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Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen losses from cropland soil in Europe

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Abstract

For the comprehensive assessment of the policy impact on greenhouse gas emissions from agricultural soils both socio-economic aspects and the environmental heterogeneity of the landscape are important factors that must be considered. We developed a modelling framework that links the large-scale economic model for agriculture CAPRI with the bio-geochemistry model DNDC to simulate greenhouse gas fluxes, carbon stock changes and the nitrogen budget of agricultural soils in Europe. The framework allows the ex-ante simulation of agricultural or agri-environmental policy impacts on wide range of environmental problems such as climate change (greenhouse gas emissions), air pollution and groundwater pollution. Those environmental impacts can be analysed in the context of economic and social indicators as calculated by the economic model. The methodology consists in four steps (i) the definition of appropriate calculation units that can be considered as homogeneous in terms of economic behaviour and environmental response; (ii) downscaling of regional agricultural statistics and farm management information from a CAPRI simulation run into the spatial calculation units; (iii) setting up of environmental model scenarios and model runs; and finally (iv) aggregating results for interpretation. We show first results of the nitrogen budget in cropland for the area of fourteen countries of the European Union. These results, in terms of estimated nitrogen fluxes, must still be considered as illustrative as needs for improvements in input data (e.g. the soil map) and management data (yield estimates) have been identified and will be the focus of future work. Nevertheless, we highlight inter-dependencies between farmer's choices of land uses and the environmental impact of different cultivation systems.

1 Introduction

Both international obligations as well as European legislation ask for the assessment of agricultural practices regarding their effects on the environment, both for accurate

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estimations of the current source strengths and for assessing possible mitigation pathways. Prominent examples, are the nitrate directive (Council Directive 91/676/EEC) – setting a maximum allowable concentration of 50 mg NO₃ L⁻¹ water intended for human consumption – the National Emission Ceilings Directive 2001/91/EC (NECD) that requires an approximate 12% emission reduction of ammonia emissions from 1990 levels for the EU-15 and the reduction of greenhouse gas (GHG) emissions under the Kyoto Protocol (United Nations Framework Convention on Climate Change). Recommended procedure for the estimation of greenhouse gas emissions from agriculture have been developed by the Intergovernmental Panel on Climate Change (IPCC) and are described in detailed guidelines (IPCC, 1997, 2000, 2006). Procedures to derive for example greenhouse gas emissions from agricultural soils are associated with a huge uncertainty range, can not differentiate regional conditions, and are not able to accommodate the effect of proposed mitigation measures. Therefore, the development of reliable independent and flexible assessment tools is needed to (i) assess the response of the environmental system to socio-economically driven pressures, while reflecting the various feed-backs and interaction between natural drivers, (ii) to consider regional differences in the response in order to (iii) finally find regionally stratified emission factors or emission functions. Process-based models are tools that can be used, for example, in the frame of GHG inventories in the near future (Leip, 2005). They are adequate to analyze the impact of changing farming practices, as they are able to cope with the complex interplay of environment and anthropogenic activities.

The main obstacle to use process-based modelling tools for policy impact assessment in agriculture from the regional to continental scale so far was the difficulty to match agricultural activities with the environmental circumstances they are taking place (Liu et al., 2006; Mulligan, 2006), as the accuracy of simulated fluxes with process-based models such as DNDC (Denitrification Decomposition) Model (Li et al., 1992) is largely dependent on the quality of input data. DNDC showed to be especially sensitive to the soil organic matter (SOM) content of the soils and to nitrogen fertilizer application rates. If no a priori information is available, the range of calculated fluxes is determined

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by the range of SOM occurring in the region, for which statistical information is available. Uncertainties by a factor of 10 or more are common (Mulligan, 2006).

The smallest unit at which agricultural statistics for EU Member States are available are the so-called NUTS regions level two or three, which correspond to administrative areas of 160 km² to 440 km² (NUTS2) or 32 km² to 165 km² (NUTS3). Areas of this size span over a wide range of natural conditions: soil type, climate, and also morphology of the landscape. As the response of process based models to climate and soil parameters or agricultural management is non-linear, their application to regional averages of those input data leads to aggregation bias. Additionally, using regional averages hides possibly large differences at local scale, which is especially disturbing in case of legislation setting local thresholds. Additionally, main drivers of environmental pressures are not covered by regional statistics, as e.g. fertilizer application rates.

However, a comprehensive assessment needs to cover both livestock and crops to ensure consistent scenarios, considering for example feedbacks between animal numbers and cropland via fodder production or between stocking densities and manure application rates. These feedbacks are inherent in the large scale economic models such as CAPRI, which capture the complex interplay between the market and policy environment and the economic behaviour of the different agents (farmers, consumers, processors) from global to regional scale. Adding also the environment's response to anthropogenic pressures in a detailed manner in these models is technically not feasible.

Examples for policy-relevant process studies for agriculture at the continental scale exist for carbon sequestration (e.g., Smith et al., 2005b), nitrogen oxide emissions from forest soils (e.g., Kesik et al., 2005a), investigating different management practices (e.g., Grant et al., 2004); examples for studies regarding livestock systems can be found for dairy farming (Weiske et al., 2006) or grassland systems (Soussana et al., 2004). There are only few examples where an overall assessment is achieved through linking economic with process-based models (e.g., Neufeldt et al., 2006), but at a much lower scale.

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This paper will focus on the methodology developed to link the large-scale regionalised economic model CAPRI and DNDC as a biophysical model into a new policy impact simulation tool. Some preliminary results are presented. The tool allows the ex-ante simulation of agricultural or agri-environmental policy impacts on a wide range of environmental problems such as climate change (GHG emissions), air pollution and groundwater pollution. Those environmental impacts can be analysed in the context of economic and social indicators as calculated by the economic model. The analysis of the trade-off between and in-between the different pillars of sustainability of such policies is such inherently built into the tool presented. The quality of such a tool depends both on the understanding and appropriateness of the parameterization of the relationship between driving forces and environmental impact, but also on the use of appropriate initialization conditions. We will therefore critically examine the quality of important data sets.

2 Methods

2.1 Models

2.1.1 DNDC

Simulation of the partitioning of nitrogen losses is done with the mechanistic nutrient DNDC (DeNitrification DeComposition) model. DNDC has been developed in 1992 and since then improved continuously (Li, 2000; Li et al., 1992, 2006, 2004). DNDC is a biogeochemistry model for agro-ecosystems that can be applied both at the plot-scale and at the regional scale. It consists of two components, the first calculating the state of the soil-plant system such as soil chemical and physical status, vegetation growth and organic carbon mineralization, based on environmental and anthropogenic drivers (daily weather, soil properties, farm management). The second component uses the information on the soil environment to calculate the major processes involved in the ex-

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change of greenhouse gases with the atmosphere, i.e., nitrification, denitrification, and fermentation. The model thus is able to track production, consumption and emission of carbon and nitrogen oxides, ammonia, and methane. The model has been tested against numerous field data sets of nitrous oxide (N₂O) emissions and soil carbon dynamics (Li et al., 2005).

DNDC has been widely used also for regional modelling studies, amongst other in the USA (e.g., Tonitto et al., 2007), China (Li et al., 2006; Xu-Ri et al., 2003), India (Pathak et al., 2005), and Europe (e.g., Brown et al., 2002; Butterbach-Bahl et al., 2004; Neufeldt et al., 2006; Sleutel et al., 2006). Our simulations are done using DNDC V.89, however introducing several modifications allowing a more flexible simulation of a large number of pixel-cluster, as described in Sect. 2.6.1. These modifications enabled us to simulate an un-limited number of agricultural spatial modelling units with individual farm and crop parameterization and with the option to individually select up to 10 different crops to be simulated in a specific calculation unit.

2.1.2 CAPRI

The application of the DNDC model presented here is closely linked with the pan-European database and the agricultural economic model CAPRI (Common Agricultural Policy Regional Impact assessment) setting a framework based on official national and international statistics, the global agricultural market and trade systems, and the agricultural policy environment and responses of agents (farmers, consumers, processors) to changes in policies and markets. The main purpose of the CAPRI is the Pan-European ex-ante policy impact assessment from regional to global scale of different policies targeting European agriculture, e.g. premiums paid to farmers, border protection by tariffs or agri-environmental legislation. CAPRI is operationally installed at the European Commission, and had been applied in a wide range of studies and research projects, e.g. in a current study by DG-Environment on ammonia abatement measures. In the exercise described here, solely parts of the data set for the current base period are used, an average of the years 2001–2003. A detailed description of

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the CAPRI modelling system is given in Britz (2005). The modelling framework aims also at depicting the flow of nutrients through the production systems. Improvements on some elements were achieved in the present study, as described below. Additionally, a spatial layer was added.

5 2.1.3 CAPRI DNDC-EUROPE model link

An overview of the link between the two models is given in Fig. 1.

We combine a socio-economic database, defined at the level of administrative regions and designed to drive economic model CAPRI, and an environmental database in a geographical information system (GIS) environment, which is mainly used to drive the process-based model DNDC. This database contains also the agricultural land use and livestock density maps, which are derived using econometric methodologies as described in Sect. 2.3. Environmental and land use/management information is used together with the estimates of production levels and farm input (see Sect. 2.4.2) at the scale of the spatial calculation units, which are obtained within the CAPRI modelling framework, to define the scenario and set-up the aggregation level and final input database to run the DNDC model (Sects. 2.6). The set of environmental indicators contains both data on soil fluxes calculated with the process-based model and emissions from livestock production systems.

2.2 The spatial calculation unit

20 We chose four delimiters to define a spatial calculation unit, which in the following is also denoted as “Homogeneous Spatial Mapping Unit” (HSMU), i.e. soil, slope, land cover and administrative boundaries. The HSMU is regarded as similar both in terms of agronomic practices and the natural environment, embracing conditions that lead to similar emissions of greenhouse gases or other pollutants.

25 The HSMUs are built from four major data sources, which were available for the area of the European Union i.e. the European Soil Database V2.0 (European Commission,

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2004) with about 900 Soil Mapping Units, the CORINE Landcover map (European Topic Centre on Terrestrial Environment, 2000), and a Digital Elevation Model (CCM DEM 250, 2004). Prior to further processing all maps were re-sampled to a 1 km raster map (ETRS89 Lambert Azimuthal Equal Area 52N 10E, Annoni, 2005) geographically
5 consistent with the European Reference Grid and Coordinate Reference System proposed under INSPIRE (Infrastructure for Spatial Information in the European Community, Commission of the European Communities, 2004).

One HSMU is defined as the intersection of a soil mapping unit, one of 44 CORINE land cover classes, administrative boundaries at the NUTS 3 level (EC, 2003; Statistical
10 Office of the European Communities (EUROSTAT), 2003), and the slope according to the classification 0 degree, 1 degree, 2–3 degrees, 4–7 degrees and 8 or more degrees. As the HSMU of at least two single pixel of one square kilometre are not necessarily contiguous, we can speak from the HSMU as of “pixel cluster”.

2.3 Estimating agricultural production

15 2.3.1 Crop levels

Statistical information about agricultural production is obtained at the regional NUTS 2 or 3 level from the CAPRI database. This database contains official data obtained from the European statistical offices (available at <http://epp.eurostat.ec.europa.eu>) and are checked on their completeness and inherent consistency, and complemented with
20 management data to make them useable for modelling purposes (Britz et al., 2002). In the case of data gaps or controversial data, the problems are fixed with a well defined algorithm staying as close as possible to the original data source.

Data on crop areas are downscaled to the level of the HSMU using a two-step statistical approach combining prior estimates based on observed behaviour with a reconciliation procedure achieving consistency between the scales.
25

The first step develops statistical regression models for estimating crop shares (expressed as percentage crop area to total area of the pixel-cluster), simulating the prob-

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ability that at a certain point a crop is grown as function of regressed parameters and local landscape characteristics (climate, soil properties, land cover etc.). Those parameters are determined based on the “Locally Weighted Binomial Logit Estimation” technique (e.g. Anselin et al., 2004), estimated with a maximum likelihood estimator maximizing the probability that the observations that were obtained from the Land Use/Cover Area Frame Statistical Survey (LUCAS, European Commission, 2003a) are realized. To account for the possibility that other factors than natural conditions influence the choice of farmers to grow a specific crop, the weight of LUCAS observations is discounted with the distance from the respective HSMUs.

The second step determines the first and second moments of a priori estimates of the land use shares for each HSMU and for each of the 29 crops for which statistical information is available. Consistency with the regional statistics is then obtained with the Bayesian highest posterior density estimator (HPD, Heckeley et al., 2005), which allows in a transparent and elegant way to combine different pieces of information, using a covariance matrix calculated according to Green (2000). The results are the most probable cropping and further land use shares at HSMU level which exhaust the area of each HSMU and are in line with given regional crop and land use data or projections.

The area under analysis covers all 27 Member States of the European Union (EU27). As explained above, land cover is one of the delineation factors for the HSMUs which allowed exclusions of such HSMUs where we assumed that no agricultural cover should be present. However, a rather wide range of land cover classes comprising 11 agricultural or mixed agricultural CORINE land cover classes and 7 non-agricultural classes was maintained. As the definition of a CORINE mapping unit requires a minimum of 25 ha of homogeneous land cover, spatial units might include fractions of other CORINE classes, e.g. we typically find some grassland in forest areas and vice versa. In regions with predominant forest land cover significant percentages of the grassland reported in agricultural statistics might be “hidden” in forest CORINE classes while in regions with prevailing “pasture” according to CORINE this share might be negligible.

