Modelling European Agriculture with Climate Change for Food Security
— a FACCE JPI Knowledge Hub —

FACCE-MACSUR

Identified grassland-livestock production systems and related models

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Abstract/Executive summary

This report describes grassland-livestock production systems, as selected for model-based studies. A list of grassland models was identified for evaluation against such datasets (WP2) and application at reference farm (WP3) and regions (WP4) across Europe and peri-European countries.

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Introduction

Process-based models represent a good way for studying the presumed causes of the effects of weather patterns in greater detail, resolving apparently contradictory effects, and projecting consequences of climate change. Models can be used to vary systematically and in combination characteristics of weather patterns, soil properties, and plant characteristics, which would otherwise be hard to achieve logistically or technically in experiments. This report is aimed at: 1) building and exploring datasets on grasslands across European (and peri-European) sites; 2) identifying a list of grassland-livestock models for use in impact assessment studies. The datasets presented, not representative of all European (and peri-European) production systems, illustrate a bench of data covering a variety of climate and management conditions for use in modelling exercises. As well, the models collected are not exhaustive of the large number of models that have been developed to simulate grassland-livestock production systems. They are an inventory of alternative modelling approaches made available through the MACSUR consortium and applied across Europe and peri-Mediterranean regions for impact assessment.

Grassland production systems

Grassland datasets

Different long-term grassland sites were identified. They cover a broad gradient of geographic and climatic conditions (Fig. 1, left) as well as a variety of management practices. Four of them (Laqueuille, France; Monte Bondone, Italy; Grillenburg, Germany; Oensingen, Switzerland) are equipped with an eddy covariance system to determine the net ecosystem exchange (NEE) of CO_2. The eddy covariance system consisted of a fast response 3D sonic anemometer coupled with fast CO_2-H_2O analyzers measuring fluxes of CO_2, latent and sensible heat, and momentum fluxes at a 30-min time step. They are essentially semi-natural grasslands in place since long time including vegetation types representative of the zone (with the exception of the Swiss site of Oensingen, which was established in 2001). Other grassland sites are from observational or experimental research, with focus on forage production under a range of conditions.

The De Martonne-Gottmann aridity index (*b*, De Martonne, 1942) was elaborated for each site. The possibility to discriminate between thermo-pluviometric conditions associated with aridity gradients (Fig. 1, right) is given by the range limits published by Diodato and Ceccarelli (2004): $b < 5$: extreme aridity; $5 \leq b \leq 14$: aridity; $15 \leq b \leq 19$: semi-aridity; $20 \leq b \leq 29$: sub-umidity; $30 \leq b \leq 59$: humidity; $b > 59$: strong humidity.

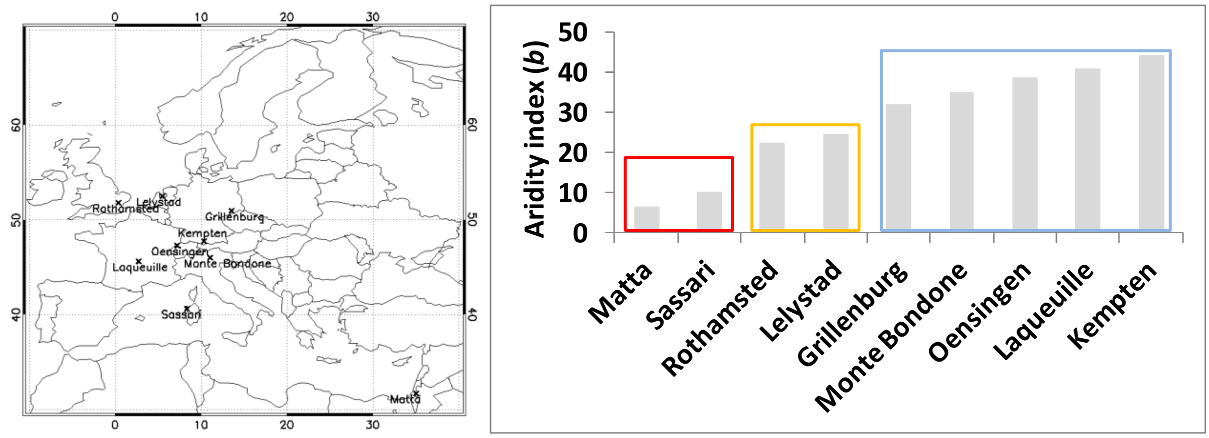

Fig. 1. Geographic location (left) and classification (right) of grassland sites with respect to De Martonne-Gottmann aridity index (*b*). Red box: arid sites; orange box: sub-humid sites; blue box: humid sites.

