Advances in Land Surface Modelling

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Abstract

Land surface models have an increasing scope. Initially designed to capture the feedbacks between the land and the atmosphere as part of weather and climate prediction, they are now used as a critical tool in the urgent need to inform policy about land-use and water-use management in a world that is changing physically and economically. This paper outlines the way that models have evolved through this change of purpose and what might the future hold. It highlights the importance of distinguishing between advances in the science within the modelling components, with the advances of how to represent their interaction. This latter aspect of modelling is often overlooked but will increasingly manifest as an issue as the complexity of the system, the time and space scales of the system being modelled increase. These increases are due to technology, data availability and the urgency and range of the problems being studied.

Keywords Land surface models · Climate models · Model frameworks

Introduction

We are approaching an interesting junction with Land Surface Models (LSMs). Early models such as the Biosphere-Atmosphere Transfer Scheme (BATS) [37, 38] and the Simple Biosphere Model (SIB) [122, 123] pioneered the use of linked soils and vegetation to describe the energy and water exchanges with the atmosphere. Since then, after decades of research, much is known about the land as a system and how to model it [109].

While originally the models were designed to capture the essential features of land-atmosphere interactions, we have learnt that provision of our food and energy also depends on these interactions between climate, soil, water and the

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vegetation. The models we have built to describe these inter-
actions are being urgently re-cast to help us make decisions
about the management of our environment to build resilience
to a changing climate.

But, there is complexity both within the land-system, and
how it interacts with other systems such as the atmosphere and
the human system. To make progress, we need to address the
challenges of heterogeneity, of complexity and of human-in-
teraction. In their 'Perspectives' paper, [49] acknowledge the
challenges of heterogeneity and complexity and propose some
practical ways forward using the current LSM framework.

In this paper, we present a review of land surface model-
ling: its history, recent advances and issues that are limiting or
inspiring a way forward, in particular to bring in the human-
interaction dimension. We focus on two important aspects to
modelling:

1. Processes within a component of the land-system.
2. Exchanges between components dealing with scale mis-
    match and heterogeneity.

This paper aims to provide a review of how these two
aspects of land surface models have evolved and how an un-
derstanding of their separate role may help us to provide a
robust future for land surface modelling.

In writing this review, we worked with a selection of
modelling groups from around the world to represent the var-
ious approaches to Land Surface Modelling. All of the models
are part of a climate or earth system model, but some have a
greater focus on land-use and carbon, while others focus more
on the global water cycle. It is not possible to capture all the
papers and model developments that have resulted from the
massive scientific effort taking this subject forward. In the
appendix, there is a table that includes the 11 of the main land
surface models in current use in climate modelling. Table 1
highlights the Climate/Earth System Models with which these
11 models are associated. The shared model developments of
these 11 models are summarised.

Basic Concepts Used in This Paper

The following schematic (Fig. 1) summarises the ideas pre-
sented in the paper. The processes are arranged in the horizon-
tal from left to right representing the different timescales:

roughly hourly to decadal. This highlights the huge range of
timescales that the land surface models perform in. The ex-
changes are clearly critical in moving across this temporal
range. In the vertical, the processes are working at different
spatial scales and the exchange schemes are designed to deal
with heterogeneity. The schematic is a generalisation of the
current model structures while every model is slightly differ-
ent. Figures 2 and 3 summarise the developments of the com-
ponents (2) and exchanges (3) in three categories: historic (pre
2000), recent and future. A summary of the papers describing
how each model treats these processes and exchanges is given
in the Appendix.

In the next 5 sections, history and development of the pro-
cesses and linkages are explored. They are grouped together
as follows:

> Section 2: Canopy Processes with Land-Atmosphere
> Exchange
> Section 3: Snow and Soil Physics with Surface-
> Subsurface Exchange
> Section 4: Water Bodies with Land-Catchment and
> Water-People Exchanges
> Section 5: Vegetation Physiology and Soil
> Biogeochemistry with Physics-Biogeochemistry
> Exchange
> Section 6: Vegetation Dynamics and Land-Use with
> Vegetation-Landscape Exchange

We will make some conclusions in the final section (7).

Surface and Canopy Processes with Land-Atmosphere Exchange

This section addresses the physics of the exchange of momen-
tum, water, energy and carbon between the land and the at-
mosphere. The processes include turbulence, evaporation and
radiation transfers while the exchange critically involves tech-
niques to accommodate the different spatial and temporal
scales of the land (small spatial scale, long time scale) and
atmosphere (long spatial scale, short time scale) through ag-
gregation of the land fluxes and disaggregation of the meteo-
rological variables. Figure 4 gives an overview of the process-
es discussed in this section.

Table 1   Eleven land surface models and their associated Climate/Earth System Model

	CABLE	CLASSIC	CLM	CoLM	G/LM	ISBA	JSBACH	JULES	Matsiro	Orchidee	TESSEL
C/ESM	ACCESS	CanESM5	CESM	CAS-ESM	ESM2M	CNRM-CM6	MPI-ESM	UKESM	MIROC	IPSL-CM5	EC-Earth
			NorESM	CAMS-CSM	ESM2G	CNRM-ESM	ICON-ESM		NICAM		
			CMCC	BNU-ESM							

Fig. 1 Schematic of Land Surface Model showing Components (process or module) and the exchanges between components across temporal scales (hourly to decadal)
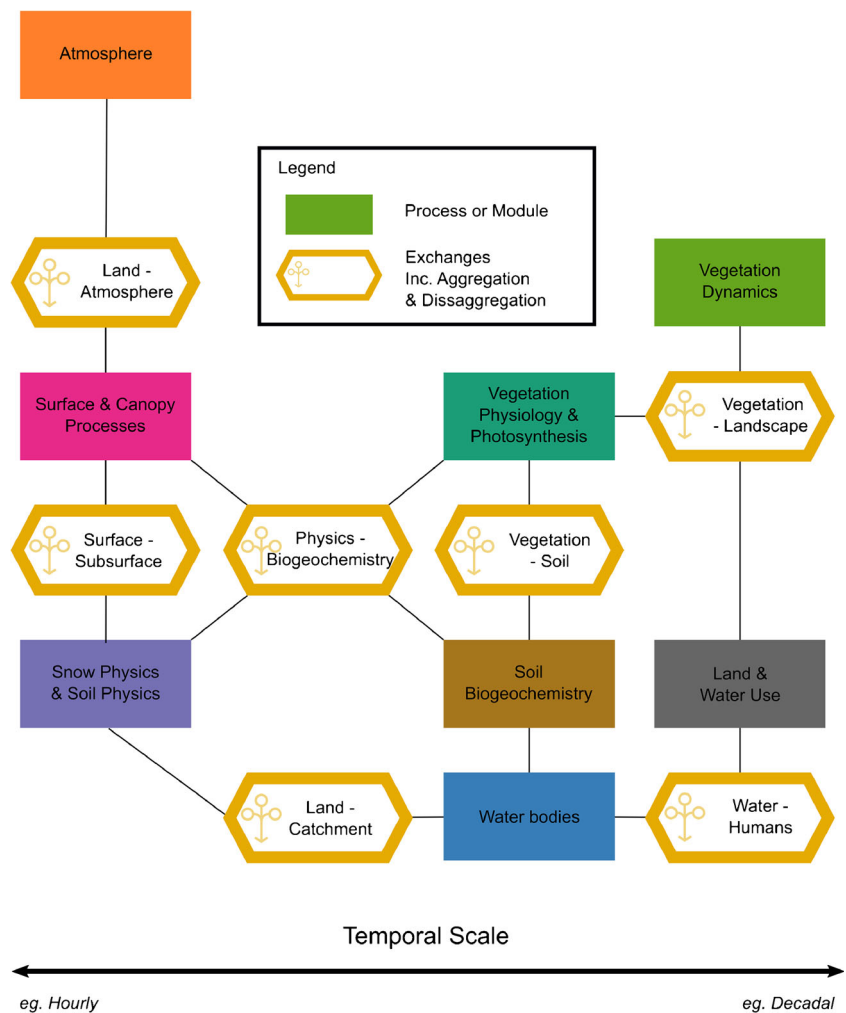
History