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The overall procedure tries to eliminate these negligible fractions of land use from the HSMU by manipulating the prior expectations. The statistical procedure is described in more detail in Kempen et al. (2007)¹.

2.3.2 Estimating animal stocking densities

5 Manure availability is linked to livestock density, and we further assume a close link between local manure availability and local application rates. In opposite to crops, there is no common Pan-European data base available which comprise at a high spatial resolution data on animal activity levels, necessary for the estimation of local parameter sets of regression functions for animal stocking densities. Instead, the data on herd
10 sizes from the Farm Structure Survey at NUTS III level (about 1000 regions for EU25) are regressed on data which are available or can be estimated at the level of single HSMUs: crop shares, crop yields, climate, slope, elevation, and economic indicators for group of crops as revenues or gross margins per ha. We will explain below how HSMU specific yields and economic performance indicators are derived. All explanatory
15 variables are offered in linear and quadratic form as well as square roots to an estimator which uses backward elimination, i.e., continues to exclude variables as long as the adjusted R^2 is increasing or as long as there are variables which are not equal to zero below the 2.5% significance level. Generally, the estimation is done for single Member States, however, in cases where not enough FSS regions are available for a
20 Member States, countries are grouped during the estimation. The regression is applied to the 14 animal activities covered in the CAPRI data base as well as for livestock unit weighted aggregates for ruminants, non-ruminants and all types of animals. The vast majority of the regressions yield adjusted R^2 above 80%. As expected, a low share of explained variance was found in a number of cases for area independent livestock
25 systems (pigs, poultry).

¹Kempen, M., Heckelei, T., Britz, W., Leip, A., and Koeble, R.: A Statistical Approach for Spatial Disaggregation of Crop Production in the EU, in preparation, 2007.

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Given the fact that the variance of the explanatory variables at HSMU level is far greater than in the FSS region sample per Member States, estimating at single HSMU level would be prone to yield outliers with a high variance regression error. Therefore, expected means for each variable and HSMU are obtained by using a distance and size weighted average of the explanatory variables of the surrounding HSMUs. Equally, the variance of the regression error per HSMU is determined from those HSMU specific averages of the explanatory variables. The resulting expected mean and variance are used as the a priori distribution of a Highest Posterior Density (HPD) estimator, approximating the t-distributed regression results with a normal distribution, so that after taking the logs of the likelihood function a quadratic function to maximise was obtained. The HPD determines those stocking densities at the level of HSMU which simultaneously recover the given herd sizes at the level of FSS region, ensure that the livestock densities per animal type aggregate up to stocking densities for ruminants, non-ruminants, and all types of animals and that the joint posterior density according to the distribution of the regression results is maximized.

2.4 Estimating agricultural management

The DNDC model requires the following agricultural management parameters: application rates and timing of mineral and organic fertilizer, tillage timing and technique, irrigation, sowing and harvesting dates, with more data such as additional information on crop phenology being optional.

2.4.1 Potential yield

DNDC simulates the crop growth using a logistic function (S-curve) which tries to obtain maximum obtainable nitrogen uptake and biomass carbon, which is pre-defined, at a daily time step. Partitioning total biomass into the plant's compartments (root, shoot, grain) at harvesting time is also given as default data in the crop library files (Li et al., 2004). In the absence of any limiting factors (nitrogen, soil water, radiation, etc.)

the pre-defined total plant carbon will be realized at harvesting time. If any stress of temperature, water or nitrogen occurs during the simulated crop growing season, a deduction of the biomass will be quantified by DNDC. We used statistical production data at the regional level, yields and area, down-scaled to the scale of HSMUs using information of potential yields for each soil polygon obtained from model simulations with the crop model WOFOST (van Diepen et al., 1989), as input values for the potential yield in DNDC.

The yields at HSMU level were used in the conjunction of input demand factors as applied to build the regional CAPRI data base to derive input coefficients per crop at the level of single HSMUs. Along with NUTS II prices for outputs and inputs, and data on agricultural subsidies, the resulting data set allows the calculation of economic performance indicators for crops at the level of HSMUs, which were used as possible explanatory variables for stocking densities.

2.4.2 Mineral and organic fertilizer application rates

Estimation of nitrogen application rate per crop at the level of HSMUs is based on a spatial dis-aggregation of estimated application rates at regional (NUTS II) level from the CAPRI regional data base. As there are no Pan-European statistics on regional application rates available, the estimation process in CAPRI at NUTS II level is briefly described. The challenge consists in defining application rates which are consistent with given boundary data – national mineral fertiliser use and manure nitrogen excreted from animals –, cover crop needs and lead to plausible distribution of nitrogen losses over crops and regions. The estimation is based on the Highest Posterior Density Estimator. Manure nitrogen in a region is defined as the difference between nitrogen intake via feed – either concentrates or regionally produced fodder – and nitrogen removals by selling animal products according to a farm-gate balance approach. Assuming no trade of nutrients across NUTS II boundaries, the available organic nitrogen must be exhausted by the estimated organic application rates. The same holds at the national level for total mineral nitrogen use in agriculture. Estimates at Member State level on

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mineral application rate for selected crops or groups of crops are available from the International Fertilizer Manufacturers Organization (FAO/IFA/IFDC/IPI/PPI, 2002) which provides as well statistics on total mineral fertilizer use in agriculture. The HDP estimator is set up as to minimize simultaneously the differences between the estimated and given national application rates and to stay close to typical shares of crop needs covered by organic nitrogen and assumed regional surpluses, ensuring via constraints that crop needs are covered and the available mineral and organic nitrogen is distributed. Upper bounds on organic application rates reflecting the nitrate directive are introduced for NUTS II regions comprising nitrate vulnerable zones.

The spatial distribution of the resulting regional application rates to single HSMUs is less demanding as in opposite to the regional distribution, interactions between crops or crop groups are not re-calculated. Based on the estimated crop yields, nitrogen removals per crop are defined and manure nitrogen application rates are estimated per crop and HSMU as described in the following. We estimate first an average of the NUTS II application rate surrounding the HSMU using the inverse distance in kilometre multiplied with the size of NUTS II region in square kilometre as weights. The same weights are used to define the average organic nitrogen available per hectare. The manure application rate per crop in the HSMU is obtained by the multiplication of three terms, i.e. (i) the average organic application rate as defined above; (ii) the relation between the crop specific nitrogen removal at HSMU level and the removal at NUTS II level; and (iii) a term depending on the relation between the organic nitrogen availability per hectare at HSMU level, which is obtained from the animals stocking density in the HSMU, the average manure availability as described above, and the size of the HSMU. The resulting estimated organic application rates per crop and HSMU are scaled with a uniform factor to match the given regional application rates. Summarizing, organic rates at HSMU will exceed average NUTS II rates if yields at HSMU are higher – which lead to higher nitrogen crop removal – or if stocking densities are higher driving up organic nitrogen availability.

Mineral application rates are defined as the difference between crop removals plus

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the relative surplus estimated at regional level minus the estimated organic application rate net of ammonia losses and atmospheric deposition. Those estimates are increased in case that assumed minimum application rates are not reached. As with organic rates, a uniform scaling factor lines the HSMU specific estimates up with the regional ones.

2.4.3 Crop sowing and harvesting dates

Crop sowing and harvesting dates are obtained from Bouraoui and Aloe (2007).

2.4.4 Number and timing of fertilizer and tillage

Number and timing of fertilizer and tillage applications is taken from the DNDC farm library (Li et al., 2004) taking for good the dates relative to sowing or harvesting and applying these time lags to the actually simulated sowing or harvesting dates, respectively.

2.4.5 Irrigation

The DNDC model treats irrigation such that a calculated water deficit is re-plenished to a pre-defined percentage. Irrigated cultures do not suffer any water deficit, while non-irrigated cultivation will feel water-stress when water demand by the plants exceeds the water supply. Percentage of irrigated area was calculated on the basis of the map of irrigated areas (Siebert et al., 2005), and was taken as fixed for all crops being cultivated within an HSMU.

2.4.6 Other management data

All other information needed to describe farm management and crop growth, such as tillage technique, maximum rooting depth and so on are taken from the DNDC default library and used as a constant for each crop for the whole of the simulated area.

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2.5 Environmental input data

2.5.1 Nitrogen deposition

Data on nitrogen concentration in precipitation was obtained from the Co-operative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP, 2001). EMEP reports the data as precipitation weighted arithmetic mean values in mg N L^{-1} as ammonium and nitrate measured at one of the permanent EMEP stations. We used the European coverage processed by Mulligan (2006).

2.5.2 Weather data

Daily weather data for the year 2000 were obtained from the JRC (MARS). The data originate from more than 1500 weather stations across Europe, which were spatially interpolated onto a $50 \text{ km} \times 50 \text{ km}$ grid by selecting the best combination of surrounding meteorological stations for each grid (Orlandi and Van der Goot, 2003).

2.5.3 Soil data

A series of $1 \text{ km} \times 1 \text{ km}$ soil rasters has been processed using pedo-transfer rules on the basis of the European Soil Database² (Hiederer et al., 2003).

The DNDC model requires initial content of total soil organic carbon data (SOC) in kg C kg^{-1} of soil including litter residue, microbes, humads and passive humus in the topsoil layer, clay content (%), bulk density (g cm^{-3}) and pH. The database contains under others rasters of topsoil organic carbon, texture, packing density, and base saturation. The latter two had been processed by Mulligan (2006) to obtain dry bulk density and pH, respectively, using linear relationships.

²Distribution version 2.0, http://eusoils.jrc.it/ESDB_Archive/ESDBv2/fr_intro.htm

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Soil organic carbon content has been derived using an extended CORINE land cover dataset, a digital elevation model (DEM) and mean annual temperature data (Jones et al., 2005). As DNDC has been parameterized for mineral soils, we restricted the simulations to spatial units with a topsoil organic content of less than 200 t ha⁻¹ (Smith et al., 2005a).

2.6 Model set-up

2.6.1 Adaptation of the model

Using the default version it was not possible to accommodate the degree of flexibility that was required in our study. Necessary adaptations regarded data handling; parameterization of the processes was according to (Li et al., 2004). First, it was necessary to allow for each modelling unit an individual number and selection of crops that are simulated; second, farm data such as fertilizer application rates are calculated individually for each simulation unit. In the default version of DNDC, the farm library is constant at province level. Third, potential yield is determined for each modelling unit; in the default version of DNDC the crop libraries are constant at national level. Last, for easier post-processing of the data, output files were grouped into single tables for each simulation year.

2.6.2 Set up of the simulation

The above-defined HSMU can be regarded as the smallest unit on which simulations can be carried out. This, however, is not always practical, as the high number of units is combined with a number of scenarios or if a multi-year simulation is carried out. Therefore, an intermediate step re-aggregates the HSMUs for each scenario that is simulated by the model, into model simulation units (MSUs) on the basis of both agronomic and environmental criteria. In this way, the design of the scenario calculations can be best matched with the objectives of the study.

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In our study, the objective of the simulation was to cover as much variability as possible in order to enable to assess the impact of the environment (represented in the model by daily weather data and soil parameters) and cultivation patterns. Therefore, for each region defined in the economic model (NUTS II), all crops that cover at least 5% of the agricultural area are included in the model. These crops were simulated on MSUs that had a crop share of more than 35% of the agricultural area within an agricultural unit (defined by a minimum of 40% of the area used for agriculture) or the crop share was at least 85% of the maximum share of the crop occurring in the region. Before eliminating single units, however, all units were clustered according to their similarity in the environmental conditions. To this purpose, a tolerance is defined for each parameter that gives the maximum spread allowed within a single cluster. For example topsoil organic matter content was clustered if the values differed less than $\pm 10\%$. The thresholds and tolerances used in this study are listed in Table 1. These moderate tolerances for soil conditions lead to an average number of more than 68 (up to 266) different soil conditions that were distinguished in each region, with add to 11 438 environmental situations for EU-15, out of which 6391 MSU were simulated with a total of 11 063 crop-MSU combinations. Each of these simulations runs over 99 years to smooth out unrealistic estimates for topsoil organic carbon in the original map.

We had complete information for 14 European countries, members of the European Union by 2004: Austria, Belgium, Finland, France, Germany, Greece, Luxembourg (simulated as part of Belgium), Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom. Statistical and weather information were centred on the year 2000. HSMU data for Ireland and the countries that joined the European Union in 2004 or 2007 have also been processed but are not yet included in the current simulation run. We simulated the following crops: cereals (soft and durum wheat, barley, oats, rye, maize, and rice), oil seeds (rape and sunflower), leguminous crops (soybean, pulses), sugar beets, potatoes, vegetables and fodder production on arable land.

We performed several scenario calculations to investigate the model's response to fertilizer input. Therefore, each simulation using the most probable management data

estimated as described in Sect. 2.4.2 was repeated without any input of mineral fertilizer or manure nitrogen. Additionally, each scenario was calculated under irrigated and non-irrigated conditions. The most probable situation is then calculated on the basis of the irrigation map described in Sect. 2.4.5 as a weighted average under irrigated and non-irrigated conditions. Simulation results were aggregated to the scale of the regions or countries as area-weighted averages.