Grassland flux-tower sites

Laqueuille, France (Klumpp et al., 2011)

This semi-natural grassland is located upland (45°38' N; 02°44′ E; 1040 m a.s.l.) in French region Auvergne. Since spring 2002, the field (6.65 ha) is divided into two adjacent paddocks, continuously grazed by heifers from May to October. One paddock (2.81 ha), referred to as intensive, is adjusted to mean stocking rate of about 1 LSU ha^{-1} yr-^{1}. The second paddock (3.4 ha, extensive) is maintained at about half the stocking rate of the intensive paddock. The intensively grazed paddock receives about 200 kg N ha^{-1} in the form of ammonium nitrate, while the extensive paddock is not fertilized.

Oensingen, Switzerland (Amman et al., 2007)

The experimental grassland site is located on the Central Swiss Plateau in the north-western part of Switzerland (47°17′ N; 07°44′ E; 450 m a.s.l.). Before the experiment, the field was under a ley-arable rotation management with a typical rotation period of eight years, including spring and winter wheat, rape, maize and bi- or tri-annual grass-clover mixture. The nitrogen input, depending on the crop type, was about 110 kg N ha^{-1} yr^{-1} on average (according to the Swiss standard fertilisation practice). In November 2000 the field was ploughed for the last time, and then the area divided into two equal parts (0.77 ha each). They were sown on May 2001 with two grass-clover mixtures typical for permanent grassland under intensive and extensive management, respectively. We refer to the intensively managed field, which was sown with a grass-clover mixture of seven species. It is cut typically four times per year and fertilized with solid ammonium nitrate or liquid cattle manure at the beginning of each growing cycle (after the previous cut). It receives in total about 200 kg N ha^{-1} yr^{-1}.

Monte Bondone, Italy (Wohlfahrt et al., 2008)

This grassland site (46°00′ N; 11°02′ E) is situated in the Italian Alps at elevation of 1500 m a.s.l. It experiences typical Alpine climatic conditions with precipitation peaking in summer. The site is managed as hay meadow, being cut between one and three times per year with occasional grazing in late autumn.

Grillenburg, Germany (Prescher et al., 2010)

This permanent grassland site (50°57' N; 13°30' E; 380 m a.s.l.) is located in the middle of the Grillenburg clearing (around 40 ha) within the Tharandt Forest (in the German Free State of Saxony). Typical and observed plant species are couch grass (*Agropyron repens* (L.) P.Beauv.), meadow foxtail (*Alopecurus pratensis* L.), yarrow (*Achillea millefolium* L.), common sorrel (*Rumex acetosa* L.) and white clover (*Trifolium repens* L.). The grassland is managed by regular cutting two to four times a year. Neither mineral nor organic fertilisers are applied at this site to fulfil criteria of a support programme.

Other grassland sites

Kempten, Germany (Schröpel and Diepolder, 2003)
This experimental grassland site near Kempten in the Alpine foothills (47°43' N; 10°20' E; 730 m a.s.l.) was established on a luvisol with silty loam. The botanical composition of the experimental field is a permanent Lolio-Cynosuretum pasture. The data cover 10 years of extensification levels differing in terms of fertilization (liquid manure, stall manure, calcium ammonium nitrate), cutting frequency (two to four) and date of first cut.

Lelystad, The Netherlands (Schils and Snijders, 2004)
This experimental grassland site (52°30' N; 05°28' E; 4 m b.s.l.) was established on a drained sedimentary calcareous light marine clay soil. The site has been used for dairy farming since 1973, first with amply fertilised perennial ryegrass dominated swards, later with moderately fertilised perennial ryegrass/white clover mixtures. In 1994, the experimental site was ploughed to a depth of 25 cm, and all plots were sown with perennial ryegrass. Additionally, the grass/clover plots were sown with white clover. We refer to grass sward type with three nitrogen levels (N0: 0 kg N ha^{-1}; N1: 200 kg N ha^{-1}; N1: 400 kg N ha^{-1}).

Matta, Israel (Golodets et al., 2013)
This experimental site refers to a "typical" Mediterranean site near Matta (31°42' N; 35°03' E; 620 m a.s.l.). Established on a clay soil, it is essentially a dwarf shrubland dominated by *Sarcopoterium spinosum* L. (Spach) and *Coridothymus capitatus* (L.) Reichb. in association with diverse communities of herbaceous (mostly annual) plant species.