Momentum transfer is a fundamental part of weather forecasting and research goes back to the early 1900s (for a review see Anderson [2]). The turbulent transfer of momentum was represented using a bulk transfer equation with a roughness length that depended on the surface. In the 1970s, it became common practice to use this approach for the latent and sensible heat transfers, but with a smaller (× 0.1) roughness length. To simplify the problem, the same roughness length was used for both water and heat (and now carbon) fluxes.

Inclusion of carbon exchanges in LSMs was introduced in the 1990s. The sensitivity of photosynthesis to light levels meant that LSMs needed to represent the filtration of light through the plant canopy. The first attempts to do this used Beer's Law [123] and then an improved 'two-leaf' model which represents a sunlit and shaded canopy ([26, 36]; Y. [139]).

One of the great challenges for the land-atmosphere exchange is the contrast of the spatial and temporal scales involved. The land has a fine spatial structure with variations in

land cover at scales of 100 m, but evolves relatively slowly (weekly), while due to the mixing of the air, the atmosphere has dominant spatial scales of 10 km or 1 km for convective systems, with a temporal scale of hours or even minutes for convective systems. The exchange of key variables such as rainfall, radiation, evaporation and momentum need to accommodate these different scales. Many of the assumptions used to aggregate and disaggregate the variables are implicit and buried within the model code. It is important that we understand these assumptions and make them explicit so that when the models change their scale (for instance as we move into convective permitting models), we can continue to correctly represent these exchanges. In the following, two examples of how models accommodate these differences in scale are described.

Precipitation given by a weather or climate model is the hourly-average over a large area (up to 100 km^2). Over this time-space, it appears to be drizzling all the time [110]. The exchange scheme needs to account for this misrepresentation of the true heterogeneous, spikey nature of precipitation. Dolman and Gregory [39] used a statistical description of

LSM Component	Basic Description	Pre 2000	Recent Advances	Future Directions
Surface & Canopy Processes	Physics of the surface affecting exchange of the momentum, water, energy and carbon.	Turbulent exchange of momentum, heat, water and carbon. Beer's law for radiation attenuation through canopy.	Multiple canopy layers for radiation attenuation.	Multiple canopy layers for energy, water and carbon exchanges. Microclimate within vegetation canopy.
Snow Physics & Soil Physics	Transfer of energy, heat and water vertically through the medium of snow or soil.	Darcy-Richards equation. Soil freezing included. Single snow layer.	Deeper soil layers for Permafrost. Organic soils included. Multiple snow layers.	Flows of water across the grid. Soil tiles for heterogeneity of soils.
Water bodies	Water that is stored and flows across the landscape, such as rivers, lakes, wetlands, glaciers and groundwater.	Riverflow transported to ocean with no losses.	Inundation, wetlands and groundwater.	Nutrients and water quality. Representation of hillslope-scale dynamics including interaction with river network and groundwater.
Vegetation Physiology & Photosynthesis	Plant processes that affect the uptake and allocation of the net carbon into roots, shoots and leaves.	Photosynthesis linked to transpiration. Phenology included. Carbon uptake affects plant growth and LAI.	Introduce dynamic nitrogen cycle to affect photosynthesis.	Acclimation of plants to temperature. Response to increase of CO_2.
Soil Biogeochemistry	Soil carbon processes and its interaction with the nitrogen cycle.	Single carbon store with respiration linked to moisture and temperature.	Multi-layered soil carbon. Linked nitrogen and soil carbon.	More nutrients such as phosphorus. Acclimation of soil carbon respiration to temperature changes.
Vegetation Dynamics	Land cover changes due to competition and disturbance including fire and mortality.	Vegetation competition based on height.	Mortality due to fire, pests and drought. Age-classes of forests introduced.	Vegetation distribution linked landscape heterogeneity through soil tiles.
Land & Water Use	How humans alter the vegetation and water distribution.	Agriculture defined as a land-cover type	Different crop-types included.	Link to other models for food and water use. Irrigation dynamic with water need and available.

Fig. 2 Land Surface Model Component development for pre 2000, recent advances and future directions

rainfall intensity distribution to counteract the drizzle effect in the JULES model [9] to improve the representation of infiltration and interception.

Up until the 1990s, each grid box had only one dominant land-cover type. The first breakthrough for representing the true heterogeneity of the land-surface came with the use of tiles, so that each land-cover occupied a fraction of the grid box with a separate energy balance equation for each. This approach was pioneered by Koster and Suarez [75] and now tiling schemes are commonly used, aided by the availability of high-resolution remote sensing datasets (1 km or finer) (e.g. [3, 45, 54, 61, 87]).

Recent Advances

Direct light throws hard shadows unlike diffuse light, which, coming from many angles reaches down further into a tree canopy. A recent improvement in LSMs is to replace the Beer's Law or the 'two-leaf' model with a 'multi-layer' scheme [12–14]. The impact of this on the carbon balance is notable [96]. The new 'multi-layer' models need the direct and diffuse components of incoming shortwave radiation to be quantified.

Recently, tiling schemes have been improved by using new data on ecological trait databases [70, 71] to increase the number of Plant Functional Types (PFTs) [62, 141]. In addition, the most advanced LSMs have included soil tiles as well as vegetation tiles [33, 48, 63, 114, 116].

Current Limitations and Future Directions

While the momentum fluxes are well represented (having the advantage of a single boundary condition of zero wind speed), the science behind the transfer of heat and water is more complex. For instance, in a typical landscape, there are several surfaces with different energy budgets which vary in time (as leaves wet up and dry out, as the sun comes in and out) and space (within a canopy, below a canopy, mixtures of vegetation and soil). All these surfaces contribute to the surface temperatures which acts as the boundary condition to the atmosphere. A good summary of this issue of heterogeneity is given by Verhoef et al. [135].