3 Results

3.1 Homogeneous Spatial Mapping Units

The HSMUs cover a wide range of sizes from a minimum area of 1 km² but some reach very large areas (up to 9723 km²) in regions with a homogeneous landscape in terms of land cover and soil. The mean area of a homogeneous spatial mapping unit, indicates the range of environmental diversity with regard to land cover, administrative, data, soil and slope, and ranges from 7 km² for Slovenia to 94 km² for Finland with an European average around 21 km² (see Table 2 and Fig. 3). In total, a number of 206 000 HSMUs cover almost 4.3 million km² in Europe. Small discrepancies in the surface area of countries stem from rounding errors during the re-sampling procedure and are higher in areas with a high geographical fragmentation (i.e., small islands, complex coastlines or borders). For EU27 we obtained in total about 138 000 HSMUs in which agricultural activities (arable land and grassland) occur, occupying about 77% of the European landscape.

3.2 Land Use and livestock density maps

Figure 4 shows a summary of the land use and livestock density maps as total agricultural area (UAAR) and total livestock units (LU/ha) in Europe. The figures are superimposed to a hill-shade and show the relationship of topography and UAA. In these

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spatial units the average area used for agriculture amounts to 47%, ranging from 8% in Finland and Sweden to more than 70% in the United Kingdom and Ireland. Differences are found between the “old” Member States (EU15), being a member of the European Union already before 1 May 2004 and the “new” Member States that became member of the EU at or after this date (EU12). For EU15, the 75% of the area belongs to a spatial unit with some agricultural use and only a little bit more than half of the area has agricultural use of more than 5%. EU12 countries have less intensive agricultural systems, and most of the surface is covered by HSMUs with some agricultural use (89%) and only 20% of the surface area has less or equal than 5% of agricultural land use. Other examples of agricultural land use maps obtained are shown in Fig. 5 for barley and permanent grassland for the year 2000.

The livestock density maps highlight the huge variance in stocking densities found in Europe linked to differences in farming systems and natural conditions. Highest stocking densities are found in parts of The Netherlands, Belgium, some German counties close to The Netherlands and Belgium, Bretagne and the Po flat in Italy. In all those cases, mixed farming systems are found both featuring ruminants and non-ruminants, and fattening processes based on concentrates. The lowest stocking densities are linked to regions where specialized crop farms are the main production system, often found where over time large-scale arable farming under favorite conditions developed. A classical example is the French plain north of Paris. Where heritage laws or other factors favored the development of smaller farms, a low land-to-man ratio rendered it useful to generate added value to crop products by fattening processes. Here, stocking densities are often in average ranges, and where part-time farming is prevalent, have declined over time.

Despite the strong link between permanent grass land and ruminants, the link between stocking densities and grass land shares is not obvious as stocking densities in grass land regions depends to a large extent on grass land productivity. In mountainous areas, low grass land yields typically lead to semi-natural grass lands with rather low stocking densities. The same holds for regions with very low average temperature,

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and in some cases, for regions with low rainfall under rainfed farming conditions. However, as statistics or land use cover maps may not account semi-natural grass land as Utilizable Agricultural Area, the stocking density map may show a combination of higher stocking densities and lower shares of agricultural area in some regions, where in reality, lower stocking densities are linked with semi-natural grass land.

Local hot spots are possible almost everywhere with area independent farming system e.g. laying hens or fattening of pig or poultry. Albeit environmental legislation requires in most countries a certain land base for manure disposal, it is often sufficient for farmers to have a contract with other landowners allowing them to spread manure on fields not primarily managed by them. That renders is somewhat difficult to link directly farming structure and manure management practise. Accordingly, as discussed above, organic application rates are linked to manure availability in larger areas.

3.2.1 Validation of the land use maps

Error assessment analyses of the agricultural land use maps have been performed both at the regional scale, using district-to regional scale from an agricultural census of the year 2000 covering the EU15 member states and at the local scale, using commune-level statistics of the Lombardia region in Italy and the Netherlands.

The economic model CAPRI uses statistical information for agricultural land use for NUTS II regions. Therefore the initial distribution of the different crops to the individual HSMUs was performed based on NUTS II agricultural statistics.

These results were compared with the data from the agricultural census of the European Union, the Farm Structure survey (FSS2000, European Commission, 2003b). For some European regions, land use statistics from the FSS2000 is available at a lower administrative level, NUTS III. Within the area where both data sets were available (see Fig. 6) the NUTSII regions are subdivided in minimum 2 and maximum 10 NUTSIII regions. This information is used as out-of-sample observation to assess the errors of the results of the dis-aggregation algorithm.

For the comparison the distribution results on HSMU level were aggregated to NUTS

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III level and compared with the FSS2000 statistics as out of sample data. For each single crop the difference between the crop area given by FSS2000 and the area of the dis-aggregation result was calculated. All positive area differences were summed up for all crops and expressed as percentage of the total NUTS II agricultural area. In this way we obtain the share of misclassified agricultural area in a NUTS II region which is shown Fig. 6 for all regions where FSS2000 data on NUTS III level was available. In addition the pie charts give the contribution of each crop to the total error.

The misclassified agricultural area within NUTS II regions ranges between 2% and 35. With the developed dis-aggregation procedure very good results (2–15% misclassified area) have been obtained for the UK, Ireland, France and Southern Spain. The errors are slightly higher in Northern/Central Spain and Portugal. For Southeastern Italy, Greece and some regions in Sweden and Finland errors of about 25–35% occur. The higher errors in Sweden and Finland can be explained by the very small agricultural area which has to be located in quite large HSMUs. Higher errors can be the result of the dis-aggregation procedure which might be not appropriate for some regions but can be also a consequence of inaccuracies and inconsistencies in the input data for the dis-aggregation (CORINE land use/cover, LUCAS survey, agricultural statistics etc). We obtain an area weighted mean error of ~12.2% for Europe (area considered; see Fig. 6).

Very rarely single crops are considered in a model exercise or in other applications. Usually the crops are grouped according to their physical similarity or the demand for analog agricultural practices. If we consider only crop groups (cereals, fallow land, rice and oilseeds, industrial crops, permanent crops and grassland and fodder), some of the distribution errors level out as within these groups requirements of the plants to the site conditions are sometimes very similar and cannot easily be distinguished by the model. For the countries included in the calculation, the dis-aggregation error decreases from 12% for individual crops to 8% for crop groups. The error of very coarse crop classes (arable crops, permanent crops and grassland and fodder) is still lower (6.2%) and 3.4% of the total UAA was attributed to wrong NUTS III regions.

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However, applying no dis-aggregation, and simply distributing the NUTS II crop shares homogeneously over the corresponding NUTS III regions, would result in twice as much mis-classified area, i.e. 24%. Looking more in detail at the NUTS II level the “no dis-aggregation” case yields large errors of 40 to 50% for a number of cases mainly in France, Spain, and Italy. Only in a few cases we find that the dis-aggregation of the data yield a larger error than the even distribution over the NUTS III regions. The region Pohjois in Finland, for example, is the only region where the dis-aggregation result yields an error above 30% of the agricultural area, which is with 35.6% slightly worse than the even distribution (32.6%). The only large discrepancy is found in (Mellestra Norrland) where the crop shares in the two NUTS II regions is very close to the mean distribution (error 4.7%) and the dis-aggregation produced an error of 18%.

Error assessments of the agricultural land use maps have also been performed at the local scale, using commune-level statistics for the year 2003 of the Lombardia region in Italy (ERSAF, 2005) and the Netherlands. The latter, however, will not be presented here.

For the Lombardy region, we compared the rice and maize distribution in 190 communes with the results of the dis-aggregation. For illustration, Fig. 7 shows the dis-aggregation result (1 km by 1 km grid resolution) and the maize fields based on ERSAF (2005) data for a set of communes. The maize pattern (light brown areas) indicating a maize share of 30–60% from the dis-aggregation result corresponds with the main maize field distribution based on ERSAF. But looking at the scatter plot (Fig. 8a) comparing ERSAF and dis-aggregation data for maize in all 190 communes it can be seen that generally the dis-aggregation blurs the distribution that is more distinct in reality. For the interpretation of this comparison, however, one has to keep in mind that the areas of the single communes are close to the mean HSMU area in this region, sometimes even larger. Our approach does not allow distributing crop area below the HSMU level and therefore some discrepancies are unavoidable. Thus, we reach herewith the maximum level of detail that can be considered. Furthermore, maize is a crop that has no single corresponding CORINE land cover class in which it occurs but is distributed

over range of classes. The contrary holds for rice as a separate class rice fields is given in CORINE, thus the dis-aggregation result for rice (Fig. 8b), corresponds closely to the communal data.

3.2.2 Validation of the livestock density map

5 The data set resulting from the distribution algorithm of the animal activities was validated using out-of-sample data available for France at the level of 36 000 communes from the Farm Structure Survey. The individual herd sizes shown per commune were aggregated to livestock units. The results obtained for the about 24 000 pixel clusters for France were averaged per commune, and the absolute error in the stocking densities calculated. A result of e.g. 0.5 indicates that the area weighted average livestock density of the HSMUs polygons intersecting the polygon of the commune is 0.5 livestock units per ha higher than the data reported in the French Farm Structure survey. The resulting map is shown in Fig. 9a. The errors are classified in 5% quantiles, so that according to the legend, in 90% of the communes, the error in estimating the stocking
10 estimating is between -0.46 or $+0.43$ livestock units per. In 80% of the communes, the errors is between -0.28 and $+0.31$ livestock units per ha.

Those errors were compared with estimates per communes using the NUTS III average livestock density, with errors shown in Fig. 9b. Those livestock densities are the boundary data to which the results of the HSMUs in that NUTS III region had been consolidated. It can be seen that the statistical estimator for the livestock densities yields results which are somewhat similar to using NUTS III averages. However, when comparing the quantiles of the error distribution, it is obvious that the error distribution of estimator is more peaked as can be also seen from the distribution diagrams shown in the figures, i.e. the number of communes with a small differences between the observed and the estimated stocking densities is higher for the estimates compared to using average NUTS III livestock densities. Further on, the map with the errors from
20 using the NUTS III livestock densities shows a sharper clustering of errors in space. That observation is important as organic fertilizer applications for a specific HSMU

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are generated inter alia depending from a distance and size weighted average of surrounding HSMUs. When errors are clustered in space, averaging over HSMUs will not reduce errors, whereas with a high variance of errors in space, especially if HSMUs with under- and overestimated stocking densities are near to each other, averaging will reduce the overall error.

3.3 Results input data

3.3.1 Nitrogen application

On average 106 kg N of mineral fertilizer are applied per hectare to the agricultural land in Europe, and 61 kg N contained in manure. Hence, the share of manure nitrogen in the total nitrogen application is 37% which is similar to the share reported in the national greenhouse gas inventory of the European Communities of 33% (EEA, 2006). There are obviously large differences between the different countries, according to the intensity of livestock production as well as between the crops. Table 3 shows the average national nitrogen application rates for mineral fertilizer and manure by crop. Belgium, Denmark and The Netherlands are able to cover most of the nitrogen needs by using manure; France, Portugal and the United Kingdom must purchase most of the applied nitrogen from mineral sources.

The low average manure application rates in countries for France, Portugal and United Kingdom can be explained by several factors. First of all, compared to Belgium, Denmark and the Netherlands, the average livestock densities are considerable lower. Secondly, stocking densities are dominated by ruminants which are linked to grass land. And thirdly, especially in France and the UK the main arable cropping regions are dominated by specialized farms without animals.

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3.3.2 Export of nitrogen with harvested material

The uptake of nitrogen by the plants is the largest single pathway of nitrogen added or recycled during a year. With an average of $233 \text{ kg N ha}^{-1} \text{ y}^{-1}$ for all countries and crops simulated it balances approximately the total input of nitrogen by fertilizer application, nitrogen fixation and nitrogen deposition ($217 \text{ kg N ha}^{-1} \text{ y}^{-1}$; see Table 4). The ratio of nitrogen uptake to nitrogen delivery is highest for cereals such as rye and barley where twice as much nitrogen is contained in the plant than was added to the system. Sunflower and paddy rice, on the other hand, were taking up only a half of the offered nitrogen. Obviously, a large part of the nitrogen that accumulates in the biomass will remain in the system, as only a – crop-dependent – fraction will be removed at harvest. Also, recycling of nitrogen in the soil (mineralization of organic matter and crop residues) contributes differently to the pool of available nitrogen.

For all crops considered the amount of nitrogen in the harvested material amounts to 40% to 70% of the total plant nitrogen. For the above-ground biomass which is not harvested, it was assumed that 90% of the crop residuals were left on the field (Li et al., 1994). These numbers suggest a simulated nitrogen surplus between 15% for oats and more than 80% for sunflower. Nitrogen surplus pathways will be discussed in more detail in Sect. 3.4.

As described above, nitrogen application rates are calculated as a function of the estimated (aboveground) nitrogen uptake. This information is translated into potential total plant carbon to be achieved without environmental stress. Generally, the reduction in assimilated plant carbon respective to the optimal situation is relatively stable for the different crops. Looking at all simulations, we achieved only a plant biomass of 66% of the potential value. Most cereals (soft wheat, durum wheat, rye and barley) range at approximately 70%–80% of the optimal yield, with maize and durum wheat scoring lowest. These crops achieved only half of the potential biomass, similar to potatoes and sugar beet. Paddy rice and soya were closest to their potential biomass carbon (approximately 90%). In most of the cases, the model was able to achieve

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the pre-defined distribution of carbon over the plant compartments (root, shoot and grain), which shows that the phenology given to the model (sowing and harvest dates) corresponds to the parameterization of plant development. Problems were observed only for crops growing in Finland, where the maturation of the plants was simulated too slowly resulting in larger fractions of carbon to be allocated in root and shoot. For example, only 17% of the carbon was contained in the grain of soft wheat at harvest, which is about half the target value, while carbon in roots and shoot was much higher.