Rothamsted, United Kingdom (Sylverston et al., 2006)
The Park Grass Experiment on permanent grasslands was started in 1856 at Rothamsted (51°48' N; 00°21' E; 128 m a.s.l.), in southeast England, established on ancient grassland. Experimental inputs include a range of mineral and organic fertilizers applied annually, with lime always applied or occasionally to maintain a target level of pH. The experiment contains several grassland types.

Sassari, Italy (Cavallero et al., 1992)
The site of Sassari (40°39' N; 08°21' E; 68 m a.s.l.), located in the Italian region of Sardinia, is representative of mixed Mediterranean grasslands dominated by annual self-reseeding grasses *Avena sativa* L., *Dasypyrum villosum* (L.) Coss. & Durieu ex P., *Bromus hordeaceus* L. and *Lolium rigidum* Gaudin.

Grassland models

Ten models were identified in the frame of Task L2.1. They are grouped as follows:

- Grassland-specific models: AnnuGrow, GRAM, PaSim, SPACSYS
- Crop models with grassland option: EPIC, STICS, ARMOSA
- Biome models including grasslands: Biome-BGC, CARAIB, LPJmL

A brief description follows. Table 1 provides synoptic information about the main processes implemented by each of these models. The types of outputs generated by models are in Table 2.

Grassland-specific models

AnnuGrow

Organization: Thünen Institute of Market Analysis (TI-MA), Germany
Web site: http://code.google.com/p/annugrow
References: Köchy (2008)
Contact: Martin Köchy (martin.koechy@ti.bund.de)

AnnuGrow is a process-based model to quantify the effect of different daily rainfall distributions and compare it to the effect of a change in mean annual amount on vegetation. The model simulates explicitly the response of soil moisture and individual plants to rainfall variability. In addition, it can consider the effects on different life stages and spatial interactions (competition, dispersal). Daily and annual rain amounts are simulated as stochastic time series with specified means. The model was conceived to simulate vegetation in the Mediterranean region, situated between water-stressed subtropical and mesic temperate regions.

GRAM – Grassland Statistical Model

Organization: Agricultural Research and Education Center (BOKU), Austria
Web site: http://www.docstoc.com/docs/108444025/PowerPoint-Pr%EF%BF%BDsentation
References: Trnka et al. (2006); Schaumberger (2010)
Contact: Andreas Schaumberger (andreas.schaumberger@raumberg-gumpenstein.at)

In GRAM, the water balance is a considerable factor in canopy development. The model assumes that grass growth depends on the soil water content in the active root zone (in combination with global radiation, air temperature and management strategies) as well as short- and long-term water stress. It further supposes that all of the supply of water can be attributed to rainfall. Water uptake is then divided mainly between the evapotranspiration and the soil evaporation and percolation to deeper soil.

PaSim - Pasture Simulation model

Organization: French National Institute for Agricultural Research – Grassland Research Ecosystem Unit (INRA-UREP), France
Web site: https://www1.clermont.inra.fr/urep/modeles/pasim.htm
References: Ben Touhami et al. (2013); Graux et al. (2013)
Contact: Raphaël Martin (raphael.martin@clermont.inra.fr)

PaSim simulates water, carbon and nitrogen cycling in grassland systems at sub-daily time step. Microclimate, soil biology and physics, vegetation, herbivores and management are interacting modules. Simulations are limited to the plot scale. Animals are only considered at pasture (not during indoor periods). Photosynthetic-assimilated carbon is either allocated dynamically to one root and three shoot compartments (each of which consisting of four age classes) or lost through animal milking, enteric methane (CH_4) emissions and returns, and through ecosystem respiration. Accumulated aboveground biomass is either cut or grazed, or enters a litter pool. The nitrogen cycle considers nitrogen inputs to the soil via atmospheric deposition, fertilizer addition, symbiotic fixation by legumes, and animal faeces and urine. The inorganic soil nitrogen is available for root uptake and may be lost through leaching, volatilization and nitrification/denitrification, the latter processes leading to nitrous protoxide (N_2O) gas emissions to the atmosphere. Management includes organic and mineral nitrogen fertilizations, mowing, and grazing, with parameters set by the user or optimized by the model.

