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Abstract: Terrestrial environmental systems are characterized by numerous feedback links between their different compartments. However, scientific research is organized into disciplines that focus on processes within the respective compartments rather than on interdisciplinary links. Major feedback mechanisms between compartments might therefore have been systematically overlooked so far. Without identifying these gaps, initiatives on future comprehensive environmental monitoring schemes and experimental platforms might fail. We performed a comprehensive overview of feedbacks between compartments currently represented in environmental sciences and explores to what degree missing links have already been acknowledged in the literature. We focused on process models as they can be regarded as repositories of scientific knowledge that compile findings of numerous single studies. In total, 118 simulation models from 23 model types were analysed. Missing processes linking different environmental compartments were identified based on a meta-review of 346 published reviews, model intercomparison studies, and model descriptions. Eight disciplines of environmental sciences were considered and 396 linking processes were identified and ascribed to the physical, chemical or biological domain. There were significant differences between model types and scientific disciplines regarding implemented interdisciplinary links. The most wide-spread interdisciplinary links were between physical processes in meteorology, hydrology and soil science that drive or set the boundary conditions for other processes (e.g., ecological processes). In contrast, most chemical and biological processes were restricted to links within the same compartment. Integration of multiple environmental compartments and interdisciplinary knowledge was scarce in most model types. There was a strong bias of suggested future research foci and model extensions towards reinforcing existing interdisciplinary knowledge rather than to open up new interdisciplinary pathways. No clear pattern across disciplines exists with respect to suggested future research efforts. There is no evidence that environmental research would clearly converge towards more integrated approaches or towards an overarching environmental systems theory.

Dear Editor,

Please, find enclosed our manuscript

Ayllón, D., Grimm, V., Attinger, S., Hauhs, M., Simmer, C., Vereecken, H., Lischeid, G.: **Cross-disciplinary links in environmental systems science: current state and claimed needs identified in a meta-review of process models**,

which we herewith submit for publication in *Science of the Total Environment* as a Review Article. As advised by the journal's guide for authors, we already consulted the Co-Editors in Chief, Drs. Barceló and Gan, concerning acceptability of topic and length of the manuscript, and submission of our review paper was encouraged.

The last decades have boosted our insight into complex relationships between numerous biotic and abiotic components of environmental sciences. However, scientific research is organized into disciplines that focus on processes within the respective compartments rather than on interdisciplinary links. So relevant feedback mechanisms between different compartments might therefore have been systematically overlooked so far. Representatives from all major German research associations and from various disciplines of environmental sciences thus performed a comprehensive survey of established links between different compartments of terrestrial environmental systems as well as of future research needs stated in the literature which might point to emerging new integrated fields in environmental sciences. To that end we used simulation models as proxies for repositories of scientific knowledge. We feel our study fits the aims and scope of the journal as we have analyzed around 350 papers and 120 simulation models from a wide variety of subject areas belonging to eight different scientific disciplines, including Atmospheric science (Meteorology and Climatology), Soil science, Geology (excluding Palaeontology), Terrestrial Ecology, Hydrology and Hydrogeology, and Freshwater science, covering thus research on all the five environmental spheres. We believe that our review provides a new, integrated view on earth system modelling and science, with unprecedented depth and width. Besides of our own conclusions, we provide material and results that can also inspire readers to draw their own conclusions, or perform further analyses following our approach.

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Looking forward to hearing from you at your convenience.

Sincerely,

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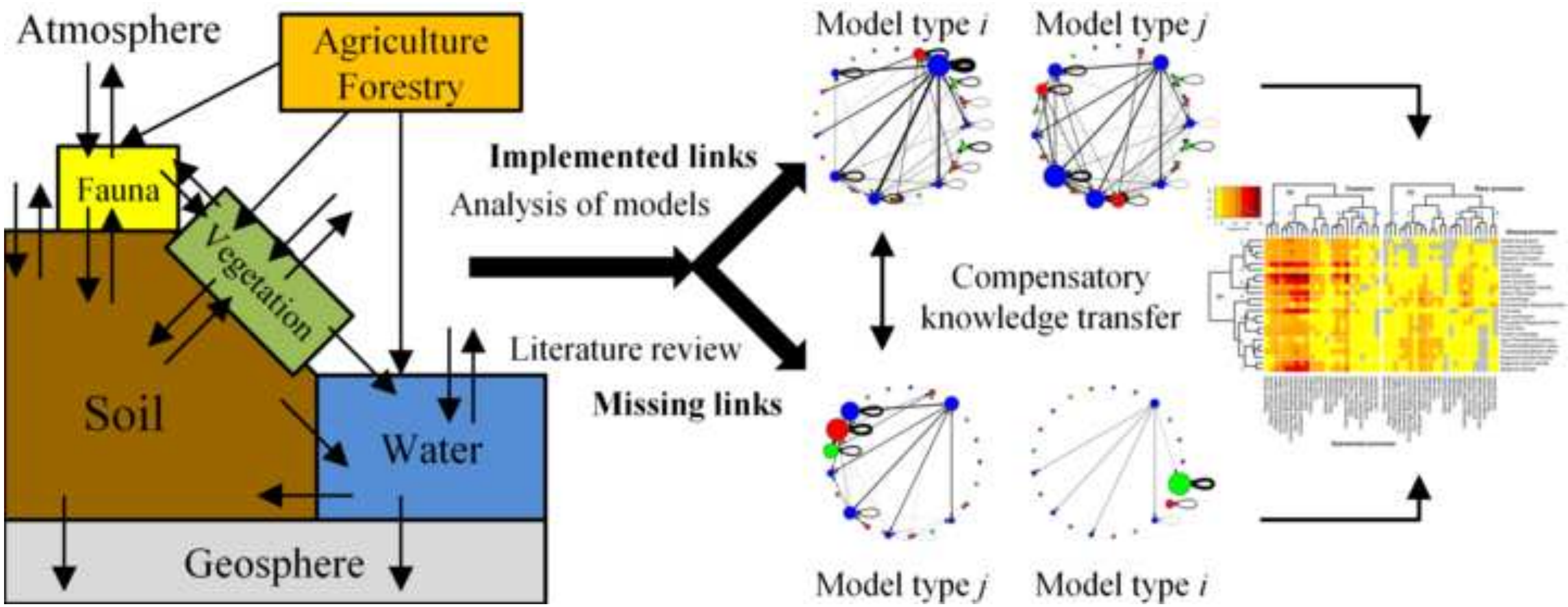
Graphical Abstract



Highlights

- We performed a survey of dynamic interdisciplinary links in environmental models
- We identified claimed missing interdisciplinary links through a literature review
- We found a strong bias towards physical processes
- Claimed research foci point to existing rather than new interdisciplinary pathways
- Environmental research does not seem to converge towards more integrated approaches

Cross-disciplinary links in environmental systems science: current state and claimed needs identified in a meta-review of process models

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ABSTRACT

Terrestrial environmental systems are characterized by numerous feedback links between their different compartments. However, scientific research is organized into disciplines that focus on processes within the respective compartments rather than on interdisciplinary links. Major feedback mechanisms between compartments might therefore have been systematically overlooked so far. Without identifying these gaps, initiatives on future comprehensive environmental monitoring schemes and experimental platforms might fail. We performed a comprehensive overview of feedbacks between compartments currently represented in environmental sciences and explores to what degree missing links have already been acknowledged in the literature. We focused on process models as they can be regarded as repositories of scientific knowledge that compile findings of numerous single studies. In total, 118 simulation models from 23 model types were analysed. Missing processes linking different environmental compartments were identified based on a meta-review of 346 published reviews, model intercomparison studies, and model descriptions. Eight disciplines of environmental sciences were considered and 396 linking processes were identified and ascribed to the physical, chemical or biological domain. There were significant differences between model types and scientific disciplines regarding implemented interdisciplinary links. The most wide-spread interdisciplinary links were between physical processes in meteorology, hydrology and soil science that drive or set the boundary conditions for other processes (e.g., ecological processes). In contrast, most chemical and biological processes were restricted to links within the same compartment. Integration of multiple environmental compartments and interdisciplinary knowledge was scarce in most model types. There was a strong bias of suggested future research foci and model extensions towards reinforcing existing interdisciplinary knowledge rather than to open up new interdisciplinary pathways. No clear pattern across disciplines exists with respect to suggested future research efforts. There is no evidence that environmental research would clearly converge towards more integrated approaches or towards an overarching environmental systems theory.

Keywords: Review; interdisciplinary links; integrated environmental modelling; research needs

1. Introduction

Human activities continue to change the environment by altering energy, momentum, sediment and water fluxes (Vörösmarty and Sahagian 2000, Syvitski and Kettner 2011) and biogeochemical cycling (Falkowski et al. 2000, Gruber and Galloway 2008), modifying the composition of the atmosphere (IPCC 2013), degrading soils and water quality (Foley et al. 2005), and impacting the biosphere (Ellis 2011). While current global trends affect all ecosystem compartments, the reactions of individual compartments to changes in climate, land cover and land use are still uncertain (IPCC 2013). Within terrestrial systems, functional relationships and exchange take place within complex and highly heterogeneous landscapes. The numerous processes that occur within individual environmental compartments (atmosphere, land surface and subsurface, geosphere, biosphere, and freshwater systems) are coupled in multiple ways through dynamic interfaces so that changes in one compartment affect the adjacent compartments likewise (Denman et al. 2007, Ciais et al. 2013), often leading to complex patterns in system state structures and variables (Vereecken et al. 2016a).

Consequently, an integrative, cross-scale, interdisciplinary and system-oriented research approach seems to be necessary to both enable the development of general environmental systems theory that consistently describes these interlinked dynamics and to create a new generation of integrated numerical model systems (DFG 2013). Fuelled by this notion, new developments that embrace such a systemic and integrated approach are underway (e.g., Zacharias et al. 2011, DFG 2013, Simmer et al. 2015). However, most of existing research and monitoring infrastructures are largely focused on specific scientific questions addressing only partial aspects of the terrestrial environmental (eco)system within the realm of single scientific disciplines.

This is because scientific research is organized into more or less disjunct disciplines that focus on processes within the respective compartments rather than on links between different compartments. Consequently, these links are not only poorly understood, but also described in different ways according to the terminology and basic paradigms of the respective disciplines. Moreover, despite scarce attempts (e.g., Schellnhuber 1999), a general environmental or earth system theory (within the framework of the dynamic system theory and its language) that would be broadly accepted throughout the environmental science disciplines and would integrate findings from different disciplines does not exist. This comes with the risk that the blind spots at the interfaces between different disciplines could result in systematic deficiencies in environmental sciences and will substantially impede our understanding of environmental systems in the long-term

This study therefore aims at a systematic survey both of known interdisciplinary links as well as of missing links identified in review and opinion papers as a contribution to strategic planning of environmental research. Two different approaches were combined.