3.3.3 Topsoil organic carbon content

Net mineralization of organic matter in soils and assimilation of mineral nitrogen into organic matter are processes that occur mainly in systems that are in a phase of transition between two different land management systems. In the model world, land use transitions can be studied applying appropriate initial conditions of the soil parameters. We simulated a loss of soil organic matter of 25% or 23 t C ha⁻¹ during 100 years using the same weather and management data. Losses were highest in the first simulation years with an average loss of 0.5 t C ha⁻¹ y⁻¹ during the first decade slowing down to 0.1 t C ha⁻¹ y⁻¹ during the last decade. The latter value is close to estimates of current carbon losses from European croplands (Vleeshouwers and Verhagen, 2002). The dynamics of carbon losses are following a first-order decay with a time constant of 0.3% y⁻¹. The dynamics of soil organic carbon during the simulation period is shown in Fig. 10 (dotted symbols) for the average relative decrease of soil organic carbon content over all spatial simulation units. After 99 simulation years, soil organic carbon stocks reached 82%±22% of the initial values corresponding to a decrease of the average soil organic carbon stocks in the top 30 cm of the soil from 93±45 t C ha⁻¹ to 70±30 t C ha⁻¹. Note that the decrease of the average carbon stocks is steeper (down to 75%), which is due to a few (10%) spatial units with high soil organic carbon content that lost 40% or more of their initial carbon. On the other side, 15% of the simulation showed an increase of soil organic carbon. The distribution is thus slightly skewed, which is also shown in Fig. 11 presenting the distribution of relative changes for se-

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lected crops. Significant increases in soil organic carbon of more than 50% occurred of the initial value only for maize in ca. 15% of cases. For all crops, the highest number of cases was observed in the classes between 0 and 10% or between 10 and 20% reduction of organic carbon during the 100-year simulation runs.

5 The dashed symbols in Fig. 10 show the impact of the declining soil organic matter content on the simulated N_2O fluxes relative to the initial situation over all simulated spatial modeling units. The average N_2O flux declines faster than the average relative N_2O flux in the single spatial modeling units, as we have seen also for the carbon stocks; while initial N_2O fluxes were $17 \text{ kg N-N}_2\text{O ha}^{-1} \text{ y}^{-1}$, they reduced after 100
10 simulation year to $2.8 \text{ kg N-N}_2\text{O ha}^{-1} \text{ y}^{-1}$ corresponding to only 16% of the initial N_2O flux simulated. Variability is very high throughout the years, even though decreasing with time. The average relative decrease shown in Fig. 10 over the units is only down to 44%. This suggests that some un-realistically high topsoil organic carbon estimates lead to extremely high N_2O fluxes in the first simulation years (even fluxes of 100 kg
15 $\text{N-N}_2\text{O}$ and more were simulated under initial conditions), which declined quickly diminishing their weight in the mean N_2O flux. The standard deviation of the average decrease of the relative N_2O flux is 200% in the tenth simulation year reflecting the same fact that large reductions in a few modeling units and smaller reduction in a higher number of modeling units occurred. N_2O fluxes and standard deviation of mean
20 N_2O fluxes are relatively stable after 50 simulation years with an average decrease of $0.05\% \text{ y}^{-1}$ which reduces to $0.04\% \text{ y}^{-1}$ during the last simulated decade.

3.4 Simulation results

All results presented in this section are related to the last simulation year, i.e. after 99 years of simulating the same management and climate situation.

25 Being a comprehensive biogeo-chemical model of nutrient turnover in agricultural soils, DNDC calculates all elements in the nitrogen balance in soils. Being a methodological paper, we restrict here to present the simulated nitrogen budget at national

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scale. Table 4 shows a summary of the quantified, i.e. reported elements in the N budget aggregated to the country scale. Outputs of nitrogen by nitrogen losses and export of plant material either of plant products or crop residues is opposed to the input of nitrogen via nitrogen application, deposition, fixation, and release of nitrogen through net mineralization of soil organic matter. Net mineralization of organic matter leads in some countries to a loss of nitrogen, if soil organic matter has been simulated to build up in that country. The two sides of the balance are large fluxes of nitrogen and cover a large range between 77 kg N ha⁻¹ y⁻¹ (Greece) to 430 kg N ha⁻¹ y⁻¹ (Belgium). The export of nitrogen with the crop has been calculated as the residual from the difference of nitrogen in- and outputs to close the nitrogen budget at the soil surface. There might be errors due to unaccounted sources or sinks of nitrogen in the simulations, such as allocation of biologically fixed nitrogen in soil compartments or leaching of organic matter. However, these are considered to be minimal, as was found in simulations where crop development was suppressed. Here the nitrogen balance was close to zero within the bound of the rounding errors. Also, C/N ratios of the exported plant biomass was in most cases identical or slightly higher (due to the higher C/N ratio in plant shoot biomass) to the pre-defined C/N ratios in grain. Presumably therefore, the error introduced by using a constant C/N ratio for mineralized soil organic matter was small. DNDC knows different pools of organic matter with defined C/N ratios. The C/N ratio of litter varies from very labile (C/N=5) over labile (C/N=50) to resistant litter (C/N=200). Other compartments comprise microbial biomass, humus and humus, which are all characterized by a C/N ratio of 12.

The nitrogen surplus generally is an important indicator for defining the environmental impact of agriculture on one hand and the effectiveness of environmental policies on the other hand. Calculating nitrogen surplus as the ratio of nitrogen not taken up by plants (both in harvested material or in removed crop residues) to the total nitrogen input during the simulation year, it ranges between 26% (United Kingdom) and 55% (Italy). The value calculated for all countries considered is 38% nitrogen surplus.

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4.1 Spatial simulation units

Regional or (sub)continental modeling studies often run their model on a regular grid of varying size depending on the area covered by, the format of available data sets, and the scope of, the simulations. Roelandt et al. (2006) for example aimed at predicting future N₂O emissions from Belgium relying on climate scenarios that were available for a 10' longitude and latitude grid; also Kesik et al. (2005b) linked the simulation of nitrogen oxides emissions from European forest soils to the available climate data set and run the model on a 50 km×50 km raster. Vuichard et al. (2007) estimated the greenhouse gas balance of European grasslands, due to computing limitations they restrict the simulations to a 1° by 1° degree grid. These approaches are efficient in fast responses for possible developments or delivering a first estimate of large-scale emissions. For detailed analysis, however, they lack the link to realistic land use data (Roelandt et al., 2006) and are too coarse for capturing local heterogeneities (Vuichard et al., 2007). For a better representation of land use, many authors run their models within the administrative boundaries, for which regional statistics are available. Examples of this approach include simulation studies on about 2500 Chinese counties to estimate soil organic carbon storage (Tang et al., 2006) or greenhouse gas emissions from rice cultivation (Li et al., 2006) using the DNDC model. To assess regional heterogeneity, the most sensitive factor (MSF) is used giving a reasonable range of emission values with a high probability to cover the true value. This “administrative approach” is also used if the study aims to give support to, or for comparison with, national greenhouse gas estimates performed with the IPCC emission-factor approach (e.g., Brown et al., 2002; Del Grosso et al., 2005; Mulligan, 2006). Mulligan points out, however, that most of the uncertainty in the emission estimates stem from the large range of environmental conditions encountered within the single modeling units.

To overcome these problems, other studies decided to use the geometry of the available information on soil properties for the delineation of the modeling units used. For

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large-scale application as in Grant et al. (2004) to assess the impact of agricultural management on N₂O and CO₂ emissions in Canada, representative soil type – soil texture combinations were defined covering the seven major soil regions in Canada.

Changes in soil organic carbon stocks or fluxes of greenhouse gases were estimated on a basis of landscape units being an intersection of a land-use map and a soil map for Belgium (Lettens et al., 2005) or a region in Germany (Bareth et al., 2001). An additional intersection with a climate map was done in a study on N₂O emissions from agriculture in Scotland (Lilly et al., 2003). These very detailed analyses, however, were so far restricted to relatively small countries or regions due to limitations of computing resources.

Schmid et al. (2006) describe a very detailed approach to simulate soil processes in Europe with the biophysical model EPIC. By intersecting landscape variables that are considered stable over time (elevation, slope, soil texture, depth of soil, and volume of stones in the subsoil) they obtained a layer of more than 1000 homogeneous response units. Each of these units was divided, on the average, into 10 individual simulation units by overlaying various maps such as climate, land cover, land use/management and administrative boundaries. Individual simulation units are then regarded as a representative field site and estimated field impact from simulated management practices are uniformly extrapolated to the entire unit.

The approach described in the present study has many similarities to the HRU/ISU approach described by Schmid and co-workers, as in both cases the philosophy is to develop a framework integrating both environmental and socio-economic impacts on soil processes. The main differences, however, are

- Selected soil characteristics are used to delineate the homogeneous response units by Schmid et al. (2006), while each geometrical unit of the soil database (the so-called soil mapping units) is maintained in the delineation of the homogeneous spatial mapping units defined here. Each soil mapping unit is a unique combination of one or several soil types. Preliminary land use simulations suggested that soil type is an integrative characteristic with relevance for both the

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agronomic-based choice of the use of the land, and for the environmental response to agronomic pressures, yielding more reliable land use estimates. Unfortunately, soil types within a soil mapping unit are not geo-referenced and soil characteristics used (texture, topsoil organic carbon content etc.) are defined at the basis of the soil mapping unit only. Integration of the pedotransfer functions into the land use mapping model and consistent estimation of soil characteristics at the level of soil types will be one of the major improvements of the present approach in the next future.

- The time window for which our methodology is applicable consequently is rather narrow and linked to the time horizon agricultural of agricultural projections, usually about 10 years. However, the methodology used for downscaling the regional information to the spatial calculation units could easily be incorporated in any other socio-economic modelling framework, provided that the main driving parameters are consistently calculated (mineral fertilizer consumption and manure nitrogen excretion, acreages for the cultivation of the crops and respective productivity).
- While the individual simulation units allow consistent integration of bio-physical impact vectors in economic land use optimization models, the homogeneous spatial mapping units are integrated part of both the economic and the biophysical model. This allows us to intimately link both modelling approaches which is a prerequisite for efficient environmental impact policy assessment.

4.2 Land use map

The legend of the CORINE Land Cover map contains eleven pure or mixed agricultural classes. Interpretation of particularly the mixed classes such as “complex cultivation patterns” is very different for different regions in Europe. The typical land-use mix for this class differs largely between countries. For example, in Germany the area covered by complex cultivation pattern is with 20 731 km² almost half of the area in

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Spain (38 581 km²). In both countries we estimate about 75% to be used as agricultural area with grassland accounting to 45% and 30% in Germany and Spain, respectively. According to the definition (Bossard et al., 2000) this class consists of a “juxtaposition of small parcels of diverse annual crops, pasture and/or permanent crops” with built-up parcels covering less than 30%. Permanent crops and cereals account in Spain for 35% and 15%, respectively, while in Germany, cereals have a large share (40%) and permanent crops are insignificant. In addition, comparisons of CORINE with detailed statistics resulted in large disagreements (Schmit et al., 2006). At the European scale a simple downscaling procedure on the basis of CORINE would therefore, beside of lacking thematic details available in the economic model, lead to biased estimation of land use shares.

From a conceptual point of view, therefore, the procedure described in Sect. 2.3 can be interpreted as a “calibration” of the CORINE Land Cover/Use map giving more detailed information on the share of individual crops in mixed and heterogeneous classes (e.g. non-irrigated arable land and complex cultivation pattern, respectively), but also the share of non-agricultural area for each class. An overview of the crop association in the main CORINE land cover classes covering about 80% of the utilized agricultural area in EU15 is given in Table 5. Grassland covers 14% of the surface area of Europe and is the most important agricultural land use for most countries, with shares up to 75% of the utilized agricultural area (Ireland). With the exception of non-irrigated arable land, grassland occupies the largest share of the area of the mixed land cover classes. With 92% the correspondence is highest for the class “natural grassland”. Also for other pure land cover classes, our model predicts high correspondence with CORINE, i.e., 78% for rice fields and 81% for olive grows. This makes it even more astonishing that in regions with a high percentage of misclassified area often grassland accounts for a significant part of the errors. This suggests that misclassification errors might not only be a consequence of a poor dis-aggregation procedure but also a result of contradictory data sources. Generally, grassland area tends to be larger in the FSS statistics than in the CORINE land cover map (Grizzetti et al., 2007). For example, the

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CORINE land cover map reports about 2 Mio ha “Pasture” and “Natural Grassland” in Spain while in the FSS statistic about 9 Mio ha Grassland are declared. Nonetheless the dis-aggregation is a significant improvement compared to the assumption of identical cropping pattern within each Nuts II region. A detailed analysis for Belgium (Schmit et al., 2006) found low reliability for grassland in CORINE, as less than half of the pixels that are classified as grassland in CORINE corresponded to grassland pixels in the reference map. Worse, only little more than 10% of the grassland in the reference map was correctly represented by CORINE.