SPACSYS - Soil Plant Atmosphere Continuum System

Organization: Rothamsted Research - North Wyke (RRes-NW), United Kingdom
Web site: http://www.rothamsted.ac.uk/people/wul
References: Wu et al. (2007); Wu and Shepherd (2011)
Contact: Lianhai Wu (lianhai.wu@rothamsted.ac.uk)

SPACSYS is a multi-dimensional, field scale, weather-driven dynamic simulation model of carbon and nitrogen cycling between plants, soils and microbes, operating with a daily time-step. It includes a plant growth and development sub-model with detailed representation of the root system, in addition to sub-models for carbon and nitrogen cycling in the soil with links to the plant, a soil water component, and a heat transfer component. Carbon and nitrogen are held in a number of above- and below-ground pools, and flows between pools are simulated. The representation of soil carbon and nitrogen processes is detailed in relation to nutrient cycling from decaying root material. The water component includes a horizontal water flow that drives heat and nitrate moving. The soil carbon cycling is a one-dimensional component. The values of state variables in a soil layer that need to be derived from the root systems are set by taking account of each root segment value within the soil layer. The model simulates the removal of carbon and nitrogen from grass or grass-clover mixtures, and the return of carbon and nitrogen from urea or dung if grazing occurs.

Crop models with grassland option

ARMOSA - Monitoring and modelling nitrogen cycle and crop growth in arable land

Organization: University of Milan - Department of Plant Production (UNIMI), Italy
Web site: http://www.diprove.unimi.it/groups/agro_rg1.htm
References: Perego (2010)
Contact: Marco Acutis (marco.acutis@unimi.it)

ARMOSA is a cropping system simulation model originally developed to estimate nitrogen dynamics in soil-crop-atmosphere continuum and evaluate the impact of agricultural management on shallow and groundwater quality. A micro-meteorological module simulates the energy balance, allowing for evapotranspiration estimation in plain and slope areas, while a plant module estimates plant development and growth using temperature and direct and diffuse radiation. A third module calculates the soil water balance, and a forth one the soil nitrogen and carbon balances.

EPIC - Environmental Policy Integrated Climate

Organization: University of Sassari – Department of Agricultural Sciences (UNISS), Italy
Web site: http://epicapex.tamu.edu
References: Gassmann et al. (2007); Williams et al. (2008)
Contact: Giovanna Seddaiu (gseddaiu@uniss.it)

Originally developed to estimate soil productivity as affected by erosion, EPIC is designed in a generic form to allow simulation of a large variety of crops and grasses. It uses one plant growth model with unique parameter values for each crop. It can be configured for a wide range of crop rotations and other vegetative systems, tillage systems, and other management strategies. It predicts effects of management decisions on soil, water, nutrient and pesticide movements, and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management.

STICS - Multidisciplinary simulator for standard crops

Organization: French National Institute for Agricultural Research – Modelling Agricultural and Hydrological Systems in the Mediterranean Environment (INRA-EMMAH), France
Web site: http://www7.avignon.inra.fr/agroclim_stics_eng/presentation
References: Brisson et al. (2003); Ruget et al. (2006)
Contact : Françoise Ruget (francoise.ruget@avignon.inra.fr)

The crop model STICS is a generic, daily-step, initially patch-scaled model, designed to give as main outputs (i) the crop development and growth, leading to estimations of yield; (ii) quantities of environmental factors (light, CO_2, water and nitrogen) used; and (iii) environmental effects on the soil such as variations of water profile and mineral nutrients, organic matter dynamics, as well as water drainage and nitrogen leaching. The aim is to represent growth over the whole cycle of crops (days to years) taking into account fixed starting data (soil status), cultivation conditions (species, cultivar, soil type) and variations imposed by climate, as well as variations in technical management. The modular structure of STICS and the basic processes covered allow for the simulation of many crops and conditions (climate types, soils, management). A set of parameters enables the model to simulate either sown or established mowed grasslands (temporary or perennial).

Biome models including grasslands

Biome-BGC MuSo - Biogeochemical cycles with multi-layer soil module

Organization: Institute of Ecology and Botany - Centre for Ecological Research of the Hungarian Academy of Sciences (IEB-CER-HAS), Hungary
Web site: http://www.ntsg.umt.edu/project/biome-bgc
References: White et al. (2000); Hidy et al. (2012)
Contact: Zoltan Barcza (bzoli@elte.hu)

Biome-BGC MuSo implements a multilayer soil module, improved grassland phenology and management routines into the Biome-BGC, which was originally developed to simulate undisturbed ecosystems. Biome-BGC is a mechanistic biogeochemical model simulating the storage and flux of water, carbon, and nitrogen between the ecosystem and the atmosphere, and within the components of the terrestrial ecosystems. It is a multi-biome generalization of FOREST-BGC, a model originally developed to simulate a forest stand development through a life cycle. Biome-BGC model family requires daily meteorological data and the definition of climate, vegetation, and site conditions to estimate fluxes of carbon, nitrogen, and water through ecosystems. Allometric relationships are used to initialize plant and soil carbon and nitrogen pools within the ecosystem.

