30–40% are possible for seeding, plant care and harvesting. The effort required for soil cultivation differs greatly between farms, but converges to a certain extent in the course of the 40 years. At harvest, the effect of yield increase already observed above is confirmed across all farms, which does not show the actual reduction in consumption in the chosen form of the diagram.

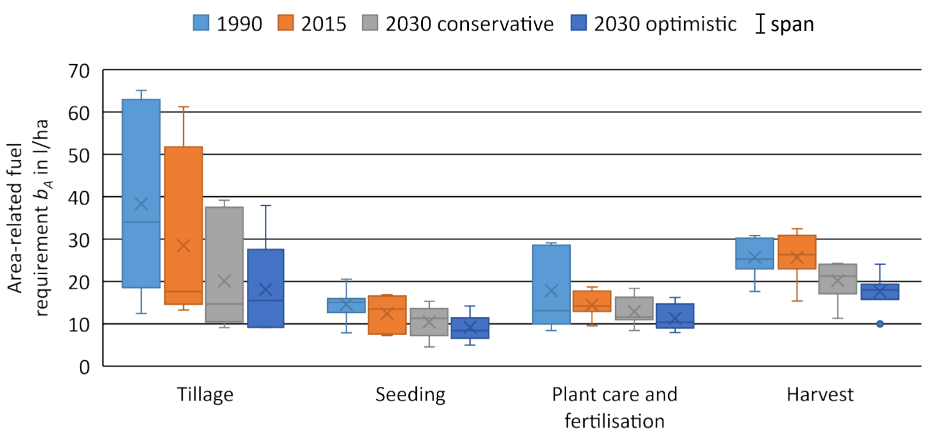


Figure 11: Average development of area-related fuel consumption since 1990 on the model farms with wheat production systems

If the results of the simulated model farms are expressed as yield-related consumption, they can be presented crop-specific as shown in Figure 12. For grassland and maize, two model farms lie behind the values. The increase in yield has been determined individually for each model farm within the project. In total, it can be seen that the reduction in fuel consumption that has already taken place from 1990 to 2015 is approximately 30% in wheat and grassland. For silage maize it is slightly higher. Until 2030, this trend can be continued in wheat and silage maize production, whereas the consumption in grassland remains at the level of 2015.

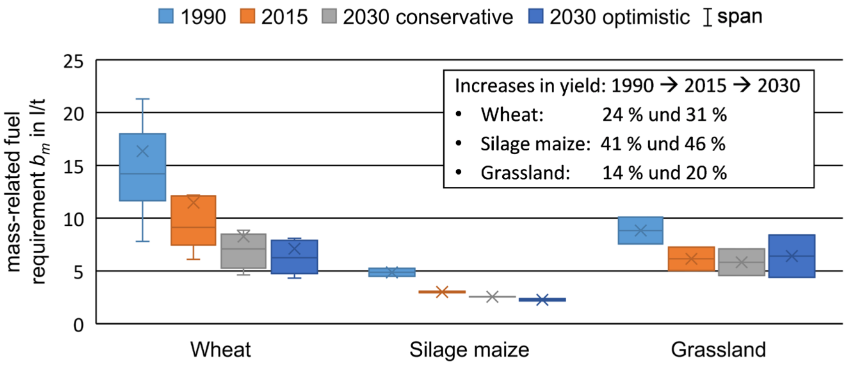


Figure 12: Average development of yield-related fuel consumption since 1990 on all model farms for the investigated crops

For 2030, the forecast is that an average reduction of up to 57% in the process chains for wheat production and an overall reduction in consumption of 35–40% can be predicted as realistic for the time period since 1990 under the boundary conditions examined (VDMA 2019). In any case, the political conditions must support the market penetration of the analysed innovations through free competition as assumed for the model regions. Focusing on legislative regulations concerning only the combustion engine will not lead to the results shown.

An empirical study by Moitzi et al. (2014) enables a correlation of these simulation results with empirical data. In the Central and Eastern European countries Austria, Serbia, Slovakia and Romania the fuel requirements of seven agricultural farms were measured. The cultivated area of the farms was very diverse, ranging from 115 to 1266 ha with average field sizes of 5 to 40 ha. For the 2012 season, the area-related fuel requirements during the production of winter wheat varied between 54 and 81 l/ha. The median of these farm-specific consumptions was 73 l/ha, the average value was 70.6 l/ha. Harvest yields of four to eight tonnes per hectare were achieved with an average value of 5.8 t/ha. The study shows an average fuel consumption for the production of winter wheat of 13.4 l/t in a wide range between 8 l/t and 18 l/t.