The comparison of the data with local field data in the province of Pavia showed that the commune level reached the limit of the spatial resolution of our approach. Nevertheless, a relationship between the dis-aggregated and the local data was found. We learned from this comparison that a large portion of the error was introduced when resampling the original CORINE land cover map at the resolution of 100 m into the 1 km by 1 km pixels. This was necessary because of computing resources as CORINE was used for the delineation of the HSMU. We expect to improve the accuracy of the dis-aggregation in future versions, if the land cover map is used at the original resolution as an attribute of the HSMUs.

For the county of Quzhou, China, Liu et al. (2006) applied a very detailed approach to cope with spatial heterogeneity in cropping patterns that were identified as a crucial component in the estimation of regional changes in organic carbon stocks. NDVI information (ASTER sensor) from May and July were used to separate vegetated and non-vegetated area, and also to distinguish between areas under wheat/maize rotation and cotton cultivation, which are the dominant crops in the area. Information from the MODIS sensor was used in three different indices to map rice cultivation and phenology in South and Southeast Asia (Xiao et al., 2006). Such a detailed analysis can not easily applied to an area such as Europe, but improvements in the parameterization of crop phenology or the land use map itself by including additional spaceborne products will be the logical next step.

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4.3 Input data

4.3.1 Fertilizer/manure input

In the majority of the cases, the nitrogen application rates from CAPRI yielded plausible results when compared to crop removals, especially in the case of mineral application rates where at least average national rates for certain crops or crop groups could be used in the estimation process. In the case of organic application rates, some outliers were however found. These outliers have been corrected in the meantime and were excluded from the simulations. As most of the crops with somewhat curious organic application rates have generally small cropping shares, the impact of those errors on the regional results is modest.

If we compare the mineral application rates for individual crops and countries with the information obtained from the International Fertilizer Manufacturer Association (FAO/IFA/IFDC/IPI/PPI, 2002) we find considerable differences as can be observed from Table 6. The reason can be found in our methodology that links total nitrogen application to nitrogen uptake by the plants. This in turn is available from statistical sources. Our approach tries to minimize both the deviation from the IFA-application rates of mineral fertilizer nitrogen and the share of nitrogen obtained from manure, taking into consideration the availability of manure nitrogen in the region. Thus, depending on the location of the crop land in relation to the stocking density of animals, and the soil quality in the region, a “transfer” of mineral fertilizer nitrogen between crops might occur. The effect of the distribution of animals and soils is ignored in the IFA estimates. These estimates are the result of a negotiation procedure between different institutions, and is based on information obtained from questionnaires to national administration and industry representatives (FAO/IFA/IFDC/IPI/PPI, 2002).

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4.3.2 Yield

Our approach aims to match as far as possible the uptake of carbon and nitrogen simulated with the bio-physical model DNDC with the available yield statistics at regional level and the estimated (yield downscaled to the spatial calculation unit) information.

5 The reason is that the link between the two models is based on the estimates of nitrogen input to the soil-vegetation system for each individual calculation unit. As shown in Sect. 3.3.2 we achieved a high score in matching estimated and simulated carbon export. This was to be expected, as stress situations tend to reduce plant growth in the simulation model. This bias is expected to have considerable impact of the fate
10 of nitrogen in the soils, as fertilizer dressing rates are calculated on the basis of nitrogen uptake plus estimated over-fertilization coefficients. These coefficients take into account the security margin a farmer would apply to assure that under normal weather conditions, optimal return to his investments is realized.

The reasons for differences found in the “performance” of crops are laid already
15 in the land use estimation model, which is based on a large number of ground-truth observations. We assume farmer’s choices of crop cultivations to be rational and taking into consideration expected revenue and different environmental requirements of the crops in relationship with the local conditions.

As an example, Fig. 12 shows the number of simulations and the corresponding
20 mean N₂O fluxes, if only simulations yielding a minimum of the carbon export estimated with CAPRI are taken into account. The figure compares two cereals, soft wheat and barley, with different performance with respect to simulated carbon export, and different level of N₂O fluxes. Soft wheat has stricter requirements on environmental conditions than barley. Due to its lower capability to store humidity, it has a higher demand on
25 summer precipitation. Therefore, stress is much higher for soft wheat with a lower average relative yield as a consequence. While the median N₂O flux of all simulations with soft wheat cultivation is only 1.3 kg N-N₂O ha⁻¹ y⁻¹, it increases continuously if plant uptake of nitrogen gets closer to the prior estimate. For the last 50 simulations

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(approx. 7%) where at least 95% of nitrogen export was simulated, we obtain an N₂O flux of 3.2 kg N-N₂O ha⁻¹ y⁻¹. This is in the same order of magnitude as the emissions from barley for the non-limited simulations, while the overall median for barley with 1.8 kg N-N₂O ha⁻¹ y⁻¹ is higher than that of soft wheat.

Thus, we observe that (i) environmental conditions play a major role both in the choices of the farmers what they are going to cultivate. In DNDC, penalties for stress conditions are smaller than in CAPRI, and decreases in expected yield thus strongly limited by fertilizer input; (ii) highest emissions remain to occur on high-productivity sites, both if expressed relative of the cultivated area, but also if expressed relative to production unit.

4.3.3 Soil map

The efforts we invested into the development of an agricultural land use map of high resolution are justified by the need to spatially match agricultural activities with environmental conditions, mainly soil parameters, which have been identified to be the major reason for high uncertainty. These efforts are currently not adequately matched by the quality of the soil map. Reason for concern is given in particular by two characteristics of the data used, i.e. (i) soil types are not directly mapped and (ii) the derivation of soil properties in the raster maps is done using fixed land use information.

The spatial components of the soil database of Europe are the so-called soil mapping units, which correspond to a soil type association, comprising a varying number of soil types with defined share of the area covered by the SMU, but unknown spatial location. However, variations in soil organic carbon or other attributes within a soil mapping unit are accounted for by including information of land use (CORINE Land Cover 1990 map), climate, and soil typological unit. Inconsistencies might particularly arise if the land use estimated in the present study differs largely from the land use that had defined the soil characteristics. We tried to account for this by “filtering” out homogeneous spatial mapping units with a high share of forest area in CORINE1990 (European Topic Centre on Terrestrial Environment, 2000) as compared to the land

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use shares estimated in our approach. Nevertheless, we observe a very high average soil organic carbon content in Finland, where only 2764 km² of agricultural area is estimated to be cultivated on organic soils (Statistics Finland, 2005) corresponding to approximately 22% of the agricultural area in our database. Thus, we are likely to overestimate nitrogen losses and N₂O emissions for Finland.

It will be therefore of highest priority to incorporate the estimation of soil characteristics into the land use share model to obtain consistent and high quality soil information to initialize biophysical modelling studies.

4.4 General discussion

It is more and more recognized that the impact of society on the environment is costly and needs to be considered when policy impact analyses are performed. Tools that are used to help are required to answer mainly two questions: “what is the impact of a certain policy pathway?” and “how much does it cost to reduce this impact?”. Prominent integrated modelling frameworks are the Integrated Model to Assess the Global Environment (IMAGE, Bouwman et al., 2006) and the RAINS model (e.g., Höglund-Isaksson et al., 2006). Integrated modelling systems link socio-economic analysis with environmental assessment working usually with a multi-sectoral approach. Due to the high number of variables they have to deal with, they are based on simple relationships or empirical functions. Sectoral “integrated model” on the other hand are able to simulate both socio-economy and environment of a single sector with great detail and are thus able to deliver targeted policy impact assessments.

Schneider et al. (2007) for example present an analysis of mitigation options in US agriculture and forestry, with a biophysical model delivering greenhouse gas emissions coefficients and carbon stock changes for various management options.

Another example of such a sectoral integrated modelling framework is the EFEM-DNDC system described by Neufeldt et al. (2006). In their system, the economic farm emission model EFEM is linked to the biophysical model DNDC via crop acreage and fertilizer intensity estimates for one of eight different regional groups in Baden-

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Württemberg, Germany, which are composed of several municipalities with similar environmental conditions and typical production systems. Downscaling of this information to the modelling units was done on the basis of the CORINE land cover map accounting for a correction factor for differences in agricultural area between the statistics and CORINE. Our approach is very similar to EFEM-DNDC. Main differences are (i) a more “elaborated” approach for downscaling and (ii) a closer link between both modelling systems as nitrogen application rates are adapted to the individual conditions of the spatial calculation units.

We regard both features as an essential element for an agricultural integrated modelling framework, particularly for a large-scale application as in the present study. One of the most important features of an integrated modelling framework is a consistent flow of nutrient in the various modules. The approach described is designed to reach maximum consistency both in term of scale (scale-consistent downscaling from national and regional statistics to a grid based on 1 km×1 km pixel) and in terms of mass-flow through agricultural sub-systems. The system maintains consistency not only in accounting between livestock production and crop production systems (within the economic model) but ideally also between the economic estimates and the values simulated with the process-based model which is built-in into the model design. However, some additional work is still required to improve this link as described in the above sections.

5 Conclusion

We presented for the first time an approach that links an economic model for agriculture with a process-based simulation model for arable soils for Europe. The linkage with national and international statistics is especially important in view of potential future applications for reporting requirements (such as the reporting under the UNFCCC).

The results in terms of estimated nitrogen fluxes must still be considered as illustrative as needs for improvements in input data (e.g. the soil map) and management data

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(yield estimates, nitrogen application rates) have been identified and will be the focus of future work. Nevertheless, we were already able to highlight inter-dependencies between farmer's choices of land uses and the environmental impact of different cultivation systems.

- 5 We developed a two-step procedure with three major advantages:
- it maintains scale consistency with the regional statistics of the economic model with which the spatial calculation units (HSMUs) are linked (i.e. for a posterior simulations also with the official EUROSTAT statistics)
 - the simulation with the bio-physical model is performed on units containing the full information of the economic model, but which are tailored to the biophysical model's need, minimizing the computational cost/benefit ratio.
 - the approach is very flexible and can be used to create for each model a different but consistent data set which is tailored to the model's needs.

15 The present study is the first step into a detailed integrated assessment of the climate impact of European agriculture. The second step will be to link the bio-physical model back to the economic model. This will improve the capability of the economic model to anticipate responses of the more detailed process-based model and increase further the consistent estimation of nitrogen fluxes in European agriculture. It will also lead to a stand-alone and fast tool for a comprehensive policy impact assessment within the boundaries of the simulated emission factors.

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Table 1. Thresholds and tolerances used to cluster HSMU into MSU and to select the simulated crops.

Parameter	Explanation	Value
MINUAAR	Minimum UAAR in a MSU for simulation	0.40
MINSHAR	Minimum share of crop in UAAR of the MSU	0.35
MINPLUS	Minimum share of crop in UAAR not yet considered	0.85
MINMINS	Limitation share to add more crops if not relevant in region	0.05
M-ID	Tolerance for daily weather condition (file-number)	0.05
NDEP	Tolerance for N-deposition values [mg N / ml rain-water]	0.05
OC_MAX	Tolerance for soil organic carbon content	0.10
CL_MAX	Tolerance for clay content	0.20
PH_MAX	Tolerance for topsoil pH	0.20
BD_MAX	Tolerance for topsoil bulk density	0.20

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Table 2. Main statistics on the layer of the homogeneous spatial mapping units (HSMU) for EU27 without Malta and Cyprus.

COUNTRY	Number [n]	Total Area [1000 km ²]	Mean size [km ²]	Number [n]	Mean size [km ²]	Total area [1000 km ²]	Mean UAAR [km ²]	Total UAAR [1000 km ²]
	All HSMUs			HSMUs w with potential agricultural activities				
Austria	2,820	83.6	29.6	1,917	38.1	73.0	45%	32.5
Belgium	2,245	30.6	13.6	1,503	16.1	24.1	54%	13.0
Bulgaria	7,275	110.6	15.2	5,637	18.4	103.7	52%	53.8
Czech Rep.	5,268	78.9	15.0	3,974	18.5	73.4	53%	38.8
Denmark	1,884	40.6	21.5	1,152	32.0	36.8	69%	25.5
Estonia	1,825	42.1	23.1	1,341	29.2	39.2	19%	7.6
Finland	3,545	334.1	94.2	2,114	129.8	274.5	8%	21.9
France	35,012	546.7	15.6	26,431	19.2	506.2	55%	276.4
Germany	17,441	356.2	20.4	12,171	26.4	321.4	53%	170.4
Greece	10,337	125.0	12.1	8,456	14.1	118.9	30%	35.3
Hungary	5,310	92.4	17.4	3,807	22.3	85.0	68%	57.9
Ireland	3,458	68.5	19.8	2,336	23.2	54.1	71%	38.4
Italy	19,890	297.8	15.0	14,873	18.2	270.0	48%	129.5
Latvia	1,940	64.0	33.0	1,423	42.5	60.5	26%	15.9
Lithuania	3,788	64.6	17.1	2,816	21.6	60.7	46%	27.7
Luxembourg	323	2.6	8.0	243	9.7	2.4	54%	1.3
Netherlands	1,546	34.3	22.2	834	34.2	28.5	70%	20.0
Poland	15,457	311.6	20.2	11,753	25.1	295.3	58%	170.6
Portugal	6,570	88.2	13.4	5,433	15.4	83.5	44%	37.0
Romania	16,421	237.9	14.5	12,130	17.7	215.0	68%	146.9
Slovakia	2,604	49.0	18.8	1,913	23.9	45.8	49%	22.4
Slovenia	2,866	20.2	7.1	2,495	7.8	19.4	27%	5.1
Spain	21,205	496.7	23.4	16,959	27.9	473.7	55%	259.5
Sweden	5,299	445.0	84.0	3,179	114.2	362.9	8%	30.4
United Kingdom	11,960	239.9	20.1	7,933	26.5	210.6	74%	155.7
TOTAL	206,289	4261.0	20.7	152,823	25.1	3,838.4	47%	1793.5

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Table 3. Application of mineral fertilizer and manure nitrogen [kg N ha⁻¹].