First, since neither an overarching environmental systems theory exists nor a common data base of environmental knowledge that could be analysed in a quantitative way, we reviewed a large set of process models of environmental systems from various disciplines, assuming that the whole set of implemented processes would reflect the state of the science. Thus models were regarded as a proxy for repositories of scientific knowledge. We scanned these models for existing links between different compartments. Secondly, a list of stated missing interdisciplinary links was compiled from the existing literature and was analysed with respect to emerging new fields of interdisciplinary environmental systems science.

Both approaches have clear restrictions. Firstly, the fact that certain links are not or only rarely implemented in existing models does not necessarily imply that they are not essential. Secondly, missing links identified in review and opinion papers have been defined from the respective view of the authors which are strongly affected by the respective disciplinary perceptions and paradigms. Thus this study does neither assess the necessity of certain missing links nor does it claim fully integrated models including all possible links irrespective of any specific modelling aim; such models are neither possible nor desirable. Nevertheless, our systematic inventory could provide a basis for identifying current biases as well as outlining a way towards a more integrated terrestrial environmental system science, including modelling as well as process studies and monitoring programs.

We reviewed a wide range of simulation model types from eight environmental scientific domains and compared them in terms of how well their modelling components are integrated across environmental compartments (cross-compartmentalization) and scientific domains (interdisciplinarity). We performed a systematic analysis of 346 published reviews, papers reporting results from model intercomparisons, and model descriptions. In total we analysed 118 simulation models from 23 model types and 1) described their representation of environmental components, processes and driving state variables, 2) assessed how well these representations hold up in the face of current understanding, and 3) set up a compilation of modelling gaps stated in the literature. The latter included both knowledge and conceptual gaps in need of focused interdisciplinary attention, and missing processes that might be important for novel applications, i.e. for purposes other than those for which the current models are being applied at present (e.g., incorporation of biogeochemistry modules in forest gap models to simulate vegetation distribution and carbon fluxes under projected global change).

Our analysis is thus focused on “process representation”, confronting what is implemented versus what is perceived as missing, with strong emphasis on processes that link different environmental compartments and, thereby potentially, scientific disciplines. *Links*, defined as processes, or environmental factors controlling a process, that connect different aspects (physical, chemical, biological) of different disciplines (e.g., soil sciences or terrestrial ecology) are thus the *central concept* of our analysis. We also tried to quantitatively assess the extent to which reported deficiencies in process representation in certain model types and disciplines are addressed by other modelling disciplines. With this, we seek to cast light on the central question of whether current interdisciplinary modelling gaps can be filled by integrating knowledge, conceptualizations, process understanding and modelling techniques across modelling fields, or if by contrast, there are still major gaps that rule out the development of an integral understanding of the environmental system. Hence, the ultimate purpose of our analysis is to push forward a fully integrated environmental system science by providing a roadmap for future modelling and monitoring decisions to be made.

2. Methods

In our survey of cross-disciplinary links in process models of environmental sciences, we do not intent to highlight disciplinary deficiencies or to rank model types but to provide an overall picture of the state of the art of integrated environmental modelling, pinpointing *what* is missing in *which* model types and *who* (in terms of model types) can transfer scientific and technical knowledge to address it. Thus, we first compiled a database of nearly 400 implemented and missing links (process representations) for a sample of 23 model types from eight environmental scientific disciplines (section *2.1. Data compilation*). Then, matrices were set up describing which compartments of environmental systems, or scientific disciplines, were respectively linked by these processes (section *2.2. Data synthesis*). Three separate types of matrices were compiled: matrices of existing links and missing links for each of the 23 model types, and one matrix combining information about existing and missing links. In a third step, these matrices were analysed using cluster analysis and network modelling approaches (section *2.3. Data analysis)*. To that end some technical terms were used that might have different connotations in different disciplines. Thus Box 1 provides a glossary of key terms and concepts used in our study.

2.1. Data compilation

We focused on simulation models, and on the processes represented in these models, from eight environmental scientific disciplines (Box 1). Selected disciplines include the Atmospheric science (Meteorology and Climatology), Soil science, Geology (excluding Palaeontology), Terrestrial Ecology, Hydrology and Hydrogeology, and Freshwater science. These disciplines focus on the processes occurring in specific compartments of the terrestrial environmental system, i.e. atmosphere, pedosphere, geosphere, biosphere, and the hydrosphere with its aquatic systems. We additionally included Agricultural and

Forestry sciences, which focus on processes and human activities that transform the terrestrial landscape for the production of animals and plants for human use, or the provision of ecosystem services, thus providing a partial representation of the anthroposphere. However, social, institutional or economic environmental models were beyond the scope of this study.

Box 1. Glossary of key terms and concepts used in this article.

(Basic science) **Category:** Aspect of the natural environment in an epistemic sense, that is, referring to either the physical (P), chemical (C) or biological (B) dimensions of the environment.

(Scientific) **Discipline:** A branch of scientific knowledge within the Environmental Sciences domain. Analysed disciplines include the Atmospheric science (AT), Soil science (SO), Geology (GE), Terrestrial Ecology (TE), Hydrology and Hydrogeology (HY), Freshwater science (FW), Agricultural sciences (AG), and Forestry sciences (FO).

Discipline-category pair: Type of basic science *category* of the environment studied by a given scientific *discipline* (e.g., the chemical aspect of soil science: SO-C).

Environmental compartment: The compartments of the terrestrial environmental system covered in our review, i.e. atmosphere, pedosphere, geosphere, biosphere, and the hydrosphere with its aquatic systems, plus the anthroposphere.

Environmental tie: Directional connection between two *discipline-category pairs*, which includes all *individual links* (i.e., processes of environmental factors; see below) connecting both pairs in a specific direction (e.g., all links connecting the physical aspect of the atmosphere to the physics of the terrestrial ecology).

Individual link: a process or environmental factor controlling a process that connects two *discipline-category pairs* in a certain direction (e.g., water evapotranspiration).

Missing link: *Individual link* between two *discipline-category pairs* that is either not included or misrepresented in models from a given model type but should be included according to experts' statements in the literature.

Model type: A branch of environmental modelling focused on predicting or understanding processes and dynamics of specific systems within the terrestrial environment (e.g., hydrologic modelling targeted at simulating the behaviour of hydrologic systems).

Weighted individual link: *Individual links* are weighted by the frequency with which they are represented in the models of the respective *model type*.

Weight of an environmental tie: Strength of the directional connection between two *discipline-category pairs* measured as the sum of all the weights of the individual directional links that characterize the *environmental tie*.

In addition to ascribing processes to the above disciplines, they were also attributed to one out of three basic science categories, that is, physics, chemistry or biology, depending on the methods used to study the aspect addressed (Box 1). The latter classification takes into account whether the respective model explicitly considers respective drivers and constraints. For example, biogeochemical transformations performed by living organisms (e.g., denitrification by microbes or assimilation by aquatic plants) are considered biological processes only when the living organisms are explicitly modelled. A counter example would be to model denitrification to occur under certain physical or chemical boundary conditions (e.g., anoxia in soils), irrespective of abundance, population growth, and limitation by resources availability of microorganisms. Another counter example would be to model plant assimilation as a mere reaction to soil and atmospheric environmental states without feedback to vegetation growth. Thus every process was ascribed to a discipline-category pair (Box 1).

We analysed 118 simulation models from a total of 23 model types, whose descriptions are summarized in Appendix A, including at least two model types from each scientific domain. The selected model types have, at least to a certain extent, a multidisciplinary focus and integrate at least some of the environmental compartments of the terrestrial system through interfaces. We restricted our study to dynamic process-based models applied at spatial scales relevant for terrestrial (eco)system management, ranging from local (field, forest stand or lake) to continental and global scales. The ecological systems modelled must be represented preferably at the ecosystem but at least at the community level of ecological hierarchy, thus excluding population models. The main criteria for differentiating model types within scientific domains were modelling aim (e.g., ecohydrologic vs. ecohydrologic biogeochemistry models, terrestrial biosphere online vs. offline models) and spatial scale of application (e.g., macro-scale vs. catchment hydrologic models, forest landscape vs. forest gap models).

The objectives of the data compilation stage were to identify for each selected model type (1) processes and primary controls implemented in existing models, and (2) modelling gaps.

2.1.1. Implemented links

We first analysed which processes and primary controls of these processes (e.g., control of CO_2 concentration on leaf stomatal conductance), are currently incorporated in models, how they are represented (level of complexity), and the frequency with which they are represented (i.e., number of models within a model type including the given processes). Human impacts addressed in models as imposed fluxes across or prescribed states at boundary conditions (e.g., water withdrawal, fishing mortality, disturbance) were accounted for in the study.

This task was performed through the analysis of representative models from each model type that reflected the state of the art in the respective discipline. Selection of models was based on knowledge from experts on the specific modelling field (see Acknowledgements), and on the status of the model in the literature (e.g., being regarded as a representative model by specialized review papers, being widely used in journal-published literature, included in model intercomparison projects, or highly cited in the literature and bibliographic searches). We carried out a comprehensive assessment of the resulting selected 80 models ("Main models" in Appendix B), extracting the information from the technical documentation (peer-reviewed journal papers or technical reports) wherein the models were comprehensively described. This analysis was complemented with the assessment of 38 additional models ("Secondary models" in Appendix B), which was focused on particular aspects, such as specific processes, representation of interfaces or of specific compartments. Great value was placed on models incorporating the most comprehensive process representation and highest degree of sophistication. Besides, the features from further 68 models ("Complementary models" in Appendix B), extracted from summary tables from model intercomparisons reported in the literature, were also taken into account to characterize the extent to which processes are represented within each model type. Overall, 184 papers and technical reports were examined for the analysis of representative models.

2.1.2. Missing links

Each model is a simplification and thus necessarily includes "gaps" in its representation of reality. However, here we focus on gaps that in the literature were considered essential for representing the feedback between compartments. We compiled the modelling gaps reported in the literature, including gaps in process representation and system conceptualization, data gaps, as well as gaps in knowledge and process understanding as perceived by the models under review. In Appendix C we provide the reported modelling gaps, their implications for prediction accuracy, and the solutions or alternative approaches suggested in the literature to overcome these problems. For this systematic review, we examined 162 review papers and publications reporting results from model intercomparisons published over the last 10 years (2007-2016). Publications were selected for inclusion from matches found on Web of Science and Google Scholar search results. Selection was not limited to papers published in high-impact factor journals, although preference was given to these papers.

Altogether, a total of 396 implemented and missing processes and primary controls were identified and provide the basis for our subsequent analyses (see Appendix D). We tried to balance the number of selected processes considered from each scientific domain and within each compartment. Selected processes were categorized by the environmental compartment wherein they take place (i.e., atmosphere, land surface, soil, freshwaters, and phytosphere and zoosphere), or by the environmental compartments they link. It has to be kept in mind that the resulting data on missing processes, or gaps, is firstly based on expert opinions, which might be biased, and secondly depends on the respective specific modelling aims. However, given the large number of models and articles from which we extracted our data, we believe that, taken together, the majority of reported gaps matters for a wide range of relevant research questions.