Even within a canopy, there are potential improvements that can be made to represent different canopy structures and their impact on the light, temperature, momentum water and carbon exchanges. One way forward is to model the different

LSM Exchange	Basic Description	Pre 2000	Recent Advances	Future Directions
Land - Atmosphere	Exchanges between the land and the atmosphere; involves aggregation of the land fluxes and disaggregation of the meteorological variables.	Rainfall intensity distribution accounted for. Tiled representation of vegetation.	Improved description and more tiles. Direct and diffuse short-wave radiation available.	Exchange scheme is flexible to match a range of model grid sizes.
Surface - Subsurface	Exchange of water and heat between the surface and soils below ground and the snow-pack.	Rainfall-runoff model assumes statistical heterogeneity of soil moisture.	Rainfall-runoff model includes topography and groundwater.	Tiled soils will include explicit description of soil heterogeneity.
Physics - Biogeochemistry	Temperature and moisture affect the plant and soil processes. Changes in structure affects the physics.	Moisture and temperature affect biological systems such as photosynthesis and respiration. Light levels affect photosynthesis. Changes to plants structure affect roughness length.	Soil moisture and temperature at deeper layers affect soil carbon.	Distribution of leaf temperatures through the canopy to affect photosynthesis. Roots respond to groundwater level. Changes to the soil hydraulic properties from changes in carbon content.
Vegetation - Soil	The movement of carbon and nitrogen between the plants and soil is through leaf-litter and nutrient uptake by the plants.	Carbon from leaf litter transferred to soils.	Nitrogen in the leaves transferred to soils. Nutrient levels in soils taken up by plants.	More information about nutrient content of leaf litter. Improved representation of plant nutrient uptake.
Vegetation - Landscape	Vegetation competition and the agriculture affect the land-cover.	Dynamic vegetation model informs tile fractions. Agriculture fraction fixed.	More tiles used to describe age-classes.	Age classes inform forestry and land-use tiles. Agriculture tiles dynamic with land-use and climate. Better description of heterogeneity to interpret land-use decisions.
Land - Catchment	Overland runoff flows laterally over large catchments. At certain hotspots, the water flows back onto the land.	Water is routed to the sea.	Inundation and irrigation can interact with the energy and water cycle.	Groundwater, river and wetland systems are fully integrated with modelled hillslope-scale soil hydrology and with energy and nutrient cycles.
Water - Humans	Anthropogenic control of water flow to and from rivers through abstractions but also transfers.	Water from the land supplies the rivers.	Irrigation and other anthropogenic water uses.	Humans will direct changes to the water abstractions, the water use and transfers.

Fig. 3 Land Surface Model Exchange developments for pre 2000, recent advances and future directions

surfaces explicitly. For instance, Ma and Liu [89] explore the impact of an explicit representation of the canopy. There are challenges in that the turbulence throughout and below the canopy affect the microclimatic profiles of air temperature, humidity and windspeed [13, 14]. Use of the many flux-tower data that capture sub-diurnal momentum, energy, water and carbon fluxes for different sun-angles, difference light-diffusiveness and different temperatures would enable us to quantify the role of canopy structure.

In addition to the increase in complexity of the component model, the exchanges between the land and atmosphere also need to be improved. The exchange needs to respond to the time and spatial scale of the atmosphere model. For instance, when using a convection permitting atmosphere model, the precipitation becomes more intense (no drizzle effect) and assumptions about the transfer of scales no longer apply. At smaller scales, the tiles may become obsolete. In its place, the heterogeneity of the water stores across the land may become more important (see Section 4).

Fig. 4 Schematic of surface and canopy processes represented in LSMs
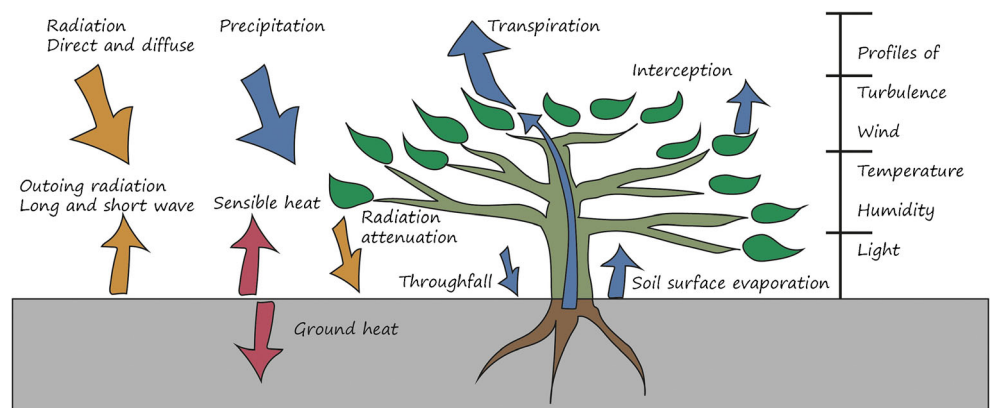
Finally, as Land Surface Models are used a finer scales and feeding policy direction for human health and wellbeing, the need for improvements to the representation of Urban land-surface is becoming more urgent. Urban areas give rise to phenomena such as 'urban islands', and are subject to more extreme flooding conditions due to the reduced infiltration capacity. The first Model Intercomparison of Urban models is just being published and shows how varied they are [57].

Snow and Soil Physics with Surface-Subsurface Exchange

This section deals with the transfer of energy, heat and water through snow or soil. Exchanges between the surface and canopy layer and the soils need to accommodate the heterogeneity of soil properties and soil-water across the landscape and with depth. Figure 5 gives an overview of the processes discussed in this section.

History

The water from precipitation has several possible fates. It might flow into the soil matrix where it will be stored before being lost through evapotranspiration or drainage. If the water remains on, or near, the soil surface it may evaporate, or if the ground is sloped or already saturated, it can contribute to runoff.

Since the early twentieth century, research has been undertaken to describe the flow of water through unsaturated soil. Combining the gravitational force and capillary force together, the flow of water in the soil can be summarised in one equation, known as the Darcy-Richards equation [117]. This equation is widely used in LSMs, although its dependence and sensitivity to the parameters of the equations mean that its usefulness is still debated [47]. The parameters for the

Fig. 5 Schematic of snow and soil physics representation in LSMs

equations can be estimated using information about the soil textures through Pedotransfer Functions (PTFs).

Closely linked to the modelling of soil moisture is the soil temperature since the specific heat capacity of water is typically 5 times greater than the dry soil, so that a wet soil is a bigger heat-sink than dry soil (although still considerably less than the ocean). In addition, when the soil freezes, the conductivity of the soil massively reduces, eventually to zero.

A critical aspect of the soil water budget is how much water enters the soil matrix. This not only depends on the saturation of the soil, but also on soil characteristics such as texture, geomorphology and the presence of crusts. Most LSMs include a rainfall-runoff scheme which uses a statistical representation of soil-moisture heterogeneity linked to the mean soil moisture (which is used in the energy and evaporation exchanges) that were originally used by hydrologists [11, 84, 99, 132].

In the Boreal and Arctic regions, one of the greatest land-based impact on the atmosphere is through the snow cover. Due to its high albedo (reflecting 80 to 90% of the sunlight), snow has a strong cooling influence. Conversely, snow also acts as a thermal insulating blanket over the soil, protecting it from cold winter conditions. Model experiments using the CLM model [81] for the latter half of the twentieth century showed that variations in the amount of snow accounted for as much as 50–100% of variations in soil temperature. Many of the land surface models include a layered snow model to better capture the reflectivity at different radiation wavelengths [9].