With an average of 83 l/ha (median 80 l/ha), the area-related simulation results for the model farms with wheat production in 2015 are about 10–15% higher than the values of the farms examined by Moitzi. In relation to the yield, the simulations show an average fuel consumption of 11.46 l/t. This corresponds to an approx. 15% lower demand. The average yield of the farms, which are mainly typical for regions in Western Europe, is 8.8 t/ha. The comparison shows that the results are of a similar scale. However, the significantly lower yields and the technology used in the Central and Eastern European farms surveyed lead to higher yield-related fuel requirement than those of the simulated model farms.

In addition, the yield level would suggest more extensive farming, which could be used to justify the lower area-related fuel consumption. For a more detailed discussion of the differences, however, the characteristic properties of the respective production systems would have to be considered. Information on process chains, machinery and farm structures is not included in the publication.

Calculation of fuel requirements in crop rotations

The above studies only take into account the most important crop grown on the respective farm and thus represent a so to speak single crop rotation (FF1). In addition to this, the simulation of complete and significantly more complex crop rotations for the year 2030 was analysed on the model farm *South Hanover*. The scenario of legislative requirements for the application of total herbicides was used as a hanger to classify the related increase in intensity in tillage, a possible extension of crop rotations and the integration of catch crops in the crop rotation in terms of fuel consumption.

For the presently predominant tripartite crop rotation (FF3) (rapeseed-winter wheat-stubble wheat/winter barley) all three process chains were designed and simulated. The result represents the basic scenario of the tripartite crop rotation. If this is set in relation to the isolated analysis of the main crop (FF1) and the averaged results of all examined model farms with wheat production, a comparison between the two approaches can be drawn based on the three diagrams in Figure 13 to classify the general system approach. With 60.9 l/ha in the reduced system approach FF1, the total consumption of 66.54 l/ha in FF3 is about 10% lower than the three-year average of 66.54 l/ha.

The reason for this is the significantly higher input for primary tillage in the two remaining crops. In the case of winter wheat after rapeseed, this is conducted comparatively shallow due to the previous crop, which results in a fuel requirement of only 16.2 l/ha. For stubble wheat and rapeseed, the process step becomes more intensive, so that an average of 21.2 l/ha is required. In relative terms, fertilisation also shows a strong increase in the annual area-related consumption from 3.4 l/ha to 4.6 l/ha by 35%. Especially with regard to rapeseed, basic fertilisation and liming measures are carried out in this region for the entire crop rotation, which is expressed in this increase. There are only minor deviations in the other process steps. In this specific example, soil tillage, in particular, is critically considered underrepresented in the overall result if only one element is selected from the crop rotation (Figure 13 A and B).

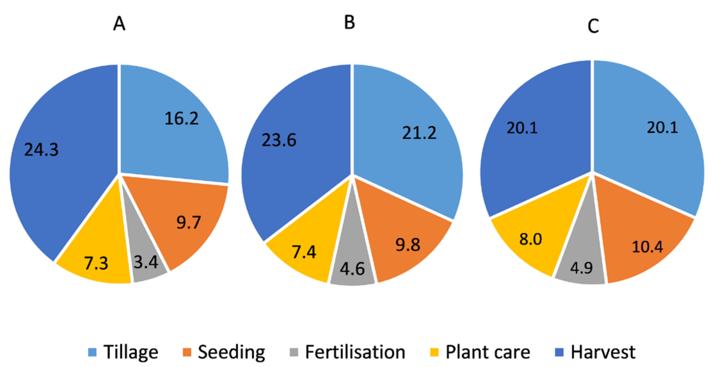
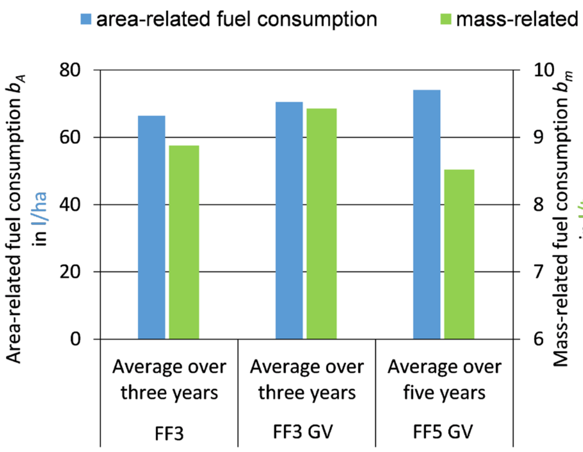