	N-input*	SHWE	DWHE	RYEM	BARL	OATS	MAIZ	PARI	RAPE	SUNF	SOYA	PULS	POTA	SUGB	TOMA	OVEG	OFAR	Average
Austria	(a)	73	75	36	69	48	83		68	83	144	59	65	137	210	76	19	75
	(b)	6	24	12	25	17	101		33	20	27	48	12	30	16	5	53	38
Belgium [§]	(a)	230		82	24	99	12		154			7	39	164	500	15	288	58
	(b)	11		31	64	43	411		80			118	346	171	73	105	49	318
Denmark	(a)	113		38	53	9	46		121				186		340		36	79
	(b)	161		61	123	112	57		344				299		304		225	177
Finland	(a)	125		46	83	82			65	35		26	53	62	432	59	29	81
	(b)	45		3	24	43			20	47		48	56	16	9	1	61	33
France	(a)	192	115	80	140	79	138		96	101	190	2	100	130	163	40	79	156
	(b)	9	15	10	10	19	61		37	39	48	18	95	86	139	14	37	28
Germany	(a)	274	176	169	92	114	44		152	129		44	95	161	279	47	154	183
	(b)	14	13	20	6	10	175		65	97		32	107	113	65	30	79	54
Greece	(a)	63	47	147	47	18	146	145		23	236		90	110	129	56	44	56
	(b)	9	17	34	1	5	1	1		9	14	1	10	1	1		8	15
Ireland	(a)	210			210	191							75	54	223	44	121	131
	(b)												23	15	2	2	78	67
Italy	(a)	134	67	87	145	95	132	184	56	136	269	21	171	104	188	45	34	94
	(b)	1	3	4	2	7	163	157	27	61	49	4	119	79	49	60	48	66
Netherlands	(a)	186		41	66	163	50		79			78	207	466	343	75	343	119
	(b)	173			56	301			163			116	178	15	272	123	216	214
Portugal	(a)	34	29	32	34	16	112	118				9	66	6			64	97
	(b)	1	0		26		20	35									27	18
Spain	(a)	65	40	100	59	59	227	147	59	31	111	5	44	125	186	69	73	60
	(b)	7	0	26	10	7	54	136	46	34	31	59	62	27	20	169	26	14
Sweden	(a)	182			67	98	70		56					81	399	90	47	63
	(b)	76			5	39	41		52					5	4	1	80	65
United Kingdom	(a)	123	197	72	91	71	59		115	65	72		107	24	307	31	60	104
	(b)	23	11	7	11	25	40		20	95	47		65	13	22	23	26	20
Average	(a)	171	61	152	64	92	113	177	131	51	173	18	126	119	205	54	55	106
	(b)	48	5	19	22	27	138	152	52	36	37	26	143	65	53	61	108	61

* (a) Mineral fertilizer nitrogen; (b) Manure nitrogen; §: Luxembourg included in the numbers of Belgium; SHWE: soft wheat, DWHE: durum wheat, OCER: other cereals, BARL: barley, RYEM: rye, OATS: oats, MAIZ: corn; PARI: paddy rice, SUNF: sun flower, SOYA: soya, POTA: potatoes, SUGB: sugar beet, ROOF: root fodder crops, TOMA: tomatoes, OVEG, other vegetables, OFAR: fodder on arable land.

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Table 4. Summary of the quantified nitrogen budget, aggregated to country-scale. All values are given in kg N ha⁻¹.

All crops	Mineral fertilizer	Manure	N-fixation	Deposition	Mineralization\$	Leaching	NH ₃	N ₂	NO	N ₂ O	Export by harvest
	Nitrogen input					Nitrogen output					
Austria	75.3	37.8	19.6	9.9	4.5	16.1	29.4	6.6	0.5	4.1	90.5
Belgium	57.6	318.1	29.4	26.6	-2.2	76.5	93.3	8.8	1.6	10.5	238.8
Denmark	79.0	177.4	107.9	6.8	8.0	101.4	47.2	4.8	0.6	2.9	222.2
Finland	80.6	32.8	2.6	1.4	38.3	27.1	10.5	65.6	0.6	5.1	46.9
France	155.8	28.2	41.0	10.9	-0.9	19.2	47.4	2.8	0.4	2.7	162.5
Germany	182.6	54.1	13.7	11.2	11.6	16.9	50.9	6.3	0.6	4.6	194.1
Greece	55.8	14.6	3.5	2.6	0.6	16.9	17.0	2.3	0.5	4.2	36.3
Italy	94.0	66.0	19.1	13.8	-9.1	19.1	67.2	5.9	0.6	3.8	87.2
Netherland	118.7	214.4	12.1	26.7	17.1	61.1	39.7	15.5	1.8	15.8	255.2
Portugal	97.2	18.2	27.0	15.1	-0.4	26.2	29.6	2.5	0.4	2.2	96.2
Spain	60.3	13.6	6.2	4.6	0.5	5.0	30.5	1.8	0.2	1.4	46.2
Sweden	62.5	64.5	151.9	3.7	40.0	102.3	8.6	27.9	0.6	3.0	180.2
UK	103.7	20.1	17.8	8.9	10.5	17.3	30.8	0.9	0.2	0.9	110.8
Average	106.1	61.4	40.8	9.1	6.1	36.0	42.3	6.6	0.5	3.1	135.0

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Table 5. Attributed land use for the main CORINE land cover classes in EU15. Reported are for each of the CORINE classes covering cumulatively more than 80% of the utilized agricultural area the ten most significant crops in descending share of the area.

CORINE CLASS	km ²	% UAAR	LAND USE CLASS	cumulative %	
NON-IRRIGATED ARABLE LAND	565 782	44.9	Soft Wheat	60.8	
			Barley		
			Fallow Land		
			Grassland		
			Maize		
			Other Fodder On Arable Land		85.6
			Rape		
			Durum Wheat		
			Oats		
			Sugar Beet		
PASTURES	209 930	16.7	Grassland	98.6	
			Other Fodder On Arable Land		
			Maize		
			Soft Wheat		
			Barley		
			Other Cereals		99.7
			Oats		
			Fallow Land		
			Durum Wheat		
			Fruit Trees		
COMPLEX CULTIVATION PATTERNS	134 759	10.7	Grassland	67.9	
			Other Fodder On Arable Land		
			Maize		
			Soft Wheat		
			Barley		
			Vineyards		91.4
			Olive Groves		
			Fallow Land		
			Fruit Trees		
			Durum Wheat		
LAND PRINCIPALLY OCCUPIED BY AGRICULTURE, WITH SIGNIFICANT AREAS OF NATURAL VEGETATION	56 783	4.5	Grassland	78.9	
			Other Fodder On Arable Land		
			Fallow Land		
			Barley		
			Olive Groves		
			Soft Wheat		94.5
			Oats		
			Maize		
			Fruit Trees		
			Durum Wheat		
NATURAL GRASSLAND	52 320	4.1	Grassland	98.5	
			Other Fodder On Arable Land		
			Fallow Land		
			Durum Wheat		
			Soft Wheat		
			Maize		99.8
			Olive Groves		
			Rye		
			Barley		
			Other Cereals		

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Table 6. Application rates of mineral fertilizer nitrogen for selected crops/countries [kg N ha⁻¹] (Source: FAO/IFA/IFDC/IPI/PPI, 2002).

	Wheat	Barley	Maize	Rape	Pulses	Potatoes	Sugar b.	Veget.	Fodder	Total
Austria	82	70	184	80	30	110	90	110	8	75
Belgium	115	98		108	2	110	85	108	92	33
Denmark	155	100		150	20	155	110	110	62	116
Finland	120	78		110		83	100	100	85	41
France	85	72		80	40	70	120	80		47
Germany	165	150	150	170	25	140	145	165	94	131
Greece	150	78		100		120	100	140	118	18
Ireland	80	120	170	155	150	35	145	45	52	59
Italy	70	75	190		40	200	140	170		64
Netherlands	160	110		150		120	180		120	49
Portugal	190	85	44	180	20	168	108	125	30	38
Spain	95	90	225	109	9	142	178	205	27	75
Sweden	80	60	160	100	5	100	150	120	80	73
United Kingdom	183	118		185	5	155	100	125	75	30
EU15	92	91	101	158	14	129	136	109	54	69

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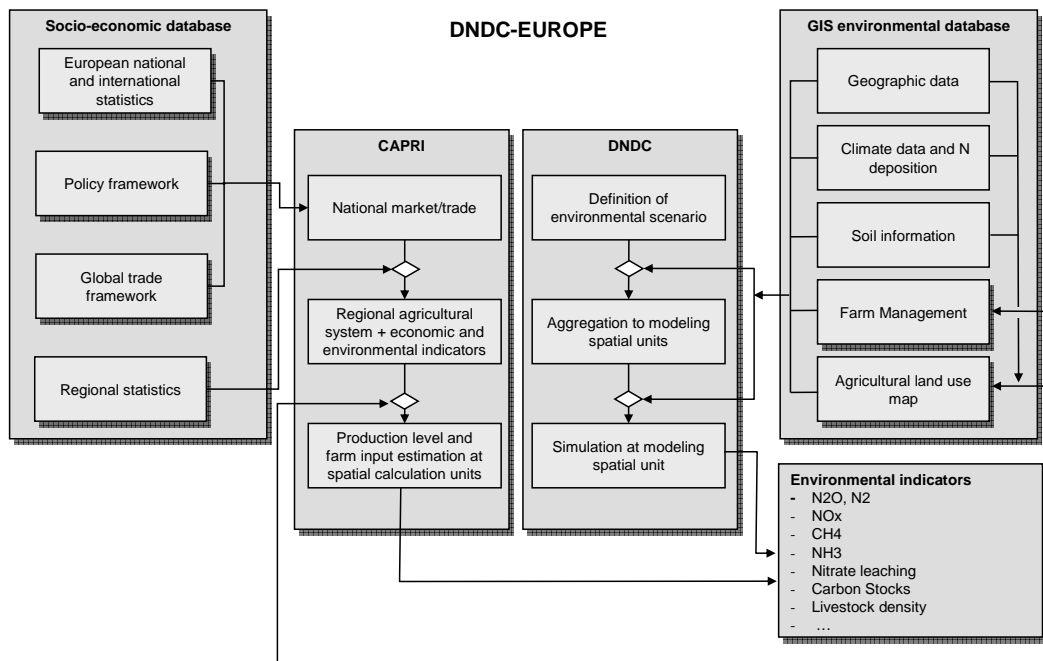


Fig. 1. Flow-diagram of the CAPRI-DNDC-EUROPE framework.

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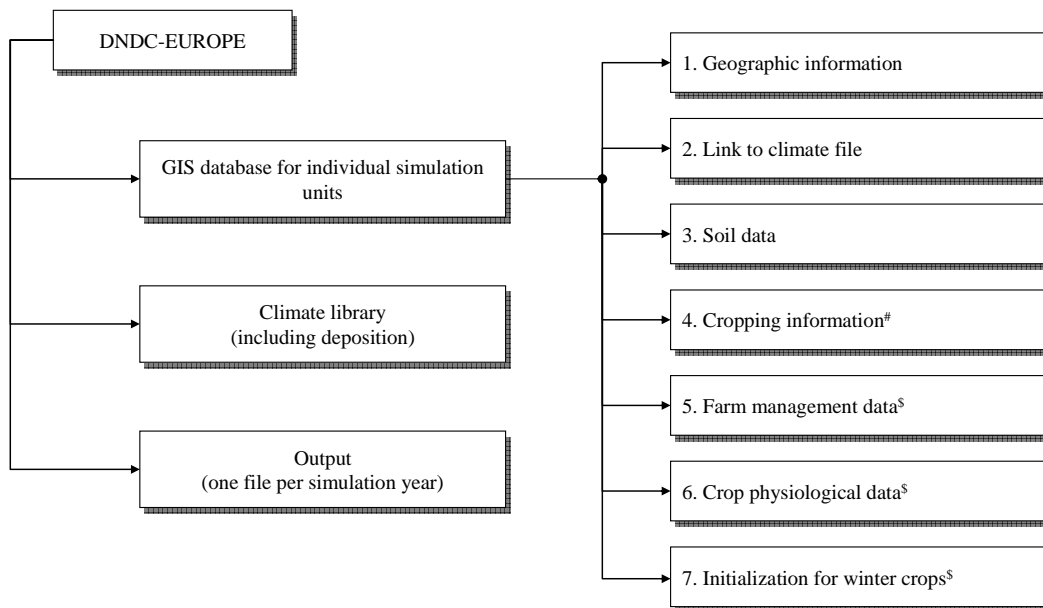


Fig. 2. Database structure of DNDC-EUROPE. # Modified GIS file; \$ Additional GIS file.