In forested areas, the snow holding capacity of trees is limited so that much of the snow falls beneath the canopy. This results in a surface that is dark and relatively warm. Betts [10] showed that the darkening and warming impact of the presence of trees in a snowy-landscape outweighs the global-cooling effect of their carbon-absorption.

Recent Advances

As research consistently demonstrated the importance of the changes in permafrost to the evolving, warming climate, LSM developers introduced deeper soils into their models and improved the representation of organic soils. Deepening the models improved the soil thermal and hydrologic dynamics on longer timescales [80] and allowed better representation of soil carbon processes. Further model advancements attempt to account for excess ground ice [6, 82, 144], whose loss through melt creates rapid surface subsidence, altered hydrologic flow [40], and enhanced soil carbon respiration [134]. Our limited knowledge about the current amounts and distribution of excess ground ice hampers modelling efforts [103, 105].

Exchanges between the soil surface and the underlying subsurface exhibit high heterogeneity over small spatial scales. To begin to address the complexity of these exchanges,
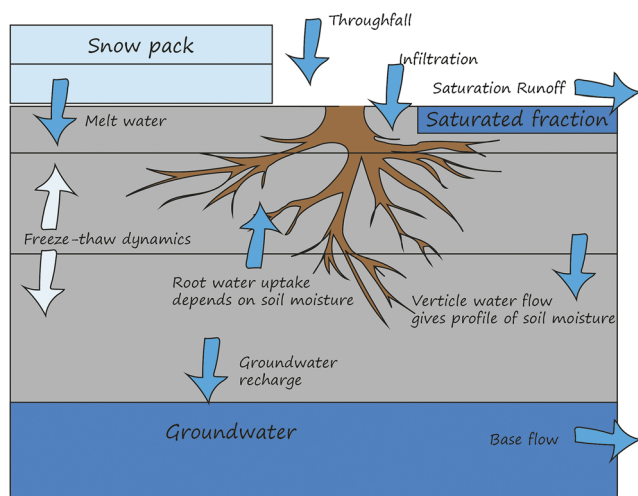
LSMs have adopted different strategies. Many models have added temporary sub-grid water stores such as ponding, although models that had a focus on cold-regions had it from the beginning [136].

Current Limitations and Future Directions

Soil modelling is strongly affected by the parameters which are derived from the observable soil texture using Pedotransfer Functions (PTFs). Most models use a single set of PTFs for their global modelling, but it is becoming apparent that this is not adequate and regional PTFs may be needed. It may also become important to include the way that soil properties change with time [138]. Farming practices and changes to permafrost regions will alter the soil organic matter, impacting the hydraulic properties of the soil. In addition, changes to the topography of the land as a result of changes in the permafrost conditions will need to be accommodated if we are to correctly model the hydrology and its impacts on the carbon cycle in the rapidly warming region [134].

Sub-grid heterogeneity is one of the largest limitations we have at present. For instance, Schultz et al. [121] showed that heat fluxes between different land cover types (e.g., trees and grasses) that share the same soil column can strongly impact the overall water and heat budgets. The use of soil tiles is probably the best option to deal with this. Already some models include soil-tiles to explicitly model the peat soils [77], to represent variations in maximum infiltration [35], soil textures [95] and irrigation [33].

Water Bodies with Land-Catchment and Water-Human Exchange

This section relates to the water that is stored or flows across the landscape, such as rivers, lakes, wetlands, glaciers and groundwater. The runoff from the land integrates over catchments and then occasionally or seasonally inundates the land. Meanwhile, there is an exchange between water and the human system: water can be used for industrial, agricultural and domestic use (abstractions) but water can be moved to create supply if needed (transfers). Figure 6 is a schematic of the processes discussed in this section.

History

In the past, most LSMs included rivers to link the precipitation runoff to the oceans. The first and widely used routing model that could be used globally was generated by Oki and Sud [102]. The routing mechanism was needed to estimate the timing of the flows to the sea, but no interaction with the energy or water balance of the landscape through which it flowed was included.

However, recent studies have shown that the movement of water across the land through rivers, inundation, irrigation and groundwater, under both natural and anthropogenic influence, can have a significant impact on the energy balance of the land-system. For instance, Martínez-de la Torre and Miguez-Macho [90] show how the presence of groundwater can affect the energy balance of the Iberian region and Keune et al. [73] show that the inclusion of groundwater in a LSM can affect the atmospheric dynamics.

A review of how and why hydrology needs to be included in Earth System Models is covered in the review article of Clark et al. [19].
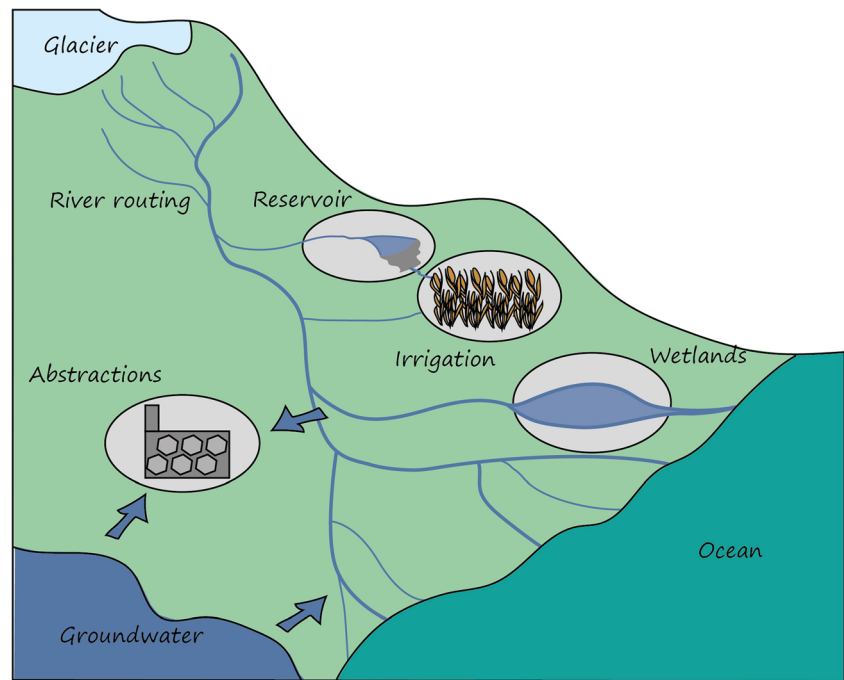
Recent Advances

New initiatives to link hydrological models to land surface models are emerging. Fan et al. [43] present a review of the need to improve the hydrology of LSMs. Some models have started to include explicit hill-slopes to represent flow across the landscape (see Appendix), some have large-scale (1000 km) groundwater flows. Inundation and wetlands are being introduced into LSMs, for instance, Nitta et al. [101] implemented a simple snow-fed wetland scheme in an Earth System Model, which not only modelled better hydrology, but also improved the representation of land-atmosphere coupling strength.