Figure 13: Area-related fuel consumption in litres per hour of individual process steps in the single (A) and tripartite (B) crop rotation in South Hanover and the average of the simulated grain farms (C) for scenarios in 2030

In general, it can be seen that, depending on the selection of the main crop from the crop rotation with the related preceding crop, there can be variations between the process steps and minor deviations in the total consumption of the process chains within one farm. However, the extent of this has to be assessed on an individual farm basis. The comparison of the distribution of the average fuel consumption of all simulated grain farms over the process steps of tillage, seeding, harvesting and plant care with the results in *South Hanover* (Figure 13 B and C) shows the deviations between the chosen method and the approach of a multiple crop rotation. It becomes clear that the different cultivation methods, preceding crops and farm structures of the examined model farms with grain cultivation lead to comparable distribution and also fuel consumption values in the production of grain and rapeseed on the model farm in *South Hanover*.

In response to a prohibition of total herbicides, two possible scenarios were drawn out. If tripartite crop rotation (FF3 GV) is maintained, soil tillage is carried out more intensively. Alternatively, the crop rotation is extended to five elements (FF5 GV) (rapeseed-winter wheat-catch crop/corn-winter wheat-winter barley) and at the same time a catch crop is added as preceding crop to corn. In discussions with experts from the Thünen-Institute and local consultants, this was identified as a potential process chain. Both scenarios were simulated and for comparison with the basic scenario the mean values of the area- and yield-related fuel consumption were calculated for all crops, fields and years of the examined period (Figure 14). Because of the restrictions in application of herbicides, both area- and yield-related consumption in the tripartite crop rotation increase by 6%. The assumptions are rather conservative, as the scenario assumes only one additional tilling operation to treat volunteer rapeseed in the process chain for winter wheat. Under certain conditions, several passes may be necessary, which would significantly increase the effect.



Yields by cultivated crop in t/ha		
	FF3 GV	FF5 GV
Rape seed	4.3	4.5
Wheat	9.5	9.5
Stubble wheat	8.6	9.0
Barley	9.0	9.5
Corn	-	11.0

Figure 14: Simulation of complete crop rotations and effects of a prohibition of total herbicides

In the five-part crop rotation, the area-related consumption increases by 12%. This is due to the additional, in parts more intensive soil tillage. A completely ploughless cultivation does not seem realistic here. Positive effects of the catch crop on the yield of the subsequent crops cannot be estimated with reliable certainty, which is why it further increases consumption. Yield-related consumption, on the other hand, will even be reduced by 4%. One explanation for this can be found in the high yield and, apart from the catch crop, the relatively low expenditure in the process chain for corn cultivation. If spring barley were grown, the result would be significantly different. The yield-related presentation reaches its limits here, although a comparison with the basic scenario is limited anyway due to the far-reaching changes in crop rotation. Possible decreases in yield caused by the elimination of the total herbicides cannot be plausibly included, but would cause a further increase in yield-related consumption.

With this analysis, it could be shown that the simulation model allows on the one hand to model and simulate several process chains on a farm and on the other hand, it also enables the simulation of a complete and complex crop rotation over several years. It should also be noted that a prohibition of total herbicides would result in an additional consumption of at least 6% for the considered scenario here. However, focusing on fuel consumption is not sufficient for further evaluation of the results. Economic aspects must be taken into account to support the conclusions.

Quantification of savings potentials

A second key application of the simulation environment is the quantification of the effect of individual innovations and savings potentials, after their impact was until now only shown in the simulation of model farms in combination with several innovations and always in interaction with structural and process changes. Here too, the framework for the simulation is set by a model farm. For each individual technology, the process steps are simulated in which an effect is achievable. Quantification is reached by comparing the calculated overall fuel consumption with activated and deactivated technology. The technologies are not simulated on all but only on the farms that promise maximum savings. Table 1 gives a summary of the examined technologies, lists the respective potential, which is always to be seen in the context of the model farms, and is considered the maximum value under the assumptions made for the simulation.