2.2. Data synthesis

To categorize processes and links, environmental compartments (Box 1) were defined as subjects of study of the selected environmental scientific disciplines; e.g., Geology was associated to the geosphere, Terrestrial Ecology to the biosphere, and so on. On the one hand, this approach facilitates a quantitative analytical evaluation of the level of multidisciplinarity of selected model types. On the other hand, it involves a certain degree of overlap as certain processes taking place in a specific compartment might be the subject of different scientific disciplines (e.g., water transport in the soil is studied by both hydrogeology and soil science and thus considered both a hydrologic and soil process; growth of crop plants is both an ecological and an agricultural process). Therefore, processes and drivers connecting scientific disciplines refer to processes that are linking the subjects of study of those disciplines, which relate to the environmental compartments they study.

We also assessed how process representation and compartment integration vary across model types depending on the different system conceptualizations and modelling perspectives of each environmental scientific discipline. We analysed the relationship amongst the studied model types following three approaches: 1) grouping model types based on the processes they incorporate; 2) grouping model types based on the modelling gaps they share based on experts' statements in the literature; 3) analysing the degree of connection between model types depending on both the processes they incorporate and the relevant processes they miss, to assess the extent to which the modelling gaps of one model type are accurately represented in models from the rest of the studied model types. This latter analysis will provide a picture of how a model type can benefit from conceptualizations, knowledge, process understanding and modelling techniques of other model types.

To quantitatively characterize all these complex relationships, we compiled matrices of existing or missing links and then analysed theses matrices using cluster analysis and network modelling.

2.2.1. Characterization of links

We first characterized the full set of processes linking environmental compartments and scientific domains that are currently implemented in selected model types or have been reported as modelling gaps in the literature (Box 1). We analyzed how physical, chemical and biological aspects were connected both within and across scientific disciplines through modelled processes. For this we developed a matrix whose rows and columns are defined by all possible discipline-category pairs (Box 1). The entries in the matrix cells are processes or controls that link two of these pairs because they represent influence, or control. Thus, if we interpret each discipline-category pair as a node in a network, each pair of nodes can be linked by one or more processes, i.e. links (Fig. 1). This representation and terminology will later allow us to use cluster and network analysis to quantify the interconnectedness of environmental sciences across compartments.

For example, “water infiltration” is a physical hydrological process that affects the physical properties of the soil and provides an input to model water movement within the soil, so there is a directional link from the physics of hydrology, HY-P, to the physics of soil science, SO-P). The “direction” of a link thus indicates influence and possibly control.

The entire set of directional links between two discipline-category pairs (nodes) defines an “environmental tie” (Box 1; e.g., the connection from the physics of the atmosphere to the physics of the soil, AT-P/SO-P). This connection is directional so that AT-P/SO-P is different from SO-P/AT-P (Fig. 1); for instance, interception of precipitation by the soil litter would be an individual process linking AT-P/SO-P, while soil evaporation would link both nodes the other way round. That means that the matrix is asymmetric, and so outflow nodes are represented as rows and inflow nodes as columns (see Appendix D).

Indirect links (interaction between compartments mediated by a third compartment; e.g., the soil-atmosphere link through plant transpiration) are represented in the matrix as if they were direct links between both compartments (Fig. 1). On the contrary, processes that are the subject of study of two disciplines (due to overlap) but are not interfacing them in any way (e.g., the description of water flows in porous media in soil science and hydrogeology), are not represented as a link between both disciplines. Each one of the processes and primary controls represents an individual directional link that contributes to one or several environmental ties. We obtained the full matrix of processes and controls by characterizing every environmental tie (see Appendix D).

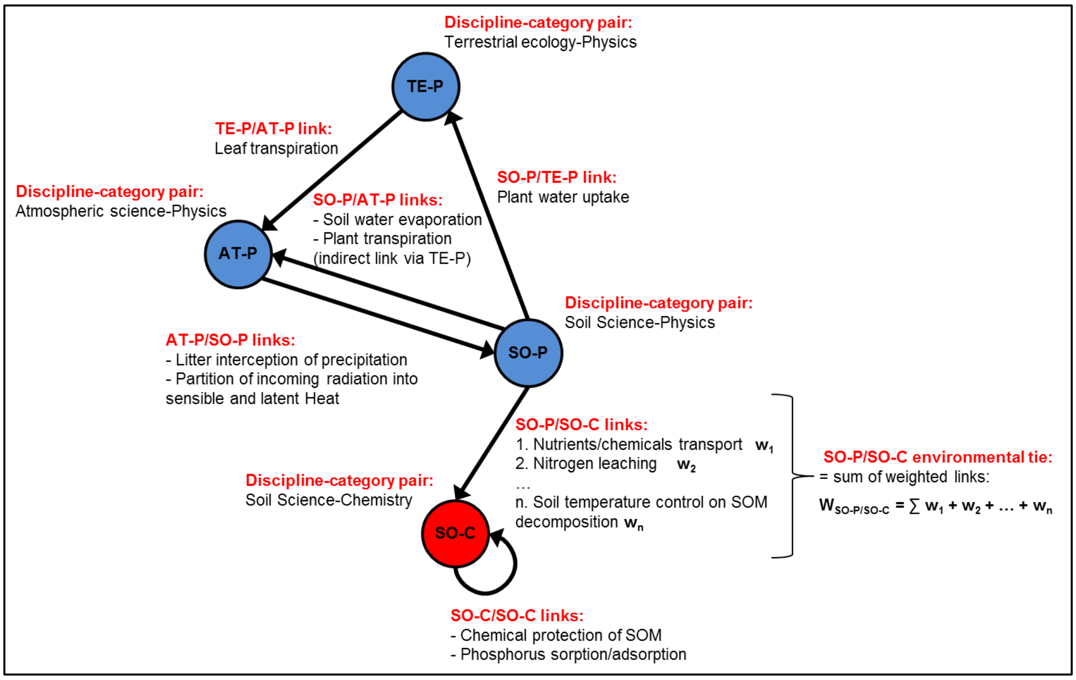

Fig 1. Examples illustrating the used terminology (in red) and concepts.

2.2.2. Matrix of existing links (MEL)

After characterizing the 396 selected processes, we developed the matrix of existing links for each model type, which represents the processes that are actually incorporated in the models of each analyzed model type. To do this, each individual directional link of the full matrix was weighted by the frequency with which it is represented in the models of the respective model type: the link would have a weight of 0 if it is never represented in the models, 1 when it is only represented in the most complex models, 2 when it is equally represented than not (some models do include the link but others do not), and 3 when it is always or almost always represented. Besides, the processes involving agricultural and forestry systems are additionally weighted by how often crop dynamics and agricultural and forestry practices are represented in the models. This procedure was based on the model assessment described in section 1.1. The sum of all the weights of the individual directional links that characterize an environmental tie defines its weight, that is, the strength of the directional connection between the two nodes.

2.2.3. Matrix of missing links (MML)

As a third step, we developed the same kind of matrix for missing links for each model type, which represents the processes that are not yet but should be incorporated in the models of each analyzed model type according to the experts' opinion. The matrix of missing links is not necessarily the opposite matrix of the matrix of existing links, as not all possible links have been considered important or necessary. This is because process representation is dictated by the purpose the model was designed for and its spatial scale of application, and constrained by data availability. For example, implementation of biogeochemistry modules to model biogeochemical fluxes are not required in model types focused on simulating hydrologic fluxes and states. Likewise, processes occurring at micro-scales are not implemented in models applied at global scales.

The identification of missing links was based on the modelling gaps reported in the published literature by experts of the different modelling fields, which were identified through the systematic literature review described in section 1.2. When the level of complexity with which missing processes should be incorporated into models was not explicitly addressed in the literature, we opted for the simplest representation and for inclusion of just the key processes considered necessary to model a particular phenomenon, the choice being constrained by model purpose and spatial scale of application as described above. As in the case of the matrix of existing links, individual missing links were weighted: a weight of 3 indicates that the necessary missing link is never implemented in models of the model type, 2 when it is only implemented in most complex models, 1 when it is equally implemented than not, and 0 when it is implemented in all or almost all models (so in this case, it would not be actually a missing link). The sum of all the weights of the individual missing links that characterize an environmental tie defines its weight (cf. Box 1).

2.2.4. Matrix of existing-missing links (MEML)

In the last step, we crossed the matrices of existing and missing links (MEL and MML, respectively), as described above, to obtain a matrix that quantifies the degree to which missing links identified for one model type are addressed by models of the remaining model types. Thus not only the unevenness of the representation of interdisciplinary links in different model types is highlighted, but possible pathways to overcome the existing restrictions are illustrated. So when the strength of the connection between two model types is high in this matrix, then there is much scope for improving process representation in the given model by integrating concepts and knowledge from the other model type. The weight or strength of the connection between two model types *i* and *j* was calculated as:

$$W_{i,j} = \frac{1}{3} * \sum_{z=1}^{n} \left(w_{i,z} * w_{j,z} \right)$$

where $W_{i,j}$ represents the weighted number of existing links in model type *i* that are missing in model type *j*, i.e. $W_{i,j}$ is a measure that indicates "how much" knowledge model type *j* can borrow or integrate from model type *i*; $w_{i,z}$ represents the weight of the individual link *z* in the MEL of model type *i*; $w_{j,z}$ represents the weight of the individual link *z* in the MML of model type *j*. Division by 3 ensures that this measure scales in the [0; 3] range to be comparable to the values in the other matrices.

For example, an individual link that is represented in all models of the model type *i* (it would have a value of 3 in the MEL) but is never represented in the models of model type *j* (value of 3 in the MML) would have a weight of 3; while an individual link that is roughly represented in 50% of the models of model type *i* (value of 2 in the MEL) but is only represented in most complex models of model type *j* (value of 2 in the MML) would have a weight of 1.33. The sum of the weights of all individual links defines the strength of the connection from model type *i* to model type *j*. Therefore, the higher the value of *Wi*,*j*, the better model type *i* could contribute to implement missing links in model type *j*. The matrix of existing-missing links represents the strength of the connection between each pair of the 23 studied model types.

2.3. Data analysis

We used two statistical analysis approaches to (1) typify groups of model types with similar process representation or common modelling gaps, and (2) characterize the patterns underlying such associations based on the structural properties of the network of implemented or neglected links.