Groundwater is a major water resource worldwide, and new attempts to include it in LSMs have been made. Fan et al. [44], de Graaf et al. [28–30], Maxwell and Condon [91] and Miura and Yoshimura [98] have all implemented new groundwater models to LSMs that can be used for assessing global future water resources.

Human intervention in the water cycle affects many aspects of the land-system. For instance, irrigation can substantially affect the energy budget of a region and several LSMs have implemented unlimited irrigation through a simple scheme in which irrigation is triggered when soil water drops below a critical threshold [120]. With this class of irrigation implementation, one can research how enhanced evaporation due to irrigation affects local and regional weather and climate (see [133]). A more complete picture of human intervention is provided by models that represent processes including water withdrawal from surface and groundwater sources, and reservoir operation (e.g. [151]). This then allows us to study the global distribution of food production and world-wide food/water/energy securities through specification of irrigation water sources [60].

Wetland soil physics and biogeochemical cycles (Section 5) are linked as saturated conditions slow the decomposition of organic matter in wetlands, leading to increased soil carbon, reduced hydraulic conductivity, and a substantial increase in the emission of methane [74, 94, 147]. Modelling of the wetland extent is key to the modelling of the methane

Fig. 6 Schematic of the
representation of water bodies in
LSMs

emission estimates, especially as the hydrology of these regions may change in a future climate [22]. Recent years have seen advances in the level of integration between inundation and river models with both soil hydrology and biogeochemical cycles. For example, Guimberteau et al. [58] describe an improved representation of floodplain dynamics and wetlands that is fully integrated into the modelled hydrological cycle and extended to look at riverine C transport. There have also been developments aimed at representing river-groundwater interactions, with reinfiltration of river water being required to reproduce observed soil moisture patterns across a catchment [153].

Current Limitations and Future Directions

While hydrological models for catchment and even smaller scales are widely used, it is only relatively recently that attempts have been made to incorporate such detailed process understanding into land surface models. The need for LSMs to capture how the flow and storage of water across a landscape is regulated by fine-scale topographic features is identified by [43]. Possible new approaches include the use of hydrological response units, and a representation of the interaction between groundwater and rivers. Although some models now include a hydrological representation of wetlands and intermittent flooding, there is still a need to better describe the effects of these on energy and nutrient cycles. A major challenge for the development of global-scale groundwater models is the difficulty in sourcing data with which to describe subsurface characteristics.

Seasonal changes in land ice and glaciers are responsible for significant changes in the river flows of many high-latitude and high-altitude basins. Current land surface models include the effects of snow and land ice on terrestrial albedo and surface energy balance, but the contribution to river flow from glacier runoff is missing and the impact on the temperature of the river-water, which may be important to the ecological community. If we want to use the land surface models to address issues of water resources, it is important to include how these quantities will respond to anthropogenic global warming [68] as it is likely that the glaciers will disappear from many areas in the next 50 years.

Many aspects of land use and land management, including the use of agricultural fertilizers, have important consequences for water quality and ecology [18], and these will need to be included in models. From an Earth System perspective, these riverine nutrient fluxes are important inputs to estuaries and shelf seas, and the interface between land and marine models will need to be developed accordingly.

The extent of anthropogenic interventions in the water cycle in many locations now places human water use at the same order of magnitude as many of the natural fluxes in the water cycle [25, 56]. It is important that these fluxes are represented in land-surface models [24] so that future changes in water availability can be addressed. Although some models already include detailed descriptions of water management activities these often rely on the prescription of simple operating rules; future developments will need to better represent the optimal management of complex catchments and consider the economics of water use.

Vegetation Physiology and Soil Biogeochemistry and Exchanges with Physics

There are two primary purposes of modelling vegetation physiology and soil biogeochemistry in LSMs. First, the physical structure of vegetation and the process of photosynthesis affect the exchange of momentum, energy, water and CO2 at the land-atmosphere boundary (Section 2). Second, the vegetation and soil processes affect allocation of the Earth's carbon to storage in the land (and oceans) compared to the atmosphere over seasonal and longer time scales. This section summarises the how the processes that govern these physical and biogeochemical interactions are modelled. Figure 7 gives an overview of the essential processes included in LSMs.

History

The process of leaf photosynthesis is well understood and most LSMs simulate photosynthesis based on theoretical models of C3 and C4 photosynthetic pathways [20, 46]. Transfer of CO2 into the plants through photosynthesis is inevitably linked with loss of water via leaf stomata. This coupling between photosynthesis and stomatal resistance is modelled via empirical relationships [7, 14, 20, 69, 83, 93].

All plant components including roots, shoots and leaves respire CO2 (referred to as the autotrophic respiration) [128]. The difference of the two large fluxes of photosynthesis (GPP) and autotrophic respiration is the net carbon gained by plants (Net Primary Production, NPP) that is allocated between the different plant components [53]. Dynamic allocation of carbon to leaves together with leaf loss associated with cold temperatures, reduced day length, and drought allow LSMs to simulate leaf phenology as a function of environmental conditions [4, 111]. The leaf phenology responds more strongly to temperature in temperate and high-latitude regions [145] and to soil moisture in tropical regions [51]. The seasonal cycle of leaves modulates the land-atmosphere energy, water and CO2 fluxes [108].

There is a transfer of carbon from the vegetation to the soil through leaf fall, turnover of shoots and roots, eventual mortality of plants. The soil carbon dynamics is often modelled using multiple pools with different turnover times [131] and affected by temperature and moisture.

These dynamical carbon processes were introduced into the LSMs in the early 2000s as the modelling centres started to focus on the response of climate to the carbon cycle.

Recent Advances

Understanding the link between photosynthesis and transpiration (Water Use Efficiency) is a priority for LSMs response to climate. New approaches have been explored recently. For instance, a new optimisation theory [93] has been included in some LSMs [31, 78, 104] which recognises that the plants will be aiming to minimise their water loss while maximising their carbon uptake. In addition, a model that accounts for how stomatal conductance respond to root zone soil moisture through explicitly modelling the cost of the hydraulic lift of the water has been developed [127, 150], although these have yet to be fully explored in LSMs (but see [119]).