Table 1: Quantification of the savings potential of specific technologies

Process step	Machine; Technology	Savings potential
Primary tillage	Tractor; Load-Sensing-Hydraulics	4.1%
	Tractor; RTK steering system	6.6%
	Tractor; Optimisation of traction through a combination of ballasting, tyres and tyre pressure control system	14.9%
	Cultivator/plough; Reduction of working depth by 5 cm	13.8%/12.8%
Stubble cultivation	Replacing the cultivator with a compact disc harrow	29.6%
Seeding	Tractor; Load-Sensing-Hydraulics	13.3%
	Tractor; RTK steering system	0.6%
	Seed drill; Container volume increased by 500 l	6.6%
Continued on next page		
Plant care	Tractor; Load-Sensing-Hydraulics	4.2%
	Tractor; RTK steering system	1.8%
	Tractor; ECO-PTO	20,7%
	Sprayer; Application rate reduced by 50%	13.0%
	Sprayer; Container volume increased by 1000 l	7.3%
	Sprayer; Working width increased by 6 m	12.0%

Process step	Machine; Technology	Savings potential
Fertilizing	Tractor; Load-Sensing-Hydraulics	4.3%
	Tractor; RTK steering system	6.5%
	Tractor; ECO-PTO	8.1%
	Fertilizer; Container volume increased by 500 l	3.9%
	Fertilizer; Working width increased by 6 m	10.1%
Grassland	Tractor; ECO-PTO at tedding/swathing	9.3%/15.4%
Harvest - Wheat	Tractor; Transport; Load-Sensing-Hydraulics	3.7%
	Combine harvester; Cruise control	6.6%
	Combine harvester; Automatic machine optimisation	12.7%
	Combine harvester; RTK steering system	4.5%
Harvest - Silage maize	Forage harvester; Cruise control	3.5%
	Forage harvester; Automatic machine optimisation	7.0%
	Forage harvester; Adaption of engine characteristic curve at partial load	4.5%
Harvest - Grassland	Forage harvester; Cruise control	4.7%
	Forage harvester; Automatic machine optimisation	9.8%
	Forage harvester; Adaption of engine characteristic curve at partial load	8.3%

From this analysis, some recommendations for action can be derived for practical machine operation. The greatest savings potential generally comes into play when power does not have to be provided in the first place. A reduction in intensity through shallower soil cultivation, for example, or the use of implements optimised for a particular job, for example stubble cultivation, should be mentioned here.

It is equally important to reduce the power requirement of unused auxiliary consumers, for example by using load-sensing hydraulics. Furthermore, a differentiation must be made between tasks in which the load of the machines being used is high and those in which the machine combination is not being utilized to full capacity. With high load, such as heavy traction in the field, it is essential to optimise the traction conditions by ballasting, tyres and correct internal tyre pressure, whereby too high machine weights can have an equally negative effect on fuel consumption and in addition soil compaction. Low capacity loads of tractors and self-propelled harvesting machines should generally be avoided by maximising the output of the implements through an increased working widths or at least making optimum use of the existing equipment with RTK steering systems. Transport tasks should be reduced as much as possible by adjusting container volumes and application rates. In the case of self-propelled harvesters, systems for automatic machine optimisation are promising, as they constantly increase the load of the machine over the entire workday. However, optimisation can also be achieved during partial load operation by enabling shifts in the operating point in the engine characteristic map using appropriate technologies, thus increasing the efficiency of the engine. Low engine speeds and high torques are the goal hereby. ECO PTO shafts provide this effect in PTO-driven implements. Thanks to intelligent engine-transmission management and adapted ratios in the drivetrain, this can also be achieved for other work in partial load operation, such as transport. By adjusting the full-load characteristic curve of the engine, combine harvesters can also gain a consumption optimization at low engine load.

Conclusions

Based on the need to define the contribution of the agricultural machinery industry to the reduction of CO_2 emissions, a consortium of industry, science and associations has been working since 2016 in the EKoTech joint research project to develop a comprehensive methodology for evaluating technical measures with regard to fuel consumption. The virtual verification process requires a standardised framework, which could be found establishing model farms. For major production regions in Germany and selected European countries, non-existent farms were formed as an average virtual reproduction of the respective region. Their characteristic features provide the input for a simulation model that is able to calculate the fuel consumption in the process chains of the model farm. By splitting the absolute consumption (in l) into the two areas, time-related consumption (in l/h) and part times (in h), two sub-models detached from each other can be used. In the course of the project a machine and a process model were newly developed.

The simulation of the process chains and calculation of fuel consumption has shown that locally very different developments can be found due to the machine technological and structural conditions, which also differ between crops. An average reduction in consumption of 35–40% can be derived as a realistic value for the period from 1990 to 2030. This is made possible, among other things, by the technologies examined at machine and process level, which were individually examined in the second part of the results. These primarily aim at increasing the overall efficiency of the powertrain through intelligent operating point shifts in the engine characteristic map and an increase in traction as well as a reduction in the power requirement of auxiliary consumers. Steering systems, automatic machine optimisation and increased working widths and transport capacities enable an efficient use of the machines.

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