2.3.1. Cluster analysis

We first used cluster analysis to identify relatedness of model types based on patterns produced by the typology of either the represented or missing processes (existing or missing weighted environmental ties). Since different results can be obtained depending on the clustering algorithm and parameter settings used in the analysis, the most appropriate clustering solution for a particular individual data set cannot be selected a priori. Therefore, we computed different clustering solutions and assessed the associated quality measures to identify the optimal one regarding the clustering algorithm and method, parameter settings, as well as expected number of clusters. We used the *WeightedCluster* R package v1.2 (Studer 2014), which compares different connectivity-based and centroid-based clustering methods through several quality statistics (Point Biserial Correlation, Hubert's Gamma, Hubert's Gamma-Somers'D, Average Silhouette width, Calinski-Harabasz index, R^2, and Hubert's C coefficient; see Studer 2014 for details). We ranked all computed clustering solutions according to each quality measure and identified the optimal solution as the one being ranked as the best solution by most of quality measures. Further, we computed additional clustering solutions applying model-based methods by means of the *mclust* R package v5.2 (Fraley et al. 2016) to compare the optimal number of clusters and final classification. Comparisons revealed that in both analyses (clustering of model types based on either existing or missing link types) agglomerative hierarchical clustering was the optimal clustering algorithm and Ward's method the optimal linkage method, with the Euclidean distance as the distance metric to calculate the dissimilarity matrix. The optimal number of clusters and the classification of model types into clusters matched the optimal solutions provided by model-based clustering. Therefore, we computed the corresponding dendrograms running the *agnes* algorithm function within the *cluster* R package v 2.0.4 (Maechler et al. 2016), which were linked to heat maps by means of the *gplots* R package v3.0.1 (Warnes et al. 2016).

2.3.2. Network modelling

Secondly we used network modelling to analyse the complexity and topology of the network linking the physical, chemical and biological aspects of environmental compartments. Similarly to the cluster analysis, we analysed the structure of both the connections already incorporated in the models and of the missing connections. Each node of the network represents a discipline-category pair from the matrices of existing or missing links, and connections amongst them represent the corresponding weighted environmental ties. We generated the respective one-mode, directed, weighted networks for each model type by means of the *igraph* R package v 1.0.0 (Csardi and Nepusz 2006). We calculated several measures to analyse the properties of the generated networks, including metrics characterizing distance (betweenness, diameter), connectivity (density, degree, reciprocity, centrality indices), clustering or transitivity (clustering coefficient), homophily (assortativity), heterogeneity (alpha coefficient in the degree distribution power function) and modularity properties (see description of calculated metrics in Appendix E). We then compared the computed measures between model types belonging to the different clusters identified in the cluster analyses. Moreover, we generated a one-mode, directed, weighted network model for the matrix of existing-missing links to analyse the extent to which the modelling gaps of each model type are accurately addressed by models from the rest of the studied model types. All statistical analyses were performed within the R environment (R Core Team 2015).

3. Results

3.1. Implemented links

Model types are clustered into six clusters based on the typology of processes they incorporate (Fig.2; see also Table 1). The first cluster encompasses exclusively weather and climate models, which separate from the rest of the model types because they are the only ones that explicitly model physical and chemical atmospheric processes. All other model types use atmospheric data only as forcing data and aggregate into two branches. The first branch, comprising the second and third cluster, include ecosystem and ecological models that implement a large number of environmental ties connecting the biological aspects of the terrestrial ecology domain with the rest of discipline-category pairs; model types from clusters of the second branch have, on the contrary, a poor representation of terrestrial biological processes.

The ecosystem models from the second cluster incorporate a comprehensive integration of most environmental compartments through physical and chemical processes that is lacking in the model types from the third cluster, which basically focus on biological processes. From the model types of the second branch, aquatic models (cluster six) separate from the rest because they neglect most landscape processes, and just focus on physical, chemical and biological processes within the freshwater system. The hydrologic models comprising the fourth cluster incorporate a more comprehensive representation of hydrologic (both in the surface and subsurface) and soil physical processes, and their connections to atmospheric physical properties, than the soil and geologic models from the fifth cluster. Besides, a main discrimination feature was that, despite the fact that hydrologic models neglect in general most biological processes, they highly incorporate environmental ties related to terrestrial ecological physical processes and controls; soil evolution and geologic models ignore most processes connected to terrestrial ecology.

There are significant differences between model types from the different clusters in the strength (sum of weights) of implemented environmental ties (ANOVA, $F_{5,17}$=9.49, $p < 0.001$). The post-hoc Tukey test revealed three categories: a group with most comprehensive process representation including model types from clusters 1 and 2 (520.4±118.5 and 523.9±70.7 average sum of weights, respectively), a second group with just hydrologic model types (cluster 4, 369.8±159.2), and a third group with fewer processes represented including model types from clusters 3, 5 and 6 (207.4±87.4, 170.6±78.6 and 232.0±106.1, respectively).

The role of single disciplines and categories is revealed by the vertical structures (columns) in Fig.1. Among the three categories, most of the identified links relate to physical processes, and the least to biological processes. In the physics category, links related to atmospheric science, hydrology and soil science are prevalent in many different model types. Among these three only soils science plays a pivotal role within the chemistry category as well, but none of them are relevant in the biology category. In contrast, terrestrial ecology is the only discipline with many interdisciplinary links implemented within all three categories (physics, chemistry and biology; Fig.2), especially within cluster one and two (number of weighted links typically over 25, orange tones in Fig. 2).

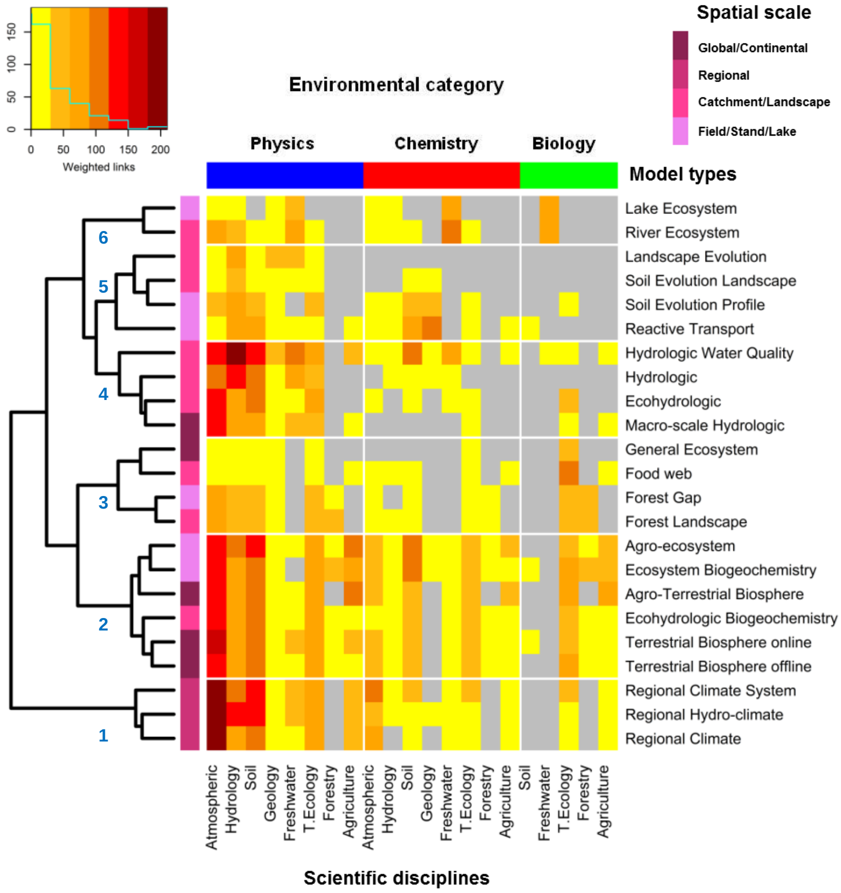

Fig 2. Number of weighted intra- and interdisciplinary links between single disciplines and categories (x-axis) to other disciplines and/or categories implemented in different model types (y-axis). The upper left inset gives the colour code for the number of weighted links (yellow to dark red) and the frequency of links per bin (cyan line). Grey cells in the main graph denote links not implemented in model types. The dendrogram at the left y-axis shows the results of a cluster analysis of model types based on number and kind of implemented interdisciplinary links. Cluster numbers are shown in the dendrogram. The purple colour code at the left y-axis denotes the approximate spatial scale of application of the respective model type (see legend to the upper right). Horizontal white lines in the main graph separate different clusters, vertical white lines separate different categories.

The network models reveal more details of the connectivity patterns for the different model types (Fig. 3). There are marked differences in network structure and complexity between model types belonging to the different clusters identified through the hierarchical cluster analysis (see Fig. E.1 and Table E.1 in the appendices). The most comprehensive ecosystem model types from the second cluster and the regional climate system model type show the highest connectivity between environmental aspects and scientific domains (higher density, mean degree and betweenness), and regularity (clustering), which indicates a better flow of information through the network (Table E.1 and Fig. E.1). These model types are also more modular than the rest of model types (Table E.1 and Fig. E.1). High modularity (dense connections between the nodes within modules but sparse connections between nodes in different modules) is an important feature as it allows the adaptation of different functions with a small amount of interference with other functions. At the other end of the spectrum, soil evolution, geologic and aquatic models show the lowest connectivity and integration, mainly incorporating processes from a lower number of compartments. All model types show a low heterogeneity in their connectivity patterns, i.e. their networks do not tend to be characterized by a few central nodes being connected to many others (Fig. E.1). The networks do not show assortative mixing by either degree or discipline, that is, high-degree nodes do not tend to attach to other high-degree nodes, as well as nodes do not tend to attach to nodes of the same scientific discipline. Nevertheless, they all show, in general, a positive assortativity by category, so that nodes have a tendency to tie to nodes of the same category (physics, chemistry, or biology).

Strong links are established between various disciplines in the physical category, especially between atmospheric science, soil science, and hydrology. A large fraction of these links describe weather and climate effects on other compartments of environmental systems. In contrast, there are only very few links between geology or freshwater systems and other environmental disciplines implemented in models. Many chemical and biological processes are restricted to links within the same discipline-category (indicated by loops) and are neither connected to the same category in other disciplines, nor to different categories of other disciplines.