Another recent advance in LSMs is to model nutrient (Nitrogen, N and Phosphorus, P) limitations on photosynthesis [140, 152]. N cycle modules in LSMs are also able to model emissions of N_2O which is a greenhouse gas [152]. LSMs are also now including emissions of the greenhouse gas methane (CH_4) associated with natural wetlands and permafrost thaw [5, 118] (see Section 4). Anthropogenic methane emissions from

Fig. 7 A schematic of the biogeochemistry represented in LSMs
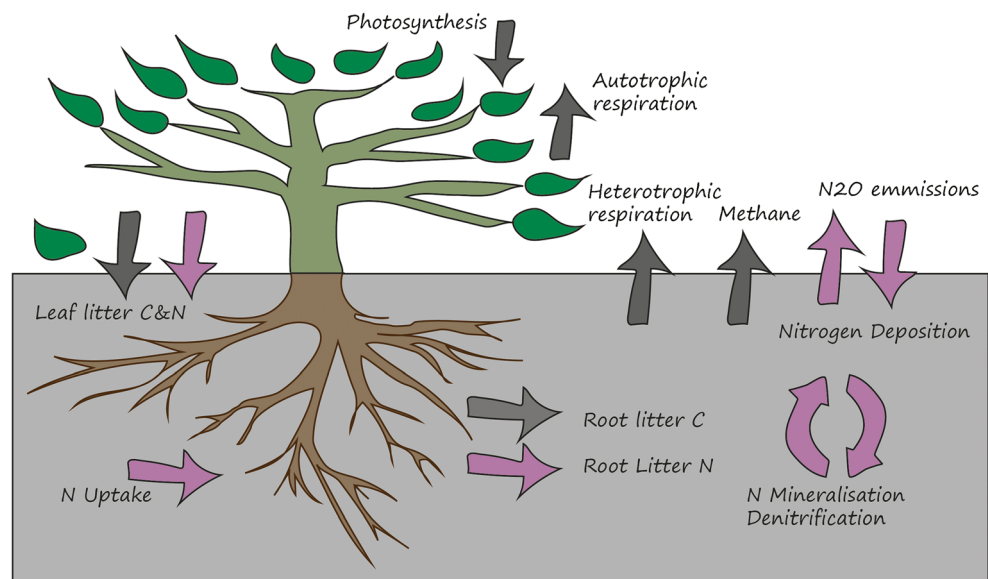
paddy rice and those from ruminants are represented in some offline vegetation models (e.g. [76]).

Current Limitations and Future Directions

The temperature response of photosynthesis is a key uncertainty in LSMs, especially the acclimation to slow temperature changes. Most models use instantaneous temperature responses, even in response to sustained warming which do not appropriately account for geographical variations (adaption) or acclimation to ambient temperature [72]. LSMs that do account for photosynthetic temperature acclimation, however, find a large influence on terrestrial carbon storage with a warmer climate [85, 97, 126].

But, new theories that relate the essential evolutionary nature of biology are emerging which might well bring new insights into the interplay of vegetation and climate [52].

The modelling of the nitrogen cycle has been shown to be critical to understand the earth-system response to climate change. But, there is a strong anthropogenic influence that is hard to incorporate. The application of fertilizers for agriculture is an area that needs to be addressed (see Section 6).

The typical turnover rate of microbes in soil (0.05 day^{-1}; [59]) implies their half-life is of the order of 15 days. Yet, soil carbon has one of the longest turnover time scales in the terrestrial carbon cycle (~ 30–50 years or up to 1000s of years in high latitudes) since decomposing organic matter is a slow and energy intensive process. This has led LSMs to model heterotrophic respiration as a function of environmental conditions (including aerobic and anaerobic conditions), and soil carbon mass, ignoring the direct role of microbes. New studies suggest the interactions between microbes and heterotrophic respiration are complex given the large diversity of microbes and their function [59, 137] and suggest that temperature sensitivity of microbial turnover may even promote soil C accumulation with warming, in contrast to reduced soil C as is predicted by traditional biogeochemical models. Wieder et al. [146] summarise how LSMs may include microbial-explicit model formulations. Modelling microbial community explicitly in LSMs is the first step toward this new functionality.

As soil-tiles are adopted (see Section 3) and canopy processes better modelled (see Section 2), then biogeochemistry can take advantage of more accurate soil moisture, temperatures, and vegetation physiology can take advantage of the range of canopy temperatures.

Vegetation Dynamics and Land-Use with Vegetation-Landscape Exchanges

Changes in the vegetation distribution affect the exchange of the land to the atmosphere through changes in the fluxes of energy, water and carbon. Vegetation distribution is altered by

both anthropogenic (agriculture, deforestation) and natural dynamics (stress, fire, insect outbreaks, or windthrow).

This section describes how the LSMs include these land cover changes. Figure 8 is an overview of the processes included in LSMs.

History

The impacts of land-use change on climate were originally assessed by imposing large-scale land cover change (e.g. [66]). This approach was used in CMIP5, where the models were provided with historical and projected land-use forcing (e.g. [16]). Natural vegetation dynamics, which were developed in stand-alone models ('dynamic global vegetation models', DGVMs) [23, 125] were introduced into Earth System Models (ESMs) in some of the LSMs used in CMIP5 [17, 21, 142].

Land-use related fluxes of carbon currently contribute about 14% of annual CO2 emissions [55] or about one quarter of emissions when other greenhouse gases such as methane (CH4) and nitrous oxide (N2O) are included (IPCC SRCCL). This biogeochemical effect is the dominant impact of land-use on climate. A smaller effect relates to the physical effect such as the cooling of irrigated areas and the darkness of trees compared to crops and grass (see Section 2). This is called the biogeophysical effects [10, 113]. In some places and at a local scale, local temperature changes due to biogeophysical changes can be as large as the biogeochemical effect on warming [32, 129, 148].

The overall observed trend in natural vegetation is a greening trend (with a recent evidence of a browning trend in some regions). LSMs explain these trends as a response to the physiological effects of rising CO2 concentration and a warming climate favouring plant growth in cold regions [149].

Recent Advances

Representations of land use and natural vegetation dynamics have been evolving rapidly. To better capture the full range of impacts of land use on the earth system, several LSMs have begun to represent agricultural practices in more detail, including specific crop parameterizations for the world's major crops along with representations of crop management practices such as planting, harvesting, irrigation and fertilization (e.g. [15, 86]). In individual models, impacts from processes such as till/no-till practices have been examined by altering parameters for soil respiration (e.g. [115]) or adjusting soil albedos to account for soil turnover due to tillage [27]. Irrigation has been implemented by adding water to eliminate plant water stress [34], also see Section 4.

Due to the rapid development of land use models, there is a wide range of the level of comprehensiveness and the specific process implementations which confounds multi-model

Fig. 8 A schematic of land-use and dynamical vegetation processes represented in LSMs
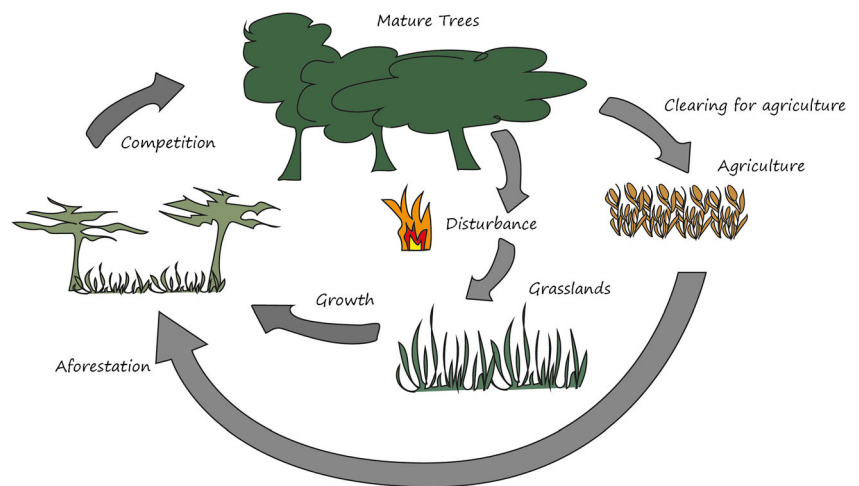
assessments of the impacts of historic and projected land-use change. In recognition of this divergence, the Land Use Model Intercomparison Project [118](LUMIP) [79] includes a large factorial set of land-only-perturbations coupled to the atmosphere models. These experiments focused in on a range of important land use processes so as to enable multi-model assessment of the impacts of specific processes on the land-atmosphere exchanges.