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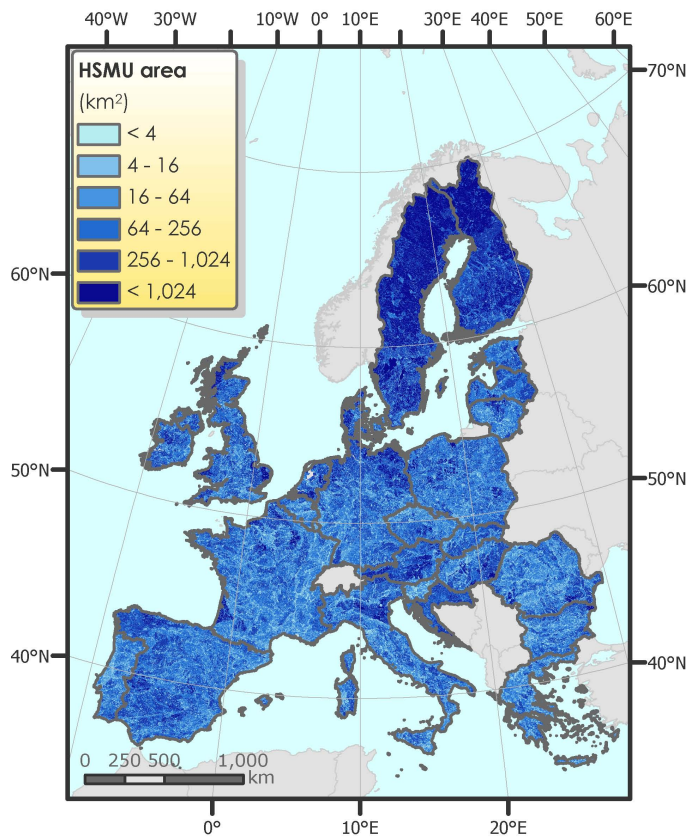


Fig. 3. Size distribution of homogeneous spatial mapping units with CCM 250 DEM hillshade.

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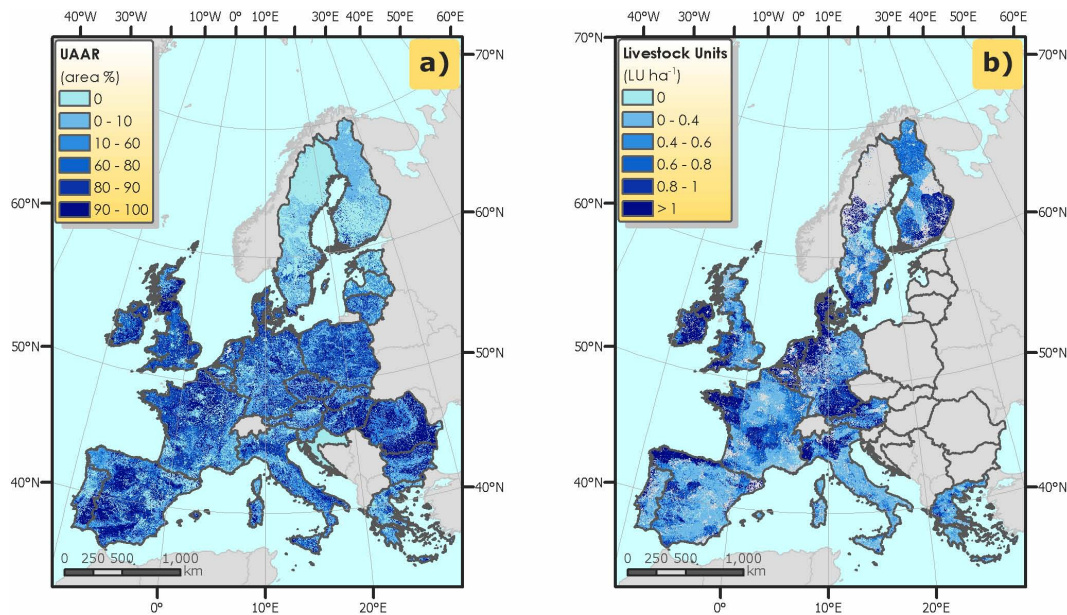


Fig. 4. (a) UAAR area (b) Livestock density in EU27.

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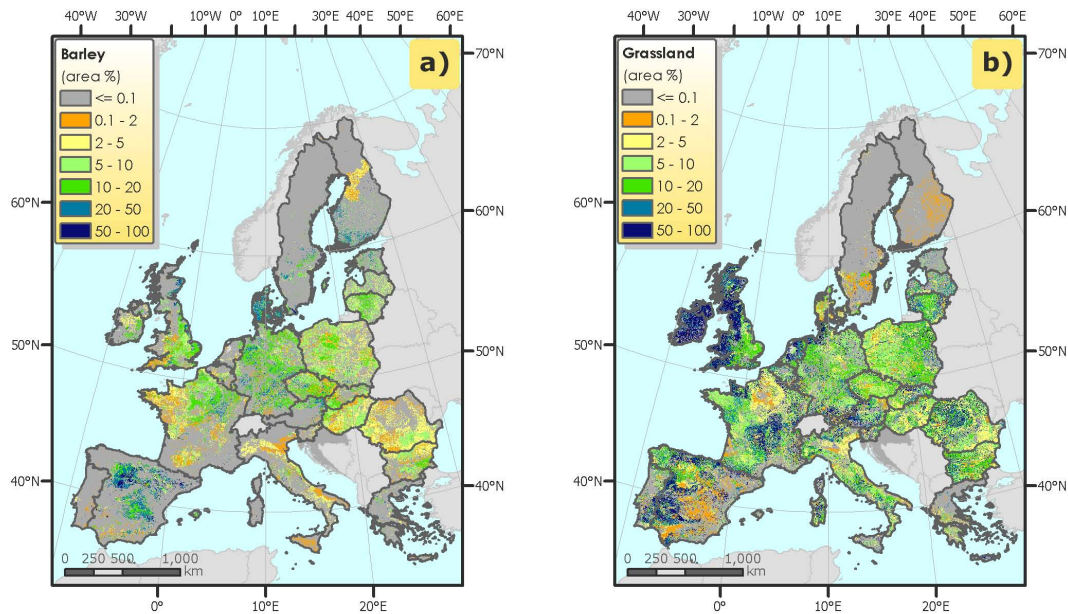


Fig. 5. Examples for the land use map (a) barley cultivation, (b) permanent grassland.

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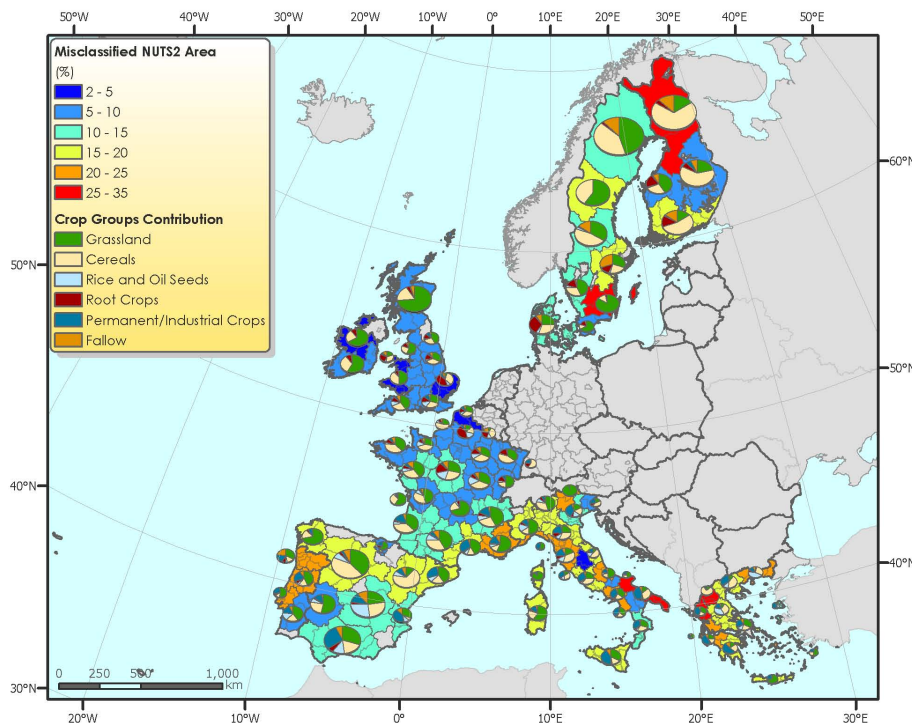


Fig. 6. Percentage of misclassified areas in validated Nuts II Regions after dis-aggregation. The pies show the contribution of different crop groups to the total error in the region (Cereals: Soft Wheat, Durum Wheat, Barley, Rye, Oats, Maize, Other Cereal; Fallow: Fallow Land; Rice and Oil Seeds: Rice, Sunflower, Soya, Texture Crops, Pulses, Other Crops; Root Crops: Potatoes, Sugar Beet, Root Crops, Rape, Nurseries; Permanent/Industrial Crops: Tobacco, Other Industrial, Vegetables, Flowers, Citrus Trees, Fruit Trees, Olive Trees, Vineyards; Grassland: Grassland, Fodder production). Note that the size of the pie is related to the area of the NUTS II region for the purpose of the visualization only.

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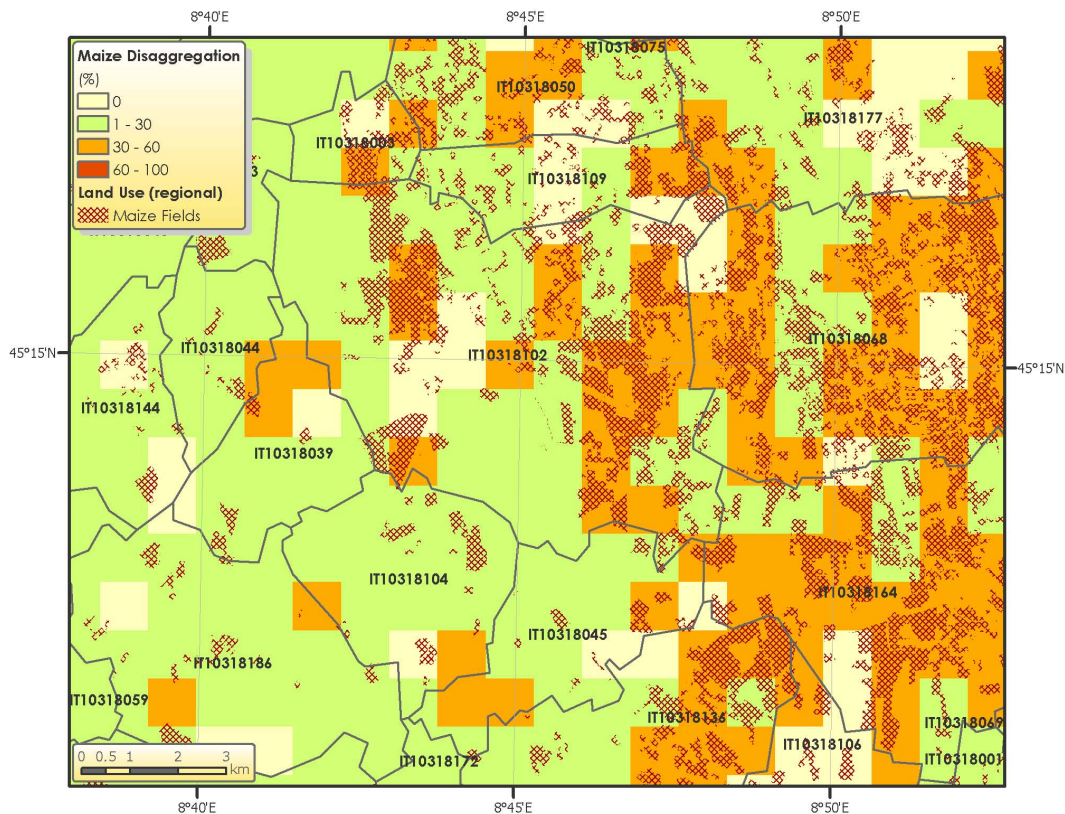


Fig. 7. Dis-aggregation result for maize and maize fields given in the ERSAF (2005) agricultural land use map. The black borders outline individual communes.

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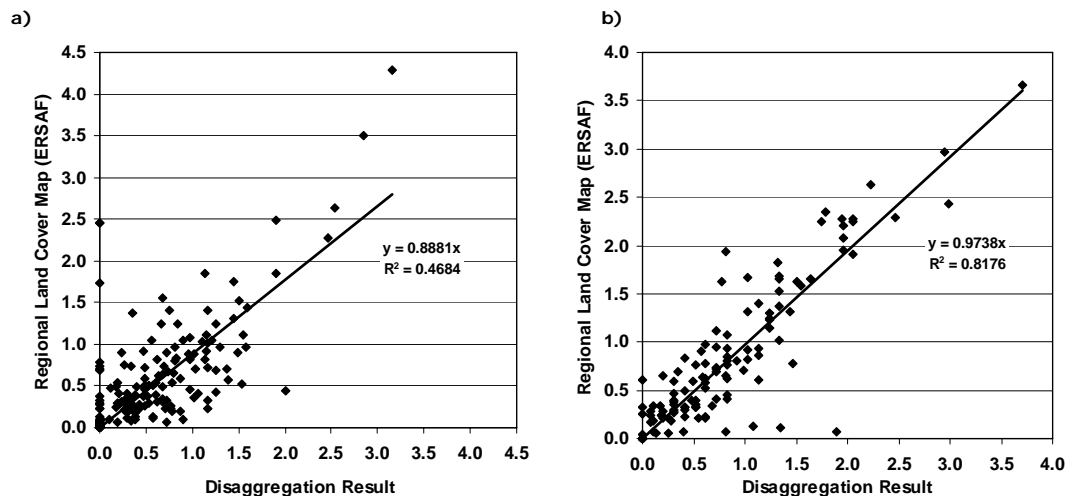


Fig. 8. Comparison of communal data (ERSAF, 2005) and dis-aggregation results for in the Pavia province (Mortara, IT208) for the 190 single communes. Maize (a) and rice (b) distribution as percentage of the total maize (rice) area within the province.