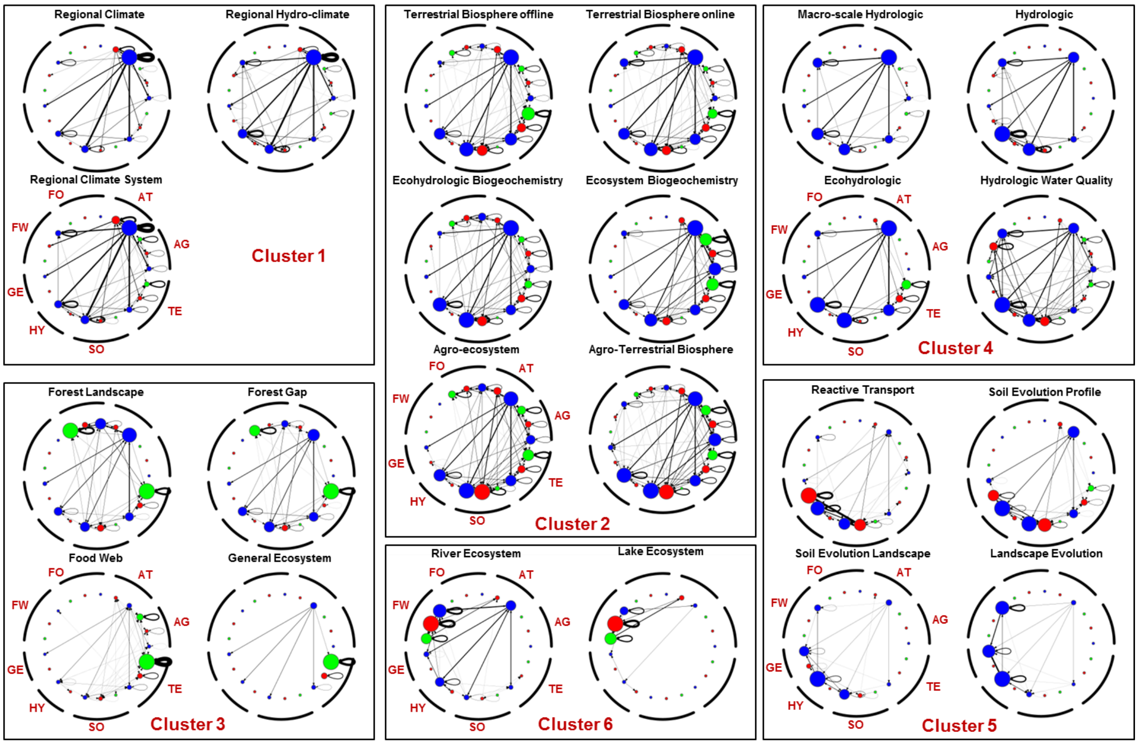

Fig 3. Network models for environmental ties in the 23 model types. Boxes delineate the six clusters of model types (cf. Fig.2). Discipline-category pairs are represented by nodes (full circles coloured according to category, same position in all networks) and environmental ties by edges (loops in case of internal links). Disciplines are coded as indicated in Box 1. Physics, chemistry and biology categories are coloured in blue, red and green, respectively. The width of the edges is scaled by the sum of weights of the individual links connecting both nodes, while node size corresponds to the sum of weights of all environmental ties flowing in and out of the node. Scaling applies within individual networks so node sizes and edge widths are not comparable across network models.

3.2. Missing links

Modelling gaps reported in the literature (see Appendix C for full description and bibliographic sources) are summarized in Table 1, differentiated according to environmental compartment.

We identified seven clusters of model types (Fig. 4; see also Table 1), exhibiting two main branches. The perceptions from expert modellers is that model types from the lower branch should incorporate a wider and more complex range of biological and biochemical processes related to disciplines from life sciences focused on terrestrial landscapes (terrestrial ecology, agricultural and forestry sciences) and processes and factors connected to soil biogeochemical cycles, compared to the model types from the upper branch. This differentiation emerges from contrasting conceptualization of the model system and the role played by the phytosphere (the zoosphere is neglected in most models) on it, which are highly dependent on model purpose.

There are significant differences in the sum of weights of missing environmental ties between model types from the different clusters (ANOVA, $F_{5,17}=6.0$, $p < 0.01$). The post-hoc Tukey test revealed that model types from the first five clusters have a significantly higher sum of weights of missing ties than model types from clusters 6 and 7. The sum of weighted missing environmental ties is higher than the sum of weighted existing environmental ties in all model types (cf. Fig. 2), and thus the mean values (686.1±240.8 and 354.8±177.0, respectively) differ significantly (ANOVA, $F_{1,44}=28.3$, $p < 0.0001$). Interestingly, there is a significant positive correlation (Pearson-r = 0.53, $p < 0.01$) between the represented and missing weighted environmental ties, so that model types including a higher number of processes and drivers are perceived to require a yet higher number of additional processes and controls.

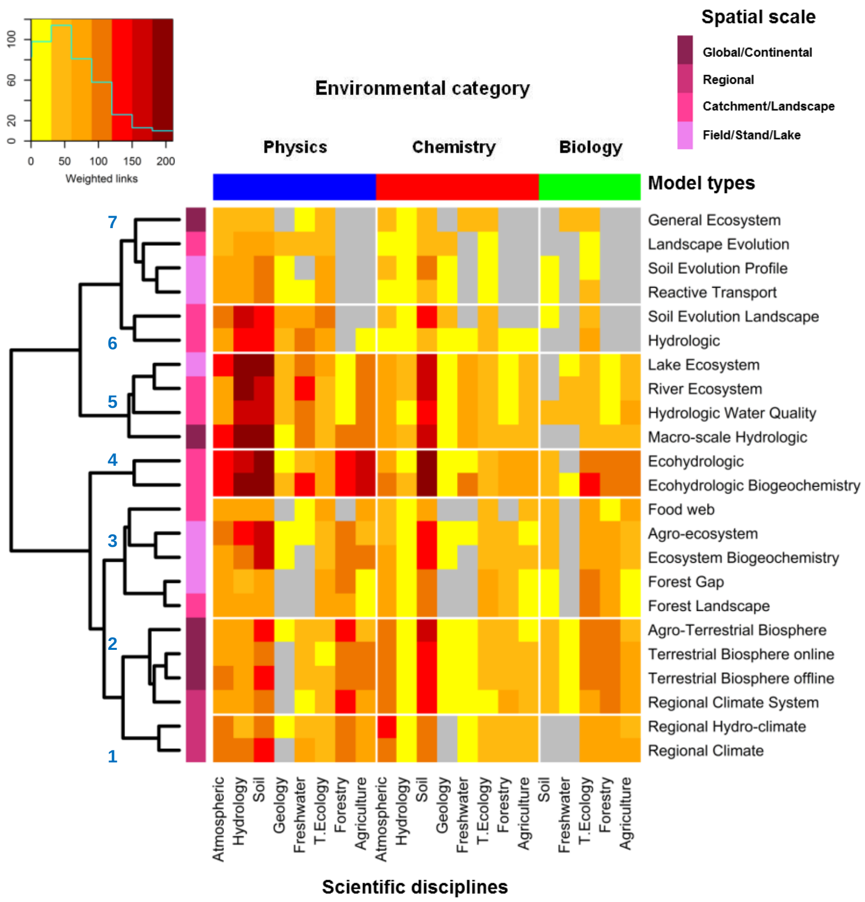

Fig 4. Number of weighted intra- and interdisciplinary missing or misrepresented links between single disciplines and categories (x-axis) to other disciplines and/or categories implemented in different model types (y-axis). Due to the different cluster structure the ordering of model types on the y-axis differs from the ordering in Fig. 2 representing the existing links. The upper left inset gives the colour code for the number of weighted links (yellow to dark red) and the frequency of links per bin (cyan line). Grey cells denote links that are either accurately represented or not considered necessary. The dendrogram at the left y-axis shows the results of a cluster analysis of model types based on number and kind of missing interdisciplinary links. Cluster numbers are shown in the dendrogram. The purple colour code at the left y-axis denotes the approximate spatial scale of application of the respective model type (see legend to the

upper right). Horizontal white lines in the main graph separate different clusters, vertical white lines separate different categories.

The networks provide detailed information about the nature of missing environmental ties (Fig. 5, Fig. E.2). The vegetation subsystem plays a central role in all model types from the lower branch of the dendrogram (clusters 1 to 4). These are models that are either targeted at simulating the dynamics of the terrestrial vegetation (forests or agricultural systems) to predict their distribution, structure, function or production, or need to incorporate it as a dynamic component to simulate fluxes and cycling of water, carbon or nutrients through the ecosystem. This requires an accurate representation of the water fluxes through the soil-vegetation-atmosphere (SVA) system, the soil biogeochemical cycles and transport of nutrients, as well as disturbance factors affecting the vegetation component. Therefore, despite a more comprehensive representation of the vegetation subsystem (see connections to TE-P; TE-C and TE-B in Figs. 2 and 3), it is perceived that these model types should still incorporate a much higher number of processes driving plant population and community dynamics, plant eco-physiological processes, and their connections to hydrological and biogeochemical fluxes and cycles, as well as to processes in the atmospheric boundary layer, than hydrologic, soil evolution and geologic model types, which actually lack or have a poor representation of the vegetation system. In consequence, biological terrestrial ecological and chemical soil processes represent dominant nodes in the networks of missing links of model types from the first four clusters resulting from hierarchical clustering based on missing links (see Fig. E.2 for representation of networks topology). In the case of regional climate and hydro-climate models, experts suggest they should naturally evolve towards regional climate system models, incorporating processes and conceptualizations from the current generation of terrestrial biosphere models, which involves a more accurate representation of the ecological system and its connections to physical and biogeochemical processes of the soil.

As a general pattern, it has often been suggested that model types from the first four clusters resulting from hierarchical clustering based on missing links (Fig. 4) should include a better representation of crop dynamics and agricultural and forestry practices (except for forest and agro-ecosystem models, of course), disturbance factors (e.g., fire or insect outbreaks), and faunal processes, due to their direct impacts on vegetation dynamics and indirect effects on carbon and nutrient cycles and emission of trace gases. As differential missing environmental ties, model types from the second cluster should improve the representation of processes driving fluxes through the SVA system (connections to AT-P node in Fig. 5 and Fig. E.2), while model types from clusters 3 and 4 lack accurate modelling of nutrient and carbon transport processes in the soil (ties from HY-P and SO-P to SO-C). Ecohydrologic models from the fourth cluster additionally lack proper connections to the aquatic systems (ties from HY and SO to FW nodes).

Model types from the upper branch of the dendrogram (clusters 5-7; Fig. 4) focus on physical and chemical transformations, and/or flow of matter (water, solutes, sediments, energy), except for the general ecosystem model type, so the vegetation component (and life forms, in general) plays a marginal, if any, role. However, it is widely accepted that its representation must be improved to model its effects on physical and chemical properties of the land surface and soil compartment and on processes taking place there. It requires the incorporation of, at least, a simple representation of the SVA system (connections between AT-P, SO-P, HY-P and TE-P nodes). Hydrologic and aquatic models from the fifth cluster should incorporate more of biogeochemical cycles and nutrients and carbon transport processes in the soil, as well as proper representations of water and biogeochemical exchanges between the soil and groundwater and the aquatic system though the hyporheic zone, in order to properly model water quality and aquatic biogeochemistry. Thus, SO-P, HY-P, SO-C, FW-P and FW-C are central nodes in the networks of missing processes (Fig. 5 and Fig. E.2). In contrast, links to or from geological and freshwater systems processes were hardly missed in the literature in spite of the small number of established links (cf. Fig. 3). Missing links to freshwater systems are considered relevant mainly in model types from clusters 4 and 5 and for the general ecosystem model type. Model types from the sixth and seventh cluster require a stronger incorporation of biochemical and geochemical processes related to soil forming processes as well as the control of water processes on them (connections from SO-P and HY-P to SO-C and GE-C). General ecosystem models need to incorporate processes modelling nutrient and water fluxes and their connection to the biological components through both the terrestrial and aquatic systems.