A key to accurate simulation of the role of vegetation on the atmosphere is a representation of forest age. This enables the modelling of harvesting of specifically aged or sized trees which is needed for a detailed forestry representation (e.g. [8]). Some models represent sub-grid forest age structures inherently, while many depict only an average tree or plant age. These latter, simpler LSMs can represent the distribution explicitly with a tile for each age classes (e.g. [100, 124]). An alternative approach is to model the relationship between the distribution of the age-class and the average growth (e.g. [65]). These new generation models rely on 'cohorts', wherein plants with similar properties (age, size, age, functional type) are grouped together ([64, 67, 143]; and see [50] for a review).

Limitation and Future Directions

A recent review of the changes in land-use under anthropogenic influences is given in Pongratz et al. [112]. Among others, they show that there is now an understanding that land management can be as impactful on climate as land-cover change [41, 42, 88] but they are un- or under-represented in present day LSMs.

Current LSMs typically represent crop phenology with relatively few phenological stages, but by doing so miss out on potential impacts of heat or water stress during key stages of the crop life cycle [106]. Further, crop modules within LSMs consider only a few of the many crop management practices in use today (i.e. mainly irrigation and fertilization). McDermid

et al. [92] gives a review of including agriculture in Earth System Models.

But, many other crop management practices affect food production, agricultural land sustainability and the impact of agriculture on climate. These include cropland harvest, irrigation (discussed in Section 4), and fertilization (Section 5), forest harvest, tree species selection, grazing and mowing harvest, crop species selection, artificial wetland drainage, pest management, tillage, fire management and crop residue management.

Pongratz et al. [112] point out that for each process, there is often a basic implementation and a comprehensive implementation. To achieve a comprehensive implementation requires overcoming challenges of data limitations, and in some cases inadequate process understanding or inadequate knowledge or ability to simplify and capture specific human behaviours (e.g. farmer decisions on when to plant crops). Peng et al. [107] argue that a much more deliberate and intensive effort to merge agroeconomic crop models and land-surface models is required to provide a 'multiscale crop modelling framework [that] will enable gene-to-farm design of resilient and sustainable crop production systems under a changing climate at regional-to-global scales'.

Capturing the impacts of agricultural management on soils is a priority and requires improved representation of plant–soil–microbial interactions (as discussed in Section 5) and the impacts of agricultural management on these interactions, such as the long-term impacts of agricultural management (including pastureland and rangeland management) on soil degradation and/or loss [138]. More realistic treatment of changes in soil health would allow, for example, for study of the potential impacts of agricultural practices on flood risk.

One of the critical problems is how to specify the role of humans in the Earth System. A potential way forward is to link the ESMs with Integrated Assessment Models to ESMs [1, 130], thus capturing feedbacks between climate, food, water and land-use.

The representation of vegetation dynamics is also evolving substantially, with first-generation DGVMs being replaced by demographic models based on a more realistic ecological understanding of the land system [50]. Next-generation demographic vegetation models include processes thought to be critical for ecosystem function and composition, including canopy gap formation, vertical light competition, competitive exclusion and successional recovery from natural or anthropogenic disturbance. They will also need to be responsive to the below-ground state such as soil depth, moisture and temperatures.

Conclusions

Land surface models need to balance two opposing requirements. They need to be complex enough to capture important processes and drivers of change in the real world, and parsimonious enough to be able to simulate and study a multitude of possible other worlds (new climates, new land and water uses and new locations).

One way to obtain this balance is to articulate the difference between the representation of processes *within* a component and the representation of the exchanges *between* the components. The former is critical to capture the response of ecosystems to changing climate conditions and is essentially a scientific problem. The latter is required to represent the heterogeneity of the land-system both in time and space and is essentially a modelling problem but requires scientific insight.

This review showed many examples of both these two aspects, across the 5 main modelling domains: surface and canopy exchanges, soil and snow physics, water bodies, biogeochemistry and plant physiology and vegetation dynamics. We showed how progress in one aspect may be independent (new models of stomata can be introduced without reference to other parts of the model) while others may need changes to the exchanges between components to make progress (for instance, if dynamic vegetation models need to link to sub-grid features such as soils, topography, wind stress and snow depth).

Separating out the two aspects (processes and exchanges) and making progress in both enables us to identify our priorities for delivering a model that includes both the complexity of the real world, while maintaining an appropriate level of parsimony. For instance, only components that affect the outcome of the problem being addressed need to be linked in a model configuration. Another example is that time and space scale of the application can dictate the appropriate

exchanges used without affecting the representation of the components.

The future of Land Surface Modelling by the large modelling centres will probably focus on the framework for coupling components together, depending on the application. As well as the coupling across time and space scales, the framework will include the external boundary conditions and evaluation of the outputs for different applications. This will enable a marketplace for the provision of the component model which can be provided by external, academic and international researchers. Such a relationship between the central operations-focussed modelling centres and the academic sector will service one of the un-spoken but critical aspects of land-surface modelling which is the support it provides for research and intellectual enquiry.

Ultimately, the goal is that future land surface models can address key societal and scientific questions related to ecosystem resilience under a range of environmental and anthropogenic pressures. By understanding and enabling independent development of the basic building blocks of the models and how they are combined, we can ensure a healthy future of the integrity of the science of Land Surface Modelling.

Appendix A. List of widely used models and their developments with references.

A 'Y' or a paper-reference indicates the process is included in the model (although not necessarily in the operational or default version of the model), a 'N' indicates it is not included in the model, and blank spaces indicate no information.

The models are as follows:

CABLE: Community Atmosphere-Biosphere Land Exchange model (Australia)
CLASSIC: Canadian LAnd Surface Scheme Including biogeochemical Cycles (Canada)
CLM: Community Land Model (USA)
CoLM: Common Land Model (China)
G/LM: Global Land Model (USA)
ISBA: Interaction Sol-Biosphère-Atmosphère (France)
JSBACH: Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg (Germany)
JULES: Joint UK Land Environment Simulator (UK)
Matsiro: Minimal Advanced Treatments of Surface Integration and Runoff (Japan)
Orchidee: Organising Carbon and Hydrology in Dynamic Ecosystems (France)
TESSEL: Tiled ECMWF Scheme for Surface Exchanges of Land (Europe).