CARAIB - Carbon Assimilation in the Biosphere

Organization: University of Liege (ULG), Belgium
Web site: http://orbi.ulg.ac.be/handle/2268/155872
References: Warnant et al. (1994); Dury et al. (2011)
Contact: Julien Minet (julien.minet@ulg.ac.be)

CARAIB is a process-based dynamic vegetation model of carbon assimilation in the biosphere. The model considers the annual and diurnal cycles. It calculates carbon fluxes between the atmosphere and the terrestrial biosphere (i.e., vegetation-soil system), and estimates the evolution of carbon pools resulting from these fluxes. Five pools are considered: (1) the leaves; (2) the rest of the plant (remaining carbon; i.e., branches, stems, and roots); (3) the litter from the leaves; (4) the litter from the remaining carbon; and (5) the humus (soil carbon; i.e., the product of litter decomposition). The model implements plant functional types (PFTs) including C3 and C4 grasses, needle-leaved evergreen and deciduous trees, temperate and tropical broad-leaved evergreen trees, and temperate and tropical broad-leaved deciduous trees. Carbon contents and fluxes in and out of each pool are estimated daily for each PFT. Specific information on vegetation distribution and properties is used at the leaf physiological level, the plant level, the ecosystem level, and the global level.

LPJmL - Lund-Potsdam-Jena managed Land

Organization: Potsdam Institute for Climate Impact Research (PIK), Germany
Web site: http://www.pik-potsdam.de/research/projects/lpjweb
References: Bondeau et al. (2007); Waha et al. (2012)
Contact: Susanne Rolinski (rolinski@pik-potsdam.de)

Based on the LPJ-Dynamic Global Vegetation Model, LPJmL simulates vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. Using a combination of eco-physiological relations, generalised empirically established functions and plant trait parameters, it computes processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, runoff, evapotranspiration, irrigation, and vegetation structure. It uses generic crop functional types (CFTs), which represent plant prototypes partly with climatically adapted varieties. Grid cells are divided into natural vegetation, agricultural land and managed grasslands.

Table 1. List of grassland models and the main processes they simulate.

Processes	Grassland models									
	Grassland-specific models				Crop models			Biome models		
	AnnuGrow	GRAM	PaSim	SPACSYS	ARMOSA	EPIC	STICS	Biome-BGC MuSo	LPJmL	CARAIB
Phenology	Daily growth rate as a function of water potential	Harvesting dates	Growing degree days	Growing degree days	Growing degree days calculated with trapezoidal approach on the BBCH-scale (Meyer, 2001) and based on STAMINA (Ferrara et al., 2009; Richter et al., 2010)	Growing degree days	Dependence on temperature, photoperiod and vernalization	Extension of growing season index (Jolly et al., 2005; Hidy et al., 2012)	Growing degree days (Sitch et al., 2003)	Dependence specific parameters f each specie
Photosynthesis	-	-	Light response curve	Johnson and Thornley (1994)	Based on gross CO_2 assimilation; partition according to development stage; stress due to nitrogen and drought (after SUCROS - WOFOST, van Keulen et al., 1982; van Keulen and Wolf, 1986)	Radiation use efficiency	Radiation use efficiency	Farquhar et al. (1980); De Pury and Farquhar (1997); Di Vittorio et al. (2010)	Farquhar et al. (1980)	Farquhar et a (1980) for C species / Coll et al. (1992) f C4 species
Stomata	-	-	Leuning (1995)	Lohammar et al. (1990)	-	Maximum stomatal conductance (Körner et al., 1979)	Analogous to stomata for water stress, ET calculation and CO_2 concentration effect	Körner (1994); Hidy et al. (2012)	Collatz et al. (1991)	Leuning (199
Carbon allocation mechanism	Life stage (mass)	-	Dependence on development stage	Dependence on development stage	Dependence on development stage	Based on CENTURY (Parton et al., 1988)	Dependence on phenological stage and partitioning option	Fixed ratio (defined by parameter)	Daily allocation according to water stress mediated leaf to root mass ratio	Simple allocati scheme depending o phenological stages
Nitrogen uptake mechanism	-	-		Michaelis-Menten (1913) kinetics plus passive uptake	Dilution curves in the root zone for nitrate and ammonium nitrogen (Justes et al., 1994)	Mass flow of NO_3-N to the roots plus optimal crop nitrogen concentration declining with growth stages (Jones, 1983)	Active absorption including two uptake systems	Controlled by competition between plant and microbial immobilization (nitrogen allocation to plant controlled by	-	-