Comparing Fig. 5 with Fig. 3 reveals two major differences: Firstly, there are many more processes restricted to single disciplines and categories in Fig. 5 compared to Fig. 3 (represented as loops in the network models). Secondly, missing links between different disciplines and categories do not show any clear pattern for most clusters, except for the fact that links to freshwater science and geology are hardly missed for most model types. Thus the assumption that the comprehensive compilation of respective review and opinion papers of various disciplines would reveal emerging hot spots of missing links did not hold true. Rather, the pattern suggests a reinforcement of already implemented links.

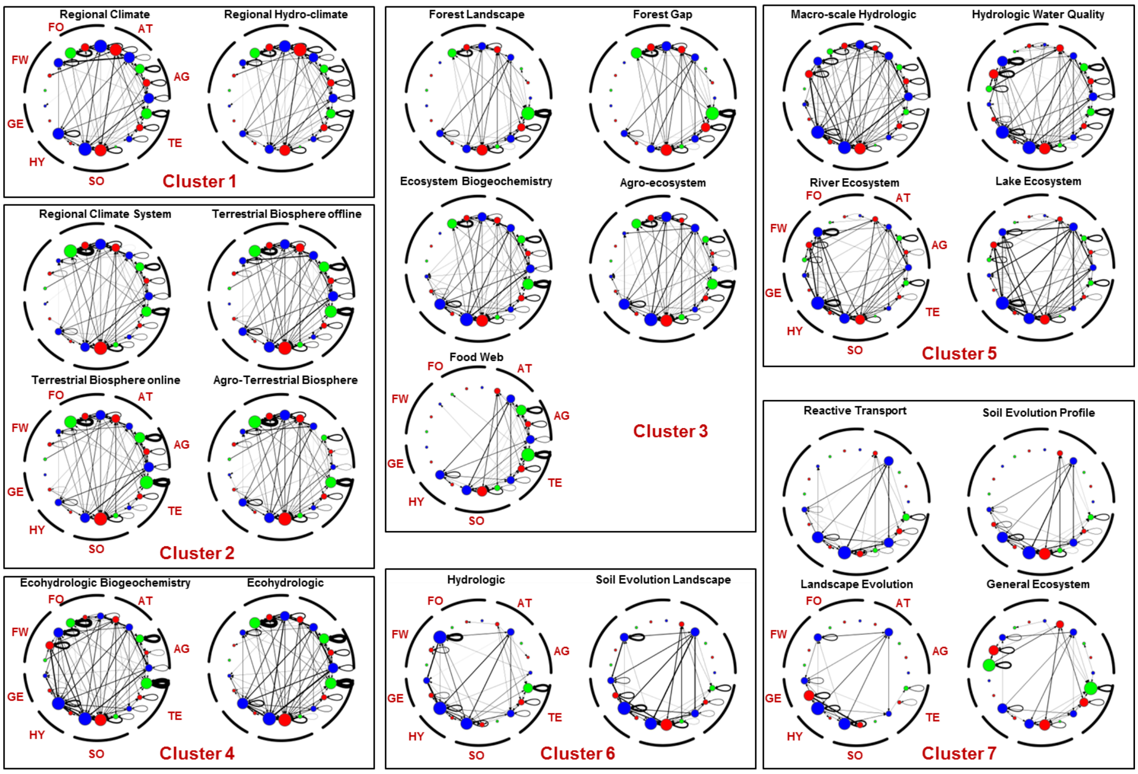

Fig 5. Network models for the 23 model types representing environmental ties missing in simulation models. Boxes delineate the seven clusters of model types (cf. Fig.4). Discipline-category pairs are represented by nodes (full circles coloured according to category, same position in all networks) and environmental ties by edges (loops in case of internal links). Disciplines are coded as indicated in Box 1. Physics, chemistry and biology categories are coloured in blue, red and green, respectively. The width of the edges is scaled by the sum of weights of the individual links connecting both nodes, while node size corresponds to the sum of weights of all environmental ties flowing in and out of the node. Scaling applies within individual networks so node sizes and edge widths are not comparable across network models.

3.3. Possible compensatory knowledge transfer between disciplines

In Fig. 6 rows denote the missing links stated in the literature for different model types, and columns denote the links that are actually implemented in the respective model types. For example, the fifth row indicates the processes that many authors recommend to consider in soil evolution landscape models. These links are actually already commonly implemented in other model types that are listed in the first nine columns, as indicated by dark raster cells. Please note that the order of model types at the x- and y-axis differs corresponding to the respective dendrograms D1 and D2, and thus the diagonal of the matrix is meaningless.

Red and dark yellow raster cells are more aligned along rows rather than along columns. That means that this analysis reveals more a lack of implementation of known processes in certain model types rather than a general lack of knowledge about and modelling of single links. However, what seems to be good news could in fact indicate a systematic bias: Experts tend to state a need for links that are already known and implemented elsewhere, and tend not to miss links that have rarely been implemented at all.

In contrast, columns 3-9 exhibit a large number of dark raster cells. This indicates that the respective rather complex regional climate system models and models of the second cluster of the represented links (D2 in Fig. 6) are characterized by the implementation of most of the links that experts are missing in other model types. These include mainly ecological and biogeochemical processes, as well as the hydrologic controls on these processes, and an improved representation of the SVA system. Likewise, all hydrologic model types can provide conceptualizations and representations of hydrological processes that are missing in soil evolution, geologic, aquatic, and less comprehensive ecological models (clusters 5-7 in D1). The opposite holds for models in the last two clusters of the represented common processes that can contribute only little to compensate for deficiencies in other model types.

However, when we focus on "rare" processes, some specific model types acquire a higher relevance as they are the only ones that incorporate important processes that are recurrently reported as missing in most model types (Fig. 6). Given that soil processes and agricultural practices (to a lesser extent) are largely misrepresented in most model types, ecosystem biogeochemistry and agro-ecosystem models play a central role in the network of connections between model types. Hydrologic models including transport of solutes can provide conceptualizations to all disciplines that aim at incorporating lateral and vertical transport of carbon and nutrients to simulate redistribution across landscapes, and also to model flux exchange with aquatic systems. A wide range of model types can incorporate modules from reactive transport models to simulate geochemical (e.g., chemical weathering) and reactive transport of pollutants or nutrients, both in terrestrial and aquatic environments. Forest models should play a relevant role on transferring representations of specific processes related to plant community dynamics, forestry practices and forest disturbance. In the same way, most complex physical-chemical processes represented in aquatic models should be incorporated in model types aimed at predicting water quality or emission of carbon or trace gases from aquatic environments (e.g., riparian areas or wetlands). In addition, there is a wide range of missing processes that are not incorporated yet in the model types included in this study but that have been accurately addressed in other intra-disciplinary models, such as microbial, bioturbation or plant-physiological models (Fig. E.3). Finally, more research is required before we can incorporate into models many relevant processes that are still missing (Fig. E.3).

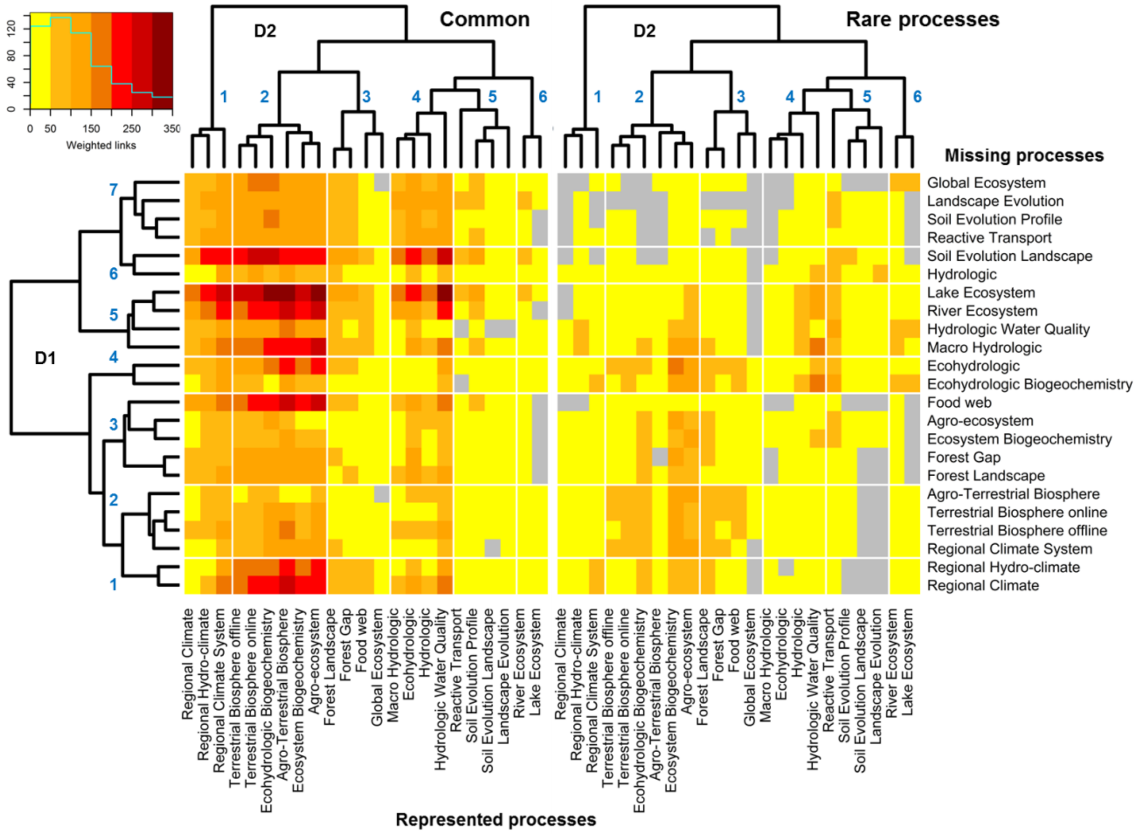

Fig 6. Relationship of the 23 analysed model types based on the processes represented and missing in the models. Model types in rows are clustered based on similarities in the typology of environmental ties misrepresented in the models (clustering in Fig. 4). Model types in columns are clustered based on similarities in the typology of environmental ties represented in the models (clustering in Fig. 2). Shading intensity in the heat maps indicates the sum of weights of all individual processes missing in model types displayed in rows that are represented in model types displayed in columns (weighted links). Grey cells indicate no connection. The graph at the top left represents the colour key for the heat map, the x-axis showing the splitting points for binning weighted links into colours, and the cyan line indicating the number of cells of the heat map within each bin. It is differentiated between common and rare missing individual processes. Common processes refer to processes that are routinely incorporated into models (weight of 2 or 3 in the matrix of existing links) of more than 10% of studied model types; rare processes refer to those that are currently represented only in most complex models (weight of 1 in the matrix of existing links) or routinely incorporated into models of less than 10% of studied model types. White lines in the heat maps separate different clusters. The dendrogram at the left y-axis (D1) shows the results of a cluster analysis of model types based on number and kind of missing interdisciplinary links, while dendrograms at the top x-axis (D2) shows the results of a cluster analysis of model types based on number and kind of implemented interdisciplinary links. Cluster numbers are shown in each dendrogram.