Table 2 Land atmosphere exchange

	CABLE	CLASSIC	CLM	CoLM	G/LM	ISBA	JSBACH	JULES	Matsiro	Orchidee	TESSEL
Tile representation of vegetation	Ca4	CL9	CM12	CO2 CO5	LM1 LM4 LM6 LM7 LM9 LM10	IS9 IS14	JS2	JU5, JU8, JU13	MA1 MA2 MA3 MA4 MA12	Y	T3 T11
Separate energy budget for components within a tile	Ca5 Ca8 Ca6 Ca7	CL13	CM18	CO2	LM5	IS3 IS7 IS9 IS12 IS13	JS3	N	MA1 MA2 MA3 MA4 MA1	N	T3 T11
Vertical layers for radiation in the canopy	N	N	CM1	CO10	Y	IS8 IS11	N	JU6	N	Y	T8
Vertical layers for water and heat in the canopy	N	CL14	CM1	N	Y	IS2 IS5 IS11 IS14	N	N	N	N OR3	N

Table 3 Soil physics

	CABLE	CLASSIC	CLM	CoLM	G/LM	ISBA	JSBACH	JULES	Matsiro	Orchidee	TESSEL
Darcy-Richards	Ca5	CL14	Y	N	LM1 LM5	IS2 IS5	JS4	JU1	MA1 MA2 MA3 MA4 MA12	Y	T12
Rainfall-runoff generation	Ca1	CL14	CM23	N	LM5	IS4	JS5	JU1	MA1 MA2 MA3 MA4 MA12		T2 T10 T11
Deep soil layers (>4m)	Ca5 Ca1	CL12	CM11 CM2 CM19 CM15	N	LM1, LM5	IS11 IS14	JS4	JU2	MA1 MA2 MA3 MA4	Y	N
Organic soils	Y	CL8 CL15	CM10	CO4 CO6	LM7	IS11	N	N	N	Y	T2
Ponding and/or other	Y	CL14	CM20 CM8	CO7	LM1 LM5	N	N	N	N		T13
Lateral flow in-grid/ hillslopes	N	N	CM21	N	LM1 LM7	IS15	N	N	N		N
Layered snow	Ca5	N	CM7	CO1 CO2	LM5	IS3 IS4 IS11	N	JU1	MA1 MA2 MA3 MA4 MA9 MA12	OR5	T1 T7

Table 4 Water bodies and hydrology

	CABLE	CLASSIC	CLM	CoLM	G/LM	ISBA	JSBACH	JULES	Matsiro	Orchidee	TESSEL
River routing	N	CL3	CM13	CO3	LM5	IS6 IS14 IS15	JS6	JU9	MA1 MA2 MA3 MA4 MA10 MA11	Y	Y
Wetlands and inundation	N	CL4	CM20 CM16 CM17	CO3	LM7	IS6 IS14	N	JU3	MA1 MA2 MA8 MA10	N	Y
Irrigation	Ca2	N	CM12 CM22	N			N	Y	MA3 MA4 MA6	Y	Y
Groundwater	Ca1	N	CM14 CM19	CO3	LM5	IS10 IS14	N	N	MA3 MA4 MA5 MA7	N	Y

Table 5 Soil biogeochemistry and plant physiology

	CABLE	CLASSIC	CLM	CoLM	G/LM	ISBA	JSBACH	JULES	Matsiro	Orchidee	TESSEL
Photosynthesis responds to environment	Y	CL5	Y	Y	Y	IS1 IS16	Y	JU3	MA3 MA4	Y	Y
Allocation of carbon to roots, stems and leaves.	Y	CL6	Y	Y	Y	IS17 IS16	JS7	JU3	MA3	Y	N
Plants acclimatise to temperature and soil moisture	Y	N	CM24	Y	N	N	N	JU12	N	N	N
Soil carbon model	Ca7	CL5	CM9	N	LM8	IS17 IS16	JS1 JS7	JU3	MA3	Y	N
Nitrogen cycle linked to carbon cycle	Ca7	CL7	CM5	N	LM2, LM3, LM8	N	JS7	JU15	MA3	OR4	N

Table 6 Vegetation dynamics, land and water use

	CABLE	CLASSIC	CLM	CoLM	G/LM	ISBA	JSBACH	JULES	Matsiro	Orchidee	TESSEL
Different crop types	N	N	CM4 CM3 CM25	N	N	IS9 IS16	N	JU10 JU11	MA3 MA4	Y	T5
Land use and land cover change	Ca4	CL1	CM26	N	Y	IS16	JS2	JU7	MA4	OR2	N
Competition between PFTs	Y	CL10	Y	Y	Y	N	JS2	JU8 JU14	N	Y	N
Water use and transfers of water between grid cells	N	N	N	N	N	N	N	N	MA3	N	N

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MATSIRO

The first 4 (MA1-4) are the latest 4 "flavors" of MATSIRO-based models. In these models, MATSIRO works as a typical land surface model, and some other models are coupled to represent different features. The latter (MA5-11) are the works in which individual processes were implemented / improved. The last one (MA12) is the original version.

MA1. (MIROC6) Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., Sudo, K., Sekiguchi, M., Abe, M., Saito, F., Chikira, M., Watanabe, S., Mori, M., Hirota, N., Kawatani, Y., Mochizuki, T., Yoshimura, K., Takata, K., O'ishi, R., … Kimoto, M. (2019). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. *Geoscientific Model Development*, *12*(7), 2727–2765. 10.5194/gmd-12-2727-2019

MA2. Nitta, Tomoko, Arakawa, T., Hatono, M., Takeshima, A., & Yoshimura, K. (2020). Development of Integrated Land Simulator. *Progress in Earth and Planetary Science*, *7*(1), 68. 10.1186/s40645-020-00383-7

MA3. (MIROC-ESM) Hajima, T., Watanabe, M., Yamamoto, A., Tatebe, H., Noguchi, M. A., Abe, M., Ohgaito, R., Ito, A., Yamazaki, D., Okajima, H., Ito, A., Takata, K., Ogochi, K., Watanabe, S., & Kawamiya, M. (2020). Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks. Geoscientific Model Development, 13(5), 2197–2244. 10.5194/gmd-13-2197-2020

MA4. (MIROC-INTEG) Yokohata, T., Kinoshita, T., Sakurai, G., Pokhrel, Y., Ito, A., Okada, M., Satoh, Y., Kato, E., Nitta, T., Fujimori, S., Felfelani, F., Masaki, Y., Iizumi, T., Nishimori, M., Hanasaki, N., Takahashi, K., Yamagata, Y., & Emori, S. (2019). MIROC-INTEG1: A global bio-geochemical land surface model with human water

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MA5. (ground water table) Koirala, S., Yeh, P. J.-F., Hirabayashi, Y., Kanae, S., & Oki, T. (2014). Global-scale land surface hydrologic modeling with the representation of water table dynamics. *Journal of Geophysical Research: Atmospheres*, *119*(1), 75–89. 10.1002/2013JD020398

MA6. (irrigation) Pokhrel, Y., Hanasaki, N., Koirala, S., Cho, J., Yeh, P. J.-F., Kim, H., Kanae, S., & Oki, T. (2012). Incorporating Anthropogenic Water Regulation Modules into a Land Surface Model. *Journal of Hydrometeorology*, *13*(1), 255–269. 10.1175/JHM-D-11-013.1

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Declarations

Conflict of Interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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