								fixed parameter)		
Root growth	Access to soil layers depending on shoot mass	-		1D root penetration or 3D root architecture	Dependence on crop sort, soil temperature, moisture, partitioning, development stage; soil water uptake by plant roots: reduction of potential rates dependent on pressure heads (function by Feddes, 1978; based on STAMINA, Ferrara et al., 2009; Richter et al., 2010)	Function of heat units and potential root zone depth	Dependence on soil temperature, moisture and physical constraints	Campbell and Diaz (1988)	Based on allometric function for root distribution depending on carbon allocated	Budget of nor leaf carbon
oil water transport	Balancing of soil water potential	Based on deep percolation in topsoil and subsoil	Darcy (1856)	Richards (1931)	Based on SWAP (van Dam et al., 2008)	Based on APEX (Williams et al., 2012)	Soil capacity approach with five layers	Chen and Dudhia (2001); Balsamo et al. (2009)	Infiltration depending on soil water content; percolation based on SWIM (Krysanova et al., 1998; after Arnold et al., 1990)	Based on soi water conductivity (calculation c drainage)
Soil temperature	-	-	Energy balance	Fourier's equation (van Bavel et al., 1976)	Heat conduction dependent on air temperature, soil surface temperature, depth (Parton, 1984)	Function of soil surface temperature, depth, and a lag coefficient	Simplified energy balance	Zheng et al. (1993)	Energy balance approach (Schaphoff et al., 2013)	Simplified calculation frc soil surface energy budge
Evapotranspiration	Empirical function of air temperature and soil water potential	Penman-Monteith equation (Allen et al., 1998), with adjustment to grassland by crop coefficient factor and to non-standard conditions	Penman-Monteith (Allen et al., 1998)	Penman-Monteith equation (Allen et al., 1998)	Penman-Monteith equation (Allen et al., 1998); bare soil evaporation dependent on soil moisture in the first 0.1 m (Campbell and Diaz, 1988)	Penman-Monteith equation (Allen et al., 1998)	Crop coefficient or resistive model (Shuttleworth and Wallace, 1985)	Penman-Monteith equation (Allen et al., 1998)	Priestley and Taylor (1972)	Fraction of potential evapotranspira n itself calculated fro Penman

		(water stress)								
Soil respiration	-	-	Based on CENTURY (Parton et al., 1988)	Q10 equation	Based on soil-plant carbon balance	-	Dependence on soil organic pools, temperature, moisture and mineral nitrogen	Sum of heterotrophic and root respiration (Thornton and Rosenbloom, 2005)	Sitch et al. (2003); Schaphoff et al. (2013)	Based on calculated valu of litter, soil carbon conten soil temperatu and soil moistu
N_2O emission	-	-	Dependence on soil moisture and temperature	Denitrification estimation or microbial activity-based estimation based on DNDC (Li et al., 2000)	Based on DNDC (Li et al., 2002)	-	Dependence on soil potential rates, temperature, moisture and mineral nitrogen	-	-	-

Table 2. Types of outputs generated by each model.

Outputs[†]	**Grassland models**									
	Grassland-specific models				**Crop models**			**Biome models**		
	AnnuGrow	**GRAM**	**PaSim**	**SPACSYS**	**ARMOSA**	**EPIC**	**STICS**	**Biome-BGC MuSo**	**LPJmL**	**CARAIB**
Gross primary productivity (GPP, g C m^{-2})	-	-	X	X	-	-	-	X	X	X
Net ecosystem exchange (NEE, g C m^{-2})	-	-	X	X	X	X	-	X	X	X
Net ecosystem respiration (RECO, g C m^{-2})	-	-	X	X	X	-	-	X	X	X
Actual evapotranspiration (ET, mm)	X	X	X	X	X	X	X	X	X	X
Soil temperature – top 10 cm (ST, K)	-	-	X	X	X	X	X	X	X	X
Soil moisture – top 10 cm (SM, m^3 m^{-3})	X	-	X	X	X	X	X	X	X	X
Harvested aboveground biomass (HAB, g DM m^{-2})	X	X	X	X	X	X	X	X	X	X

[†] Yearly or higher resolution.

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