4. Discussion

4.1. Analysing numerical models as repositories of scientific knowledge

Our study aimed at surveying the state of current scientific knowledge about dynamical links between different compartments of terrestrial environments that are the subject of different scientific disciplines. A comprehensive survey of the literature of the respective disciplines would have been far from feasible. Instead, we performed an analysis of a selection of comprehensive process models deemed to be representative by experts of the respective disciplines. That approach is based on the basic assumption that models can be regarded as condensed repositories of scientific knowledge, or as "collective intelligence" of the respective discipline (Beven 2001).

In general, (natural) science can be regarded as "a process of constructing predictive conceptual models" (Gilbert 1991). Here, the term "computer model" or "process model" is restricted to approaches of dynamic system theory of deterministic cause-effect relationships, being aware of the fact that a plethora of other model approaches exist, e.g., to mimic observed behaviour. However, this does not necessarily mean computer models that try to mimic the interplay of various single processes in a quantitative way. This type of modelling is more common in some disciplines of environmental sciences compared to others which surely introduced some bias in our analysis. In addition, computer models usually serve specific aims and are restricted to certain temporal and spatial scales rather than aiming at representing the complete state of science. That does not only affect the selection of single processes being modelled but also the selection of links between different compartments. For example, geological processes act at different time scales compared to biogeochemical processes in freshwater systems and thus are rarely linked in numerical models. Correspondingly, links that turned out not to be implemented in coupled environmental models are not necessarily deemed essential by experts, as has been shown in this study (cf. Appendix F: Ratio of process representation).

In addition numerous subjective decisions had to be taken that can all be questioned, e.g., with regard to the selection of models, the identification and classification of disciplines, processes, etc. They have been extensively discussed within the group of authors and with additional experts in order to minimize any bias as far as possible.

4.2. Existing and missing links in environmental sciences

Our analysis reveals strong dichotomies in system conceptualization and large differences in process representation and level of integration of environmental compartments among model types. Six main conceptualization issues stand out:

1) In general, the total number of processes linking different disciplines is clearly the largest for the physics category, and the least for the biology category. This has not necessarily to be interpreted in terms of shortcomings of knowledge or of modelling activities in environmental biology. Rather it might point to the fact that quantitative models are more characteristic for the aspirations in the physical categories of environmental disciplines to assess quantitative predictions from first principles whereas there are hardly any rigorous basic equations in biology due to the flexibility

and adaptability of biological systems. Thus a type of models with strict cause-effect relationships might be considered less suitable within biological sciences. On the other hand, the flexibility and adaptability of biological systems significantly hampers the implementation of the respective feedback in physics-type models, wherein they are often treated as more or less static properties. Moreover, this limited predictability might be a reason why highly-interconnected models are less common within the biology category (Figs. 3 and 5) as the uncertainty of coupled models would increase substantially.

2) On the one hand, ecological model types (forest, food web, general ecosystem) have a simplified representation of the physical and chemical environment where the biological system is embedded. On the other hand, models focused on physical and chemical transformations, and/or flow of matter (water, solutes, sediments, energy), have a simplified representation of life forms and biological processes. This pattern was consistent in all physical and chemical model types, from atmospheric and hydrologic modelling (e.g., Lyon et al. 2008) to reactive transport (Steefel et al. 2015), soil evolution and landscape evolution model types (Minasny et al. 2015). Only model types aimed at predicting carbon cycling, trace gas emissions or biogeochemical fluxes (terrestrial biosphere, ecosystem and ecohydrologic biogeochemistry models), or models for which soil biogeochemistry is pervasive for their purpose (agro-ecosystem and water quality models) have a more balanced representation of physical, chemical and biological processes, and a more comprehensive integration of environmental compartments (see Appendix F).

3) There seems to be an important mismatch in the conceptualization of the landscape-aquatic continuum between model types from freshwater sciences and the rest of scientific disciplines in which this continuum is relevant at their spatial scale of application. Aquatic models do not typically integrate landscape (both land surface and soil) and aquatic aspects, and do not explicitly model delivery and transformation processes occurring in the different terrestrial compartments, which are then included as boundary conditions (Bouwman et al. 2013). Conversely, catchment hydrologic model types, including water quality and ecohydrologic models, conceptualize rivers as delivery mechanisms of matter and nutrients to aquatic ecosystems rather than considering them as aquatic ecosystems in their own right, and hence include no or only few in-stream biogeochemical processes, assuming that landscape generation processes are dominant in determining river nutrient loads (Robson 2014). Likewise, integrated models of the terrestrial system (regional climate and terrestrial biosphere models) typically consider three stacked media - subsurface, including ground and surface water, vegetation, and atmosphere, in which freshwaters play a minor role as only physical processes and exchange fluxes of water, energy and momentum between large water bodies and the atmosphere are accounted for. In those model types, biogeochemical and ecological processes are not considered, and rivers, floodplains and wetlands are

neglected despite their role on global carbon cycling and trace gas emissions (Arneth et al. 2010, Fisher et al. 2014, Sutfin et al. 2016).

4) Vertical transport of matter is predominantly represented over lateral fluxes in most model types except for hydrological and hydrogeological models. Overall, the processes of erosion and the transport of sediments, carbon and nutrients in surface runoff and their spatial distribution across the landscape and their delivery to streams and other water bodies are hardly represented in current models from the analysed model types (Minasny et al. 2015, Doetterl et al. 2016, Vereecken et al. 2016b). Likewise, transport of matter in the soil is an issue that overall requires much improvement in many model types analysed here based on the experts' statements (see Table 1). Most model types, except hydrologic, regional climate and reactive transport models, neglect lateral flows of water, sediment, organic matter, and nutrients, and so redistribution across soilscapes.

5) Regarding the conceptualization of the biosphere, faunal processes are hardly considered compared to plant processes, even in ecological model types (except for food web and general ecosystem models), despite their direct and indirect impacts on hydrology (Westbrook et al. 2013) and vegetation and crops dynamics (van der Putten et al. 2009, Fisher et al. 2014), their influence in soil formation and evolution (Samouëlian and Cornu 2008), and their role on mediating carbon dynamics and other biogeochemical cycles (Schmitz et al. 2010, 2014). Fluxes of water, energy, nutrients and pollutants between the atmosphere and soil compartments across the land surface interface are predominantly governed by transport and turnover processes in the soil-vegetation continuum (Grathwohl et al. 2013). In consequence, much emphasis has been put into modelling with ever increasing accuracy plant eco-physiological processes and vegetation dynamics while neglecting their above and belowground interactions with higher trophic level organisms and other life forms.

6) The naïve assumption, that the set of missing links (Fig. 4) would present a pattern inverse to that of implemented links (Fig.2), did not hold. Instead, the emerging patterns show remarkable similarities, not only with regard to a strong bias towards the physical category. This could indicate that even with respect to missing interdisciplinary links researchers tend not to think outside the box of the well-known processes and models. This is in line with another observation, that is, that no clear pattern emerged with respect to suggested future research efforts. Thus our results can hardly be used as a guideline for research strategies. In contrast, there seems to be urgent need for integrated system approaches and a corresponding theoretical basis rather than simply combining results and model approaches from different disciplines. The present study also shows that, in general, missing processes are primarily located in the soil compartment, including mainly chemical - e.g., carbon and nutrients cycles, soil-forming processes and geochemical transformations - and physical - e.g., water,

sediment, solutes and gas transport - processes. In addition, experts claim also a need to better integrate soil physical and chemical knowledge with agronomic and plant physiological knowledge. In addition, despite the importance of soil biological activity, modellers currently lack adequate tools to predict rates of biological processes in specific soil environments or link genetic diversity to soil ecosystem functioning (Vereecken et al. 2016b). Most relevant is the fact that microbial processes are still far from being well understood and accurately incorporated in models. Experts feel that there is need to explicitly consider microbial growth kinetics instead of using conceptual approaches based on first-order decay kinetics of multiple soil organic matter pools, to link specific features affecting model parameters of microbial growth, physiology and activity with spatial and temporal variation in soil physical and chemical properties, to model changes in microbial activity linked to adaptive mechanisms, or to incorporate functional groups to represent microbial diversity (Treseder et al. 2012, Wieder et al. 2013, Tang and Riley 2014).

4.3. Towards an integral understanding of environmental systems

According to the perceptions of the experts we are still far from a full quantitative understanding of environmental systems, as the number of reported missing links is much higher than the number of represented links in most model types. It is not only the fact that relevant links are still missing even in high-end more complex research models, but also that these next-generation models are perceived to be in need to incorporate a larger number of processes and drivers than more simple model types (Figs. 2 and 4). There is a self-reinforcing mechanism at play by which the more complex models get the more complex modellers believe they should evolve. There are certainly highly relevant missing processes that are acknowledged by and recurrent in the literature of most model types. However, the need to incorporate other processes is vastly dependent on the modeller’s perception, and the benefits of their implementation for prediction accuracy compared to their actual constraint to model performance are decidedly uncertain. Thus our meta-analysis was not successful with respect to assessing the paths through which environmental sciences should evolve and determine where future efforts should be focused on. We were able to compile, though, a guidance for in which other discipline modellers might find suitable representations for the links claimed missing in their own discipline (Fig. 6).

According to our results, models used for regional climate systems, ecosystems (i.e., ecosystem biogeochemistry, agro-ecosystem and (agro-) terrestrial biosphere) and water quality processes exhibited the largest degree of interconnectedness (see Appendix F). The dynamic links implemented in these models could be used in other models to replace boundary conditions with simple approaches and conceptualizations borrowed from other interdisciplinary or disciplinary modelling fields (Figs. 6 and E.3), and thus allow for representation of driving feedback interactions between compartments. In this respect, while most comprehensive ecosystem models can transfer conceptualizations and representations of a wider range of processes and factors that are missing in many analysed model types, there are key model types that incorporate rare but potentially highly relevant processes that are missing in most model types, and thus could be central nodes for the evolution of complex integrated numerical models. The transfer of knowledge, conceptualizations and modelling approaches from disciplinary model types that were not covered in this study (e.g., river ecohydrologic, microbial, root, or eco-physiological plant models) will certainly play also a key role in this evolution (Fig. E.3).

Our analysis also reveals that there are still many gaps in knowledge about potentially relevant feedback mechanisms and processes interfacing environmental compartments that preclude the development of more integrated models (Appendix B, Fig. E.3). In this respect, the pedosphere seems to be the great unknown despite its pivotal role on controlling energy and matter (water, sediment and solutes) transfer across the whole terrestrial system as it shares dynamic interfaces with all the rest of environmental compartments, and thus, it is wherein considerable research efforts should focus on to attain a full understanding of the integral environmental system.