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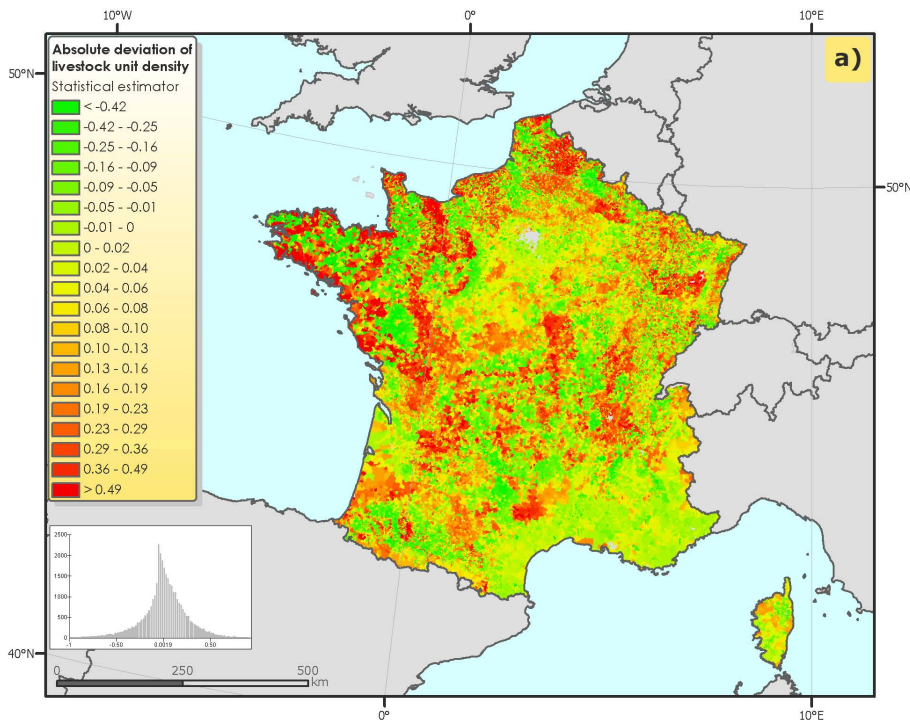


Fig. 9. Error distribution of the distribution algorithm of animal activities, expressed in absolute deviation of the livestock unit density from activity level at commune level for **(a)** the statistical estimator and **(b)** average NUTS III livestock densities.

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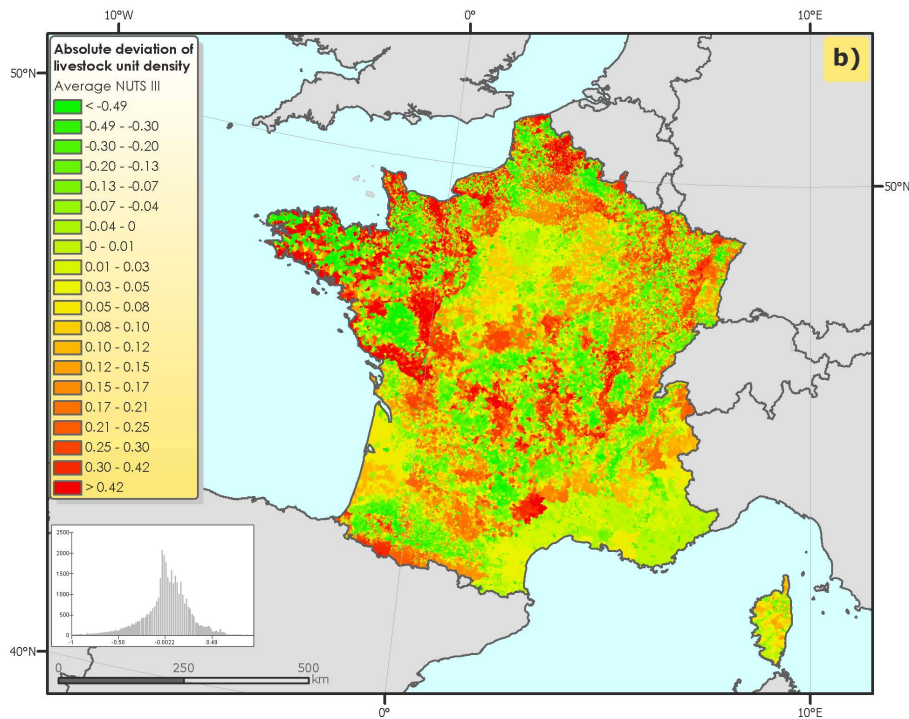


Fig. 9. Continued.

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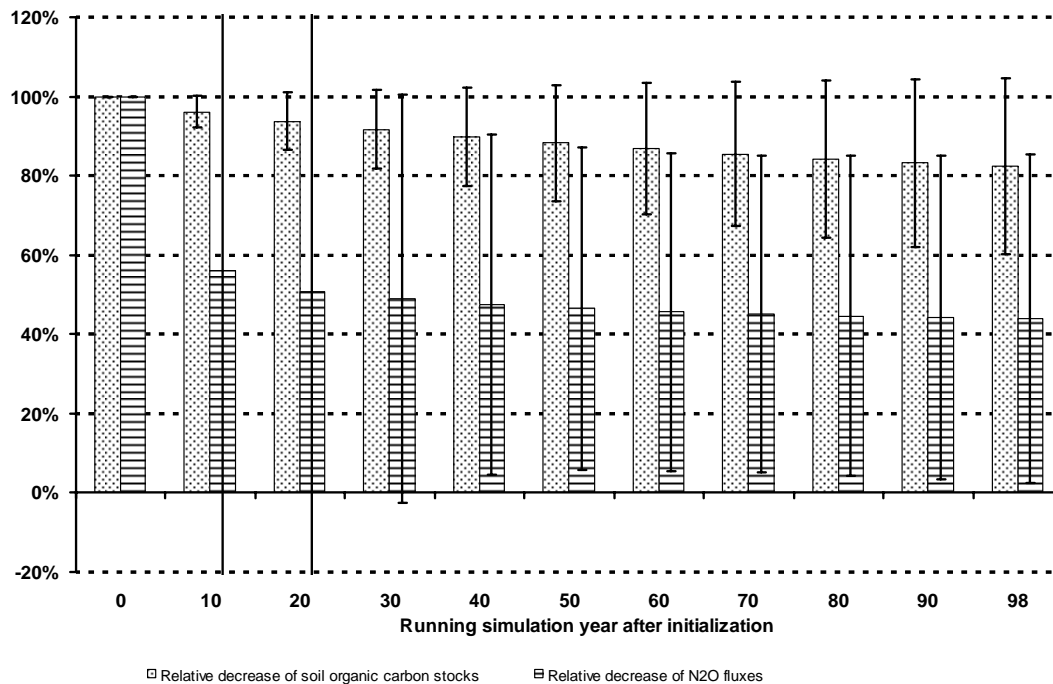


Fig. 10. Decrease of relative mean soil organic carbon content in the top 30 cm of soils (dashed symbols) and relative N₂O flux from the soil surface (dotted symbols), both relative to the situation in the initial simulation year.

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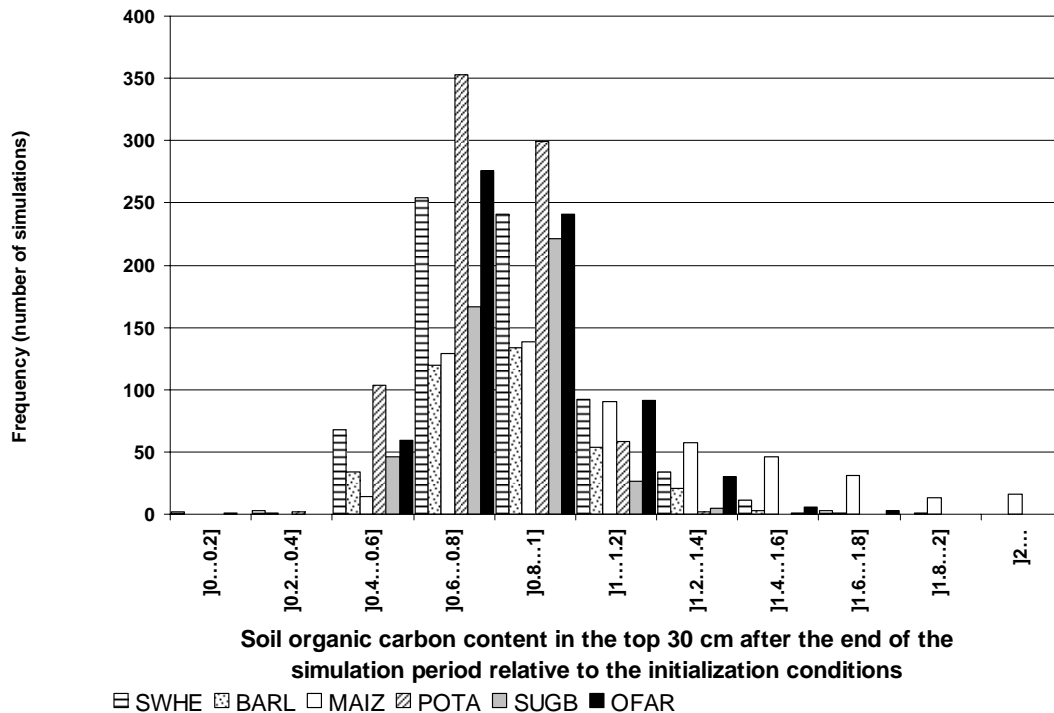


Fig. 11. Histogram for relative changes in soil organic carbon in the top 30 cm of soil for selected crops. SWHE: soft wheat, BARL: barley, MAIZ: corn, POTA: potatoes, SUGB: sugar beet, OFAR: fodder on arable land

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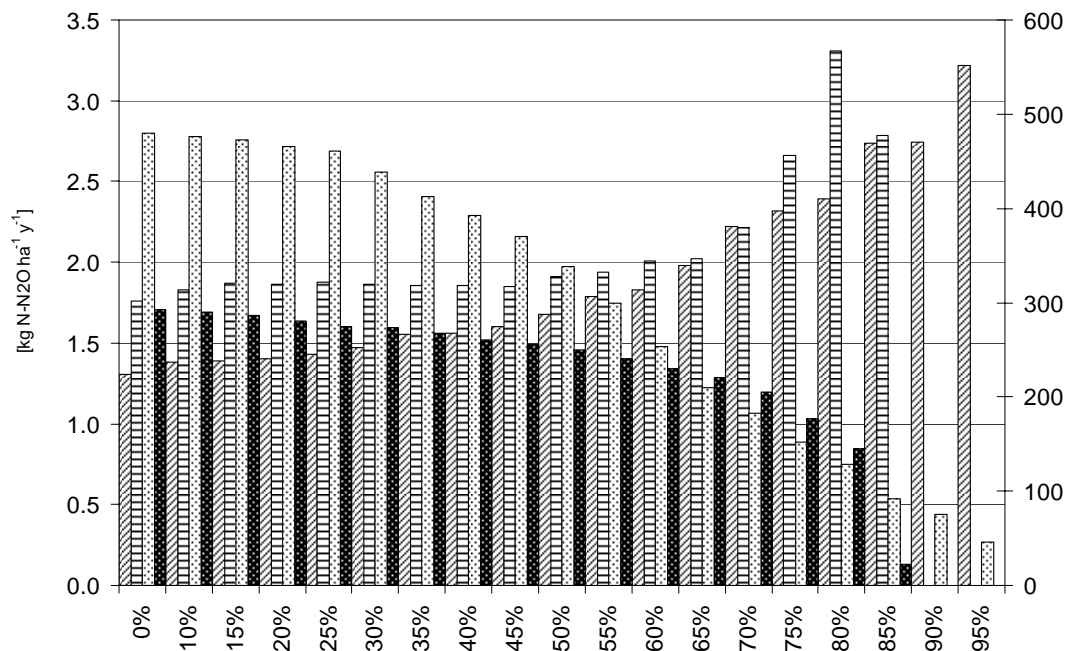


Fig. 12. Number of soft wheat simulations yielding a certain percentage of estimated carbon export during harvest and the corresponding mean fluxes of N₂O. Dotted columns (⋯ and ■) are the number of simulations yielding at least a given percentage of estimated plant carbon uptake (right axis) for soft wheat and barley, respectively, and hatched columns (▨ and ▨) are mean N₂O fluxes estimated on the respective sub-sample of simulations (left axis).

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