No clear pattern emerged from our analysis of proposed dynamic links between different environmental systems' compartments that future research should focus on. This might be considered indicative of a more fundamental problem. Contrary to, e.g., physics or chemistry, environmental sciences so far lack a common sound theoretical basis that would guide research activities outside the boxes of scientific disciplines. Our findings suggest that there is little hope that environmental research would inevitably or pragmatically converge towards an integrated environmental systems theory.

In any case, there seems to be an evident need of integrated system-based terrestrial research platforms in which ecosystem-level monitoring and long-term cause/effect-based experimentation can provide data and understanding on interactions and feedbacks between physical, chemical and biological processes in such a way that novel modelling approaches and theoretical frameworks can be developed and tested. These research infrastructures should employ a cross-scale and multi-compartment approach, covering large spatial scales to allow for testing novel upscaling techniques.

5. Conclusion

Environmental systems have been proven to be subject to numerous links and feedbacks between the realms of different scientific disciplines. However, these links are neither well studied due to the disciplinary structure of environmental research, nor is there a systematic survey for possible blind spots in science. This study aimed at providing some basic information and first evidence. To that end, an extensive review was performed, analysing 346 review papers with respect to interdisciplinary links implemented in 23 model types (118 models) from eight environmental disciplines as well as compiling missing links postulated in the scientific literature.

Key findings and their implications were:

- There were clear and significant differences between model types and disciplines with respect to implemented interdisciplinary links. The most wide-spread interdisciplinary links are between physical processes in meteorology, hydrology and soil science that drive or set the boundary conditions (e.g., air temperature, precipitation) for other processes. In addition, there are many interdisciplinary and/or inter-category links established from or to terrestrial ecology processes, comprising physical as well as chemical and biological processes. In contrast, freshwater and geological processes were hardly linked to processes in other environmental disciplines.
- Interdisciplinary physical processes were the most commonly implemented, and biological processes the least ones. That could be, partly at least, due to principally differing basic properties of physical versus biological systems. Including more biological processes in existing models seems to be more than just a technical challenge due to less strict cause-effect relationships of biological compared to physical processes in environmental systems.
- Many of the missing links postulated in the literature for single model types are already implemented in other model types. Thus single model types could benefit substantially from other model types.
- Missing interdisciplinary links stated in the literature tended to mimic the pattern of existing links. In addition, missing links have mostly been postulated for complex models. Thus there is a clear tendency in the scientific literature to reinforce the existing rather than at identifying new emerging fields of interdisciplinary environmental sciences as a guideline for future research strategies.

This study is a first step. We highly encourage similar studies following different approaches. We strongly feel that an inventory of the state of the science and identification of strengths and weaknesses of current research of the terrestrial environment would be worthwhile to foster scientific progress beyond disciplinary boundaries.

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Table 1. Degree to which analysed model types represent main categories of processes and factors from the different environmental compartments based on model purpose. Symbols indicate: ✓ accurate representation, ≈ representation should be improved, × poor or lack of representation, — representation not necessary.

Scientifc disciplines	Atmospheric science			Hydrology					Soil science			Geology		Terrestrial ecology				Freshwater science		Agricultural sciences		Forestry sciences	
Processes/Model types	RCM	Hydro-RCM	RCSM	Hydro	Macro-Hydro	Hydro-WQ	EcoHydro	EcoHydro-BGC	Ecosyst-BGC	Soil-Evo-prof	Soil-Evo-land	React-Trans	LEM	TBMoff	TBMon	Food-web	GEM	River	Lake	Agro-Eco	Agro-TBM	Forest-land	Forest-gap
Atmosphere																							
Atmospheric physics	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Atmospheric chemistry	✓	×	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Land surface																							
Land surface-Atmosphere water fluxes	✓	✓	✓	✓	≈	≈	✓	✓	≈	×	×	×	—	✓	✓	—	—	×	×	≈	✓	×	×
Land surface-Atmosphere energy fluxes	✓	✓	✓	≈	≈	×	≈	≈	≈	×	×	×	—	✓	✓	—	—	—	—	×	✓	—	—
Land surface hydrology	≈	✓	✓	✓	≈	✓	✓	✓	≈	×	≈	×	≈	≈	✓	×	×	×	×	≈	≈	×	×
Soil erosion	—	—	—	✓	×	✓	×	×	×	×	✓	×	✓	—	—	—	—	×	×	≈	×	—	—
Sediment transport	—	—	—	✓	×	✓	×	×	×	×	✓	×	✓	—	—	—	—	×	×	×	×	—	—
Solute transport	—	—	—	✓	×	≈	×	×	×	×	×	×	—	—	—	—	—	×	×	×	×	—	—
Soil																							
Surface-subsurface water flow coupling	×	✓	✓	✓	×	×	×	×	—	—	—	×	—	—	×	—	—	—	—	—	—	—	—
Soil hydrology	×	✓	✓	✓	≈	≈	≈	≈	≈	≈	×	✓	×	≈	≈	×	×	×	×	≈	≈	×	×
SOM cycling	×	×	✓	—	×	≈	×	✓	✓	≈	×	—	—	✓	✓	×	×	×	×	✓	✓	≈	≈
N cycling	×	×	×	—	×	≈	×	≈	✓	×	×	—	—	≈	≈	×	×	×	×	✓	≈	×	×
P cycling	×	×	×	—	×	≈	×	×	≈	—	—	—	—	×	×	—	—	×	×	≈	×	×	×
Trace gas emissions	×	×	≈	—	—	—	—	≈	✓	—	—	✓	—	≈	≈	—	—	—	—	≈	≈	×	×
Microbial processes	×	×	×	—	—	×	—	×	≈	×	×	×	—	×	×	×	×	×	×	×	×	×	×
Chemical weathering	—	—	—	×	—	×	×	×	×	✓	≈	✓	×	—	—	—	—	—	—	—	—	—	—
Heat transfer	≈	✓	✓	≈	×	×	≈	≈	≈	×	×	✓	×	≈	✓	—	—	—	—	≈	×	—	—
Gas transport	—	—	×	—	—	—	—	×	≈	≈	×	✓	—	×	×	—	—	—	—	—	×	—	—
Solute transport	—	—	—	✓	×	✓	×	×	×	≈	×	✓	—	×	×	×	—	×	×	×	×	×	×
Reactive transport	—	—	—	×	—	×	—	—	×	≈	×	✓	×	—	—	—	—	—	—	×	—	—	—
Soil genesis and evolution	—	—	—	×	—	×	×	×	×	✓	≈	×	×	—	—	—	—	—	—	×	—	—	—
Vegetation																							
Soil-Plant-Atmosphere system fluxes	✓	✓	✓	×	×	≈	✓	✓	✓	×	×	×	—	✓	✓	×	—	×	×	≈	✓	≈	≈
Plant eco-physiology	×	×	≈	×	×	≈	✓	✓	≈	×	×	×	×	✓	✓	×	×	×	×	≈	✓	≈	≈
Vegetation dynamics	×	×	≈	×	×	×	≈	≈	≈	×	×	×	×	≈	≈	≈	≈	×	×	≈	≈	✓	✓
Trace gas emissions	×	×	≈	—	—	—	—	≈	≈	—	—	—	—	≈	≈	—	—	—	—	—	≈	×	×
Root dynamics	×	×	×	×	×	×	≈	≈	≈	×	×	×	—	≈	≈	—	—	×	×	≈	≈	≈	≈
Roots-Soil interactions	×	×	×	×	×	×	×	×	≈	×	×	×	—	×	×	—	—	×	×	≈	×	×	×
Soil-Plant biogeochemistry coupling	×	×	×	—	×	≈	×	≈	✓	×	×	×	—	✓	✓	×	×	×	×	✓	✓	×	×
Disturbances	×	×	≈	×	×	×	≈	≈	×	×	×	—	×	≈	≈	×	×	×	×	×	≈	✓	✓
Forestry																							
Harvest	×	×	×	—	×	×	×	≈	≈	—	—	—	—	≈	≈	—	—	—	—	—	—	✓	✓
Forestry practises	—	—	—	—	—	—	×	×	≈	—	—	—	—	×	×	—	—	—	—	—	—	✓	✓
Agriculture																							
Crops dynamics	×	×	×	—	×	≈	×	≈	≈	—	—	—	—	≈	≈	—	—	×	×	✓	✓	—	—
Harvest	×	×	×	—	×	≈	×	≈	≈	—	—	—	—	≈	≈	—	—	×	×	✓	✓	—	—
Agricultural practises	×	×	×	—	×	≈	×	≈	≈	—	—	—	—	×	×	—	—	×	×	✓	≈	—	—
Irrigation	×	×	×	×	×	≈	×	≈	≈	—	—	—	—	≈	≈	—	—	×	×	✓	✓	—	—
Fauna																							
Plant-hervibore interactions	—	—	—	—	—	—	×	×	×	—	—	—	—	×	×	✓	✓	—	—	×	×	×	×
Trophic interactions	—	—	—	—	—	—	×	×	×	—	—	—	—	×	×	✓	✓	—	—	—	—	×	×
Non-trophic interactions	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	≈	×	—	—	—	—	—	—
Nutrients flux across trophic levels	—	—	—	—	—	—	×	×	×	—	—	—	—	×	×	×	×	—	—	—	×	×	×
Freshwaters																							

Groundwater-surface water flow/solutes fluxes	×	≈	×	✓	×	≈	×	×	—	—	—	—	—	×	×	—	—	×	×	—	×	—	—
Atmosphere-surface water water/energy fluxes	≈	×	≈	≈	≈	×	×	×	—	—	—	—	—	×	✓	—	—	✓	✓	—	×	—	—
River routing	×	≈	≈	✓	✓	✓	✓	✓	—	—	×	—	✓	×	≈	—	×	✓	✓	—	×	—	—
Channel erosion/deposition	—	—	—	×	×	≈	×	×	—	—	×	—	✓	—	—	—	—	≈	—	—	—	—	—
Solute transport	—	—	—	✓	×	✓	—	×	—	—	—	—	—	—	—	—	—	✓	—	—	—	—	—
Biogeochemistry	—	—	×	—	×	≈	—	×	—	—	—	—	—	—	—	—	×	✓	✓	—	—	—	—
Trophic interactions	—	—	—	—	—	×	—	×	—	—	—	—	—	—	—	—	×	✓	✓	—	—	—	—
Riparian areas	—	—	×	×	×	×	×	×	—	—	—	—	—	×	×	—	—	×	×	—	—	—	—
Lakes/wetlands/Reservoirs	≈	≈	≈	×	≈	≈	×	×	—	—	—	—	✓	×	✓	—	×	✓	✓	—	×	—	—
Trace gas emissions	×	×	×	—	—	—	—	×	—	—	—	—	—	×	×	—	—	✓	✓	—	×